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ATTENUATION OF LYMAN-ALPHA EMISSION BY DUST IN DAMPED LYMAN-ALPHA SYSTEMS

STÉPHANE CHARLOT[1] AND S. MICHAEL FALL
Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218
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ABSTRACT

We derive relations between the Lyα surface brightness, star formation rate, and abundance of dust in damped Lyα absorption systems. These are idealized as plane-parallel objects in which the sources of Lyα photons are either distributed throughout the gas or confined to a thin, central sheet. For the dust-to-gas ratio in the damped Lyα systems, we adopt the typical value inferred from the reddening of background quasars. We then use the results of several recent searches for Lyα emission to set limits on, and in one case, estimate the star formation rate per unit area of the damped Lyα systems. When the H I column density exceeds 5×10^{20} cm^{-2}, the attenuation of Lyα emission is large and the star formation rate can be one or two orders of magnitude higher than that in the solar neighborhood. The large uncertainties are caused by the unknown orientations of the damped Lyα systems and the unknown distributions of stars, gas, and dust within them. However, when the H I column density is less than 5×10^{20} cm^{-2}, the attenuation is smaller and the limits on or value of the star formation rate per unit area are similar to that in the solar neighborhood, a few $M_\odot$ Gyr^{-1} pc^{-2}.

Subject headings: cosmology — galaxies: evolution — galaxies: formation — galaxies: interstellar matter — quasars — radiative transfer

1. INTRODUCTION

The damped Lyα systems discovered as strong absorption features in the spectra of background quasars are generally thought to be the high-redshift analogs or progenitors of ordinary galactic disks (see Wolfe 1990 for a review). In the past few years, there have been several searches for Lyα emission from the damped Lyα systems, both by narrow-band imaging and long-slit spectroscopy (Foltz, Chaffee, & Weymann 1986; Smith et al. 1989; Wolfe 1989; Deharveng, Buat, & Bowyer 1990; Hunstead, Pettini, & Fletcher 1990; Pettini, Boksenberg, & Hunstead 1990). The objective of these searches was to determine the star formation rates and linear sizes of the damped Lyα systems. All but one produced null results. Recently, dust has been detected and confirmed in the damped Lyα systems through the reddening of the background quasars (Fall, Pei, & McMahon 1989; Pei, Fall, & Bechtold 1991). The best estimate of the typical dust-to-gas ratio in the damped Lyα systems is 5%–20% of that in the Milky Way. Is this enough dust to extinguish the Lyα emission; or do the null results of the searches imply that the star formation rates in the damped Lyα systems are lower than those expected in galactic or protogalactic disks? Our purpose is to answer these questions. The formulae presented here should also be useful in the interpretation of future searches for Lyα emission from damped Lyα systems and other objects at high redshifts.

2. PRODUCTION OF LYMAN-ALPHA PHOTONS

We first calculate the Lyα emission of a star-forming system with no dust. Lyα photons, with energy $h\nu_\alpha = 10.2$ eV, are produced in case B recombination if the H I column density of the ambient medium exceeds the inverse cross section at the Lyman limit, about 10^{17} cm^{-2}. The fraction of ionizing photons that lead to the emission of Lyα photons is then $\alpha^{\rm eff}_{2\,^2P}/\alpha_{\rm B}$, where $\alpha_{\rm B}$ is the case B recombination coefficient (i.e., to all levels with $n \geq 2$), and $\alpha^{\rm eff}_{2\,^2P}$ is the "effective" recombination coefficient to the $2p$ level (Osterbrock 1989). This fraction, which depends weakly on the temperature, is 0.68 for 10^4 K (Spitzer 1978). Lyα photons are produced mainly in H II regions ionized by massive stars and in the radiative shocks of supernova remnants. We compute these two contributions, $L_{\rm H\,II\alpha}$ and $L_{\rm SNR\alpha}$, to the total Lyα luminosity L_α of a galaxy forming stars at a rate $\dot{M}_S$ with an initial mass function $\phi(m)$ [abbreviated IMF and defined such that $\phi(m)dm$ is the number of stars created with masses between m and $m + dm$].

The Lyα luminosity produced by H II regions can be expressed as

$$\frac{L_{\rm H\,II\alpha}}{\dot{M}_S} = 0.68 h\nu_\alpha \frac{\int_0^\infty dm\phi(m)\dot{n}_{\rm UV}(m)t_{\rm MS}(m)}{\int_0^\infty dm\, m\phi(m)} , \tag{1}$$

where $\dot{n}_{\rm UV}(m)$ is the average number of ionizing photons emitted per unit time by a star with an initial mass m during its main-sequence lifetime $t_{\rm MS}(m)$. Both $\dot{n}_{\rm UV}(m)$ and $t_{\rm MS}(m)$ depend on the metallicity. We adopt $Z = 0.1\ Z_\odot$, consistent with recent observations of several damped Lyα systems (see Pei et al. 1991 for a critical discussion). Using atmospheres and evolutionary tracks for massive stars with this metallicity (Kurucz 1988; Maeder 1990), we derive the approximate formulae

$$\log\,[t_{\rm MS}(m)/{\rm yr}] = 9.23 - 2.32 \log\,(m/M_\odot) + 0.49 \log^2\,(m/M_\odot) , \tag{2}$$

$$\log\,[\dot{n}_{\rm UV}(m)/{\rm s}^{-1}] = 39.78 + 8.74 \log\,(m/M_\odot) - 1.83 \log^2\,(m/M_\odot) , \tag{3}$$

for $m \gtrsim 10\ M_\odot$. Shull & Silk (1979) have computed the UV luminosity produced by a distribution of supernova remnants using a radiative-shock code for low metallicities. We use their results, which depend on the supernova rate, the ambient density $n_{\rm H}$, and the typical supernova energy E_0, to compute

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[1] On leave from Observatoire de Paris and Université Paris VII.

$L_{\mathrm{SNR}\alpha}$. Reexpressing the supernova rate in equation (1) of Shull & Silk in terms of the star formation rate and IMF, we obtain

$$\frac{L_{\mathrm{SNR}\alpha}}{\dot{M}_S} = 5.9 \times 10^{61} h\nu_\alpha \left(\frac{n_{\mathrm{H}}}{\mathrm{cm}^{-3}}\right)^{-1/2} \times \left(\frac{E_0}{10^{51}\ \mathrm{ergs}}\right)^{3/4} \frac{\int_{m_{\mathrm{SN}}}^{\infty} dm\, \phi(m)}{\int_0^{\infty} dm\, m\phi(m)}, \qquad (4)$$

where m_{SN} is the lower mass limit for a star to explode as a supernova, about 8 $M_\odot$ according to current estimates (Kennicutt 1984).

To evaluate $L_{\mathrm{H\,II}\alpha}/\dot{M}_S$ and $L_{\mathrm{SNR}\alpha}/\dot{M}_S$, we assume that the IMF can be approximated by a single power law, $\phi(m) \propto m^{-(1+x)}$, with an exponent x and lower and upper cutoff masses m_L and m_U. Inserting this in equations (1) and (4) and using equations (2) and (3) gives

$$\frac{L_{\mathrm{H\,II}\alpha}}{\dot{M}_S} = 2.1 \times 10^{12} \frac{(1-x)\exp(y^2)}{(m_U^{1-x} - m_L^{1-x})} \times [\mathrm{erf}(0.76 \ln m_U - y) - \mathrm{erf}(1.76 - y)]\ \mathrm{ergs\ g^{-1}}\,, \qquad (5)$$

$$\frac{L_{\mathrm{SNR}\alpha}}{\dot{M}_S} = 4.8 \times 10^{17} \left(\frac{n_{\mathrm{H}}}{\mathrm{cm}^{-3}}\right)^{-1/2} \left(\frac{E_0}{10^{51}\ \mathrm{ergs}}\right)^{3/4} \times \frac{(x-1)(m_U^{-x} - m_{\mathrm{SN}}^{-x})}{x(m_U^{1-x} - m_L^{1-x})}\ \mathrm{ergs\ g^{-1}}\,, \qquad (6)$$

with $y \equiv 4.21\text{–}0.66x$ and m_L and m_U in units of the solar mass. Since both $L_{\mathrm{H\,II}\alpha}$ and $L_{\mathrm{SNR}\alpha}$ are produced by massive stars, the ratio $L_{\mathrm{H\,II}\alpha}/L_{\mathrm{SNR}\alpha}$ depends very weakly on m_L. Figure 1 shows $L_{\mathrm{H\,II}\alpha}/L_{\mathrm{SNR}\alpha}$ as a function of the IMF slope and upper cutoff mass with several values of the ambient density. For $x \lesssim 2$ and $m_U \gtrsim 50\ M_\odot$, $L_{\mathrm{H\,II}\alpha}$ exceeds $L_{\mathrm{SNR}\alpha}$ over a wide range of n_{H}. In particular, for a Salpeter IMF ($x = 1.35$) with an upper cutoff $m_U = 100\ M_\odot$, and for $n_{\mathrm{H}} \approx 1\ \mathrm{cm}^{-3}$, as in the solar neighborhood, we have $L_{\mathrm{H\,II}\alpha}/L_{\mathrm{SNR}\alpha} \approx 7$. Hence, supernova remnants make only a minor contribution to the total Lyα luminosity. For completeness, however, we include $L_{\mathrm{SNR}\alpha}$ in all the calculations reported in this paper.

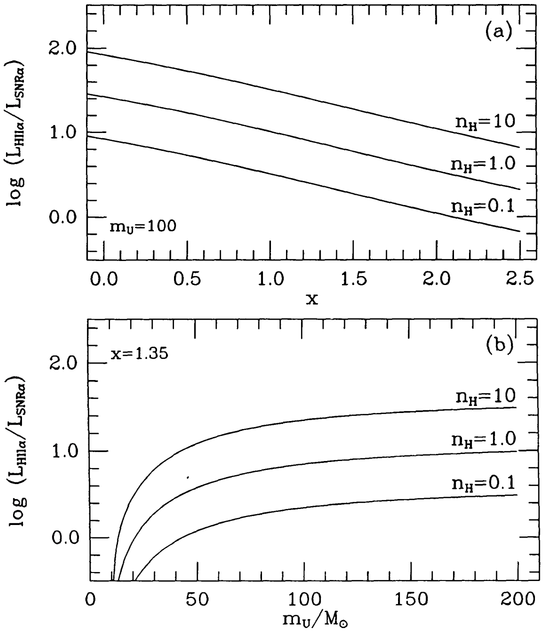

FIG. 1.—Ratio of the Lyα luminosity produced by H II regions to that produced by supernova remnants $L_{\mathrm{H\,II}\alpha}/L_{\mathrm{SNR}\alpha}$ for different values of the ambient density n_{H} (in cm^{-3}) (*a*) as a function of the IMF slope x, with fixed upper mass cutoff m_U; and (*b*) as a function of m_U, with fixed x. The models have the metallicity 0.1 $Z_\odot$.

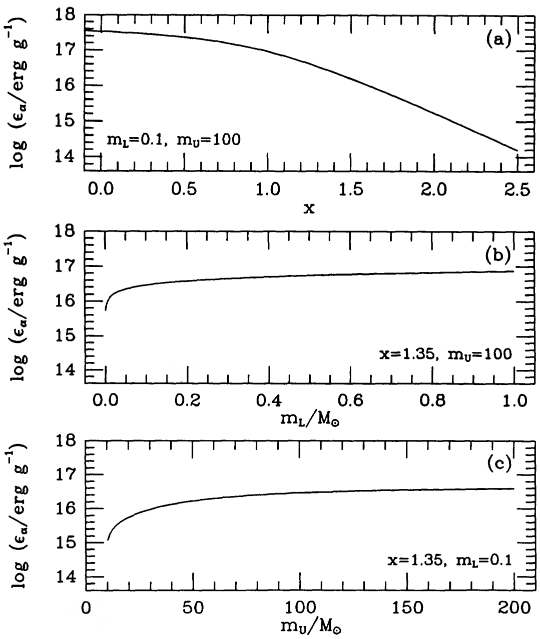

FIG. 2.—Efficiency parameter $\epsilon_\alpha \equiv L_\alpha/\dot{M}_S$ for the production of Lyα photons: (*a*) as a function of the IMF slope x, with fixed upper mass cutoff m_U and lower mass cutoff m_L; (*b*) as a function of m_L, with fixed x and m_U; (*c*) as a function of m_U, with fixed x and m_L. The models have the metallicity 0.1 $Z_\odot$.

We relate the total Lyα luminosity to the star formation rate by the "efficiency" parameter

$$\epsilon_\alpha \equiv L_\alpha/\dot{M}_S = (L_{\mathrm{H\,II}\alpha} + L_{\mathrm{SNR}\alpha})/\dot{M}_S\,. \qquad (7)$$

Figure 2 shows the dependence of ϵ_α on the IMF parameters x, m_L, and m_U. As the IMF steepens, the birth rate of massive stars and hence the production of ionizing photons decrease relative to the total star formation rate. However, ϵ_α depends only weakly on the lower and upper cutoff masses. In the following, it proves convenient to express the efficiency in units of $\epsilon_{S\alpha} = 2.9 \times 10^{16}$ ergs g^{-1}, the value for a Salpeter IMF with $m_L = 0.1\ M_\odot$ and $m_U = 100\ M_\odot$. The efficiency parameter would be about 15% smaller if we had used models with solar abundances. Our expressions for $L_{\mathrm{H\,II}\alpha}/\dot{M}_S$ and $L_{\mathrm{SNR}\alpha}/\dot{M}_S$, and therefore ϵ_α, are valid so long as the star formation rate varies slowly over the lifetimes of the stars that produce the ionizing radiation, about 10^7 yr.

3. ABSORPTION OF LYMAN-ALPHA PHOTONS

The resonant scattering of Lyα photons by atomic hydrogen increases enormously their chances of absorption by dust grains. We now quantify this effect. We define f_e as the fraction of Lyα photons that escape in all directions from a damped Lyα system, idealized here as a plane-parallel medium. The damped Lyα systems may in fact be planar objects, but in any case, the transfer of Lyα radiation has only been solved accurately for this geometry. Hummer & Kunasz (1980) have computed f_e numerically for two configurations of a static, plane-parallel medium: one in which Lyα photons are produced at a rate proportional to the local density of the gas ("distributed" sources) and the other in which Lyα photons are produced only in a thin, central sheet ("midplane" sources). Neufeld (1990) has derived an analytic expression for the attenuation with midplane sources that agrees with the results of Hummer & Kunasz. In the Milky Way, the layer of H II regions and supernova remnants is about half as thick as the H I layer (Guibert, Lequeux, & Viallefond 1978), suggesting a case intermediate between distributed and midplane sources.

The calculations by Hummer & Kunasz (1980) and Neufeld (1990) indicate that, over a wide range of parameters, f_e can be expressed as a function of the single variable $\Delta \equiv N_{\mathrm{H\,I}\perp}/N_{\mathrm{H\,Icrit}}$, where $N_{\mathrm{H\,I}\perp}$ is the H I column density of a damped Lyα system viewed face-on, and $N_{\mathrm{H\,Icrit}}$ is the "critical" value at which Lyα photons are thermalized. $N_{\mathrm{H\,Icrit}}$ depends on the line-of-sight velocity dispersion σ_V and on the abundance of dust. Following Fall et al. (1989), we use the notation $k \equiv 10^{21}(\tau_B/N_{\mathrm{H\,I}})\ \mathrm{cm}^{-2}$, where τ_B is the extinction optical depth in the rest-frame B band. Arguments first given by Adams (1975) then imply

$$N_{\mathrm{H\,Icrit}} = 1.85 \times 10^{20}(\sigma_V/10\ \mathrm{km\ s}^{-1})^{1/2}(k\delta/0.2)^{-3/4}\ \mathrm{cm}^{-2}\ , \tag{8}$$

where δ is the ratio of the absorption optical depth in the continuum near Lyα to the extinction optical depth in the B band.[2] Both k and δ depend on the properties of the dust. The absence of strong extinction near 2200 Å in the rest frames of several damped Lyα systems probably rules out Galactic-type dust but is consistent with LMC or SMC-type dust. The most probable values of the dust-to-gas ratio in the damped Lyα systems, inferred from the reddening, are $k_p = 0.09^{+0.06}_{-0.02}$ (LMC) and $0.06^{+0.03}_{-0.01}$ (SMC) (Pei et al. 1991). By adjusting the proportions of silicates and graphite in the Draine & Lee (1984) model to reproduce the observed extinction curves in the LMC and SMC, Pei (1990) computed $\delta = 2.1$ (LMC) and 2.7 (SMC), which imply $k_p\delta = 0.19^{+0.13}_{-0.04}$ (LMC) and $0.16^{+0.08}_{-0.03}$ (SMC). We therefore consider the range $0.1 \leq k\delta \leq 0.3$. We also adopt $\sigma_V = 10\ \mathrm{km\ s}^{-1}$, a value that is likely to be typical in the "quiescent" component of the gas in damped Lyα systems (Turnshek et al. 1989).

We use the following approximations to the fraction of escaping Lyα photons:

$$f_e(\Delta) = \begin{cases} (2\Delta/3)^{-1}[1 - \exp(-2\Delta/3)] & \text{for distributed sources}\ , \\ \mathrm{sech}\,(\Delta^{2/3}) & \text{for midplane sources}\ . \end{cases} \tag{9}$$

The first expression provides a good fit to the numerical results of Hummer & Kunasz (1980) over the range $0 \lesssim \Delta \lesssim 25$ (with an accuracy of 1% or better). It has the required limiting form $f_e(\Delta) \propto 1/\Delta$ and should therefore remain valid for $\Delta \gtrsim 25$. The second expression, derived by Neufeld (1990), breaks down for $\Delta \gtrsim 40$. This does not affect our results because the strongest damped Lyα systems have $N_{\mathrm{H\,I}\perp} \lesssim 5 \times 10^{21}\ \mathrm{cm}^{-2}$, implying $\Delta \lesssim 30$. Figure 3 shows $f_e(\Delta)$ as computed by Hummer & Kunasz and from equation (9). The attenuation is weaker for distributed sources because in this case some Lyα photons are produced near the surface, where they have a better chance of escaping. For $\Delta \lesssim 3$, corresponding to $N_{\mathrm{H\,I}\perp} \lesssim 5 \times 10^{20}\mathrm{cm}^{-2}$, the value of f_e for distributed sources differs from that for midplane sources by less than a factor of two. However, for $\Delta \gtrsim 10$, and hence $N_{\mathrm{H\,I}\perp} \gtrsim 2 \times 10^{21}\ \mathrm{cm}^{-2}$, the difference is more than a factor of eight.

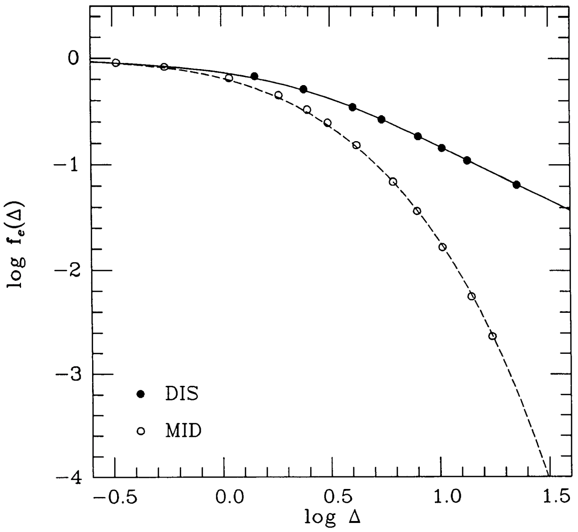

FIG. 3.—Fraction of escaping Lyα photons f_e as a function of the dimensionless column density $\Delta \equiv N_{\mathrm{H\,I}\perp}/N_{\mathrm{H\,Icrit}}$ in plane-parallel geometry. The numerical solutions of Hummer & Kunasz (1980) are indicated by filled circles for distributed sources and by open circles for midplane sources. The approximations given in eq. (9) are shown as the solid and dashed curves.

The examples of distributed and midplane sources considered above might not encompass all possibilities. Depending on the topology of the H II regions in which the Lyα photons are produced, the range of attenuations could be even wider than that shown in Figure 3. If all the H II regions were isolated from each other, the surrounding H I would repeatedly scatter the Lyα photons back into the H II regions, where they would eventually be absorbed by dust (Spitzer 1978). The fraction of Lyα photons that escape from the damped Lyα systems would then be lower than the values given by equation (9). If, on the other hand, all the H II regions were connected to each other and to the outside surface, the embedded H I clouds would scatter the Lyα photons throughout the system (Neufeld 1991). The fraction that escape could then be very close to unity. Hence, while we adopt the two expressions in equation (9) as an illustrative range for f_e, we emphasize that the actual range, with realistic interstellar media, could be even wider.

4. SURFACE BRIGHTNESSES AND STAR FORMATION RATES

We now use the relations given in the previous sections to interpret the results of searches for Lyα emission from damped Lyα systems. The Lyα surface brightness of a damped Lyα system viewed at an angle θ to the normal at a redshift z can be written as $I_\alpha = f_e(\Delta)g(\theta)l_\alpha/4\pi(1+z)^4$, where l_α is the Lyα luminosity produced per unit area of the system, and $f_e\,g(\theta)/4\pi$ is the fraction of Lyα photons emitted per unit solid angle in the direction θ. In terms of the efficiency parameter ϵ_α and the star formation rate per unit area $\dot{\mu}_S$, we have $l_\alpha = \epsilon_\alpha \dot{\mu}_S$. The face-on H I column density of a damped Lyα system is related to the observed (i.e., line-of-sight) value by $N_{\mathrm{H\,I}\perp} = N_{\mathrm{H\,I}} \cos\theta$, implying $\Delta = N_{\mathrm{H\,I}} \cos\theta/N_{\mathrm{H\,Icrit}}$. We then have

$$I_\alpha = 3.6 \times 10^{-16}(1+z)^{-4}g(\theta)f_e(N_{\mathrm{H\,I}}\cos\theta/N_{\mathrm{H\,Icrit}})(\epsilon_\alpha/\epsilon_{S\alpha}) \times (\dot{\mu}_S/M_\odot\ \mathrm{Gyr}^{-1}\ \mathrm{pc}^{-2})\ \mathrm{ergs\ s^{-1}\ cm^{-2}\ arcsec^{-2}}\ . \tag{10}$$

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[2] Our expression for $N_{\mathrm{H\,Icrit}}$ has the same dependence on σ_V and k as the one proposed by Fall et al. (1989) but is larger by about 25%. We have chosen the coefficient in eq. (8) so that Δ is $Y_0^{3/2}$ in the notation of Neufeld (1990), which simplifies eq. (9) for midplane sources. In the notation of Hummer & Kunasz (1980), Δ is $2.40\alpha^{3/4}$ for distributed sources and $1.84\alpha^{3/4}$ for midplane sources.

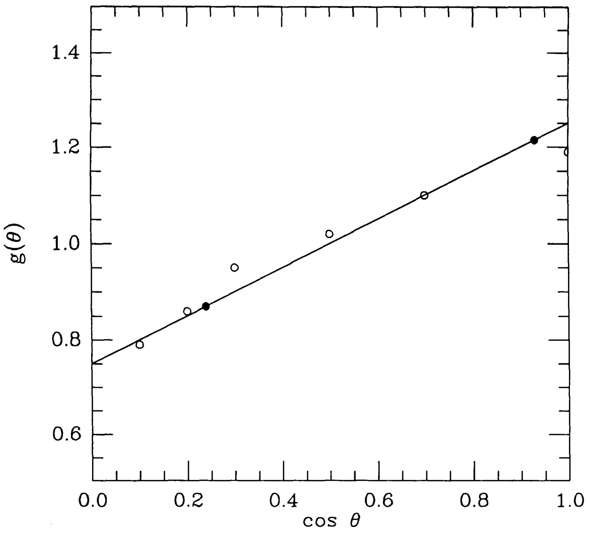

FIG. 4.—Limb darkening g as a function of the cosine of the angle θ to the normal of a plane-parallel atmosphere. The numerical solutions of Vardavas (1976) for dipole scattering and of Shine et al. (1975) for isotropic scattering are indicated respectively by filled and open circles. Both sets of calculations include partial redistribution in frequency with Doppler and radiation broadening. The approximation adopted here is shown by the straight line.

This formulation, in terms of the Lyα surface brightness and the star formation rate per unit area, is independent of the Hubble constant, the cosmological deceleration parameter, and the unknown sizes of the damped Lyα systems.

The "limb-darkening" function $g(\theta)$ for the resonance-line radiation emitted by a plane-parallel atmosphere has been calculated in several different approximations. These include isotropic and dipole scattering, complete and partial redistribution in frequency, and in the last case, pure Doppler and a combination of Doppler and radiation broadening (Hummer 1970; Milkey, Shine, & Mihalas 1975; Shine, Milkey, & Mihalas 1975; Vardavas 1976). While the limb darkening is moderately sensitive to the redistribution in frequency, it depends remarkably little on the angular form of the scattering. This is shown in Figure 4 for the more realistic case of partial redistribution in frequency with Doppler and radiation broadening. As an approximation, we adopt $g(\theta) = 0.75 + 0.50 \cos\theta$, which matches the values computed by Vardavas with dipole scattering for $\cos\theta = 0.24$ and 0.93 and has the required normalization $\int_0^1 d(\cos\theta) g(\theta) = 1$. It appears, from the two calculations known to us, that the limb darkening is little affected by the continuum opacity and therefore the abundance of dust in the medium (Hummer 1970; Vardavas 1976).

We list in Table 1 the observational limits on the Lyα surface brightness of several damped Lyα systems (Smith et al. 1989; Wolfe 1989) and, for the absorber toward Q0836+113, a possible measurement of I_α (Hunstead et al. 1990).[3] Also listed are the limits on $\dot{\mu}_S$ from equation (10) for a Salpeter IMF, two possible orientations of the damped Lyα systems, $\theta = 0°$ and $60°$, and two assumptions about the dust, $k\delta = 0.1$ and 0.3. The upper limits on the star formation rates range from 4 up to 900 $M_\odot$ Gyr^{-1} pc^{-2} and, in one case, 4×10^4 $M_\odot$ Gyr^{-1} pc^{-2}. For comparison, the value in the solar neighborhood is $\dot{\mu}_S \sim$ 1–5 $M_\odot$ Gyr^{-1} pc^{-2} (Tinsley 1980). The wide range of limits on the star formation rates in damped Lyα systems with the highest H I column densities is caused by a combination of the unknown orientations and unknown distributions of stars, gas, and dust (exemplified here by distributed and midplane sources). We note that the claimed detection of Lyα emission from the absorber toward Q0836+113 implies $5 \lesssim \dot{\mu}_S \lesssim 14$ $M_\odot$ Gyr^{-1} pc^{-2} for $0.1 \leq k\delta \leq 0.3$. In this case, the modest range of star formation rates is a consequence of the relatively small H I column density.

Irrespective of the star formation activity in the damped Lyα systems, some Lyα emission will be induced by the extragalactic UV background (Hogan & Weymann 1987; Songaila, Cowie, & Lilly 1990). We now estimate the magnitude of this effect. Most of the ionizing photons incident on a damped Lyα system produce Lyα photons after they have traversed a column density of order 10^{17} cm^{-2}. The interior H I then scatters nearly all Lyα photons back into intergalactic space (Neufeld 1990). We refer to this process as "reflection" even though the emitted photons have wavelengths different from the absorbed photons. The ionized outer layers of the damped Lyα systems have column densities so much smaller than $N_{\rm H\,Icrit}$ that absorption by dust can be neglected.

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[3] There are four other limits in the literature: $I_\alpha < 8.2 \times 10^{-17}$ and 9.4×10^{-17} ergs s^{-1} cm^{-2} arcsec^{-2} at the 3 σ level, respectively, for the absorbers toward PHL 957 and Q1331+170 (Foltz et al. 1986), $I_\alpha < 4.5 \times 10^{-17}$ ergs s^{-1} cm^{-2} arcsec^{-2} at the 3 σ level for the absorber toward PHL 957 (Pettini et al. 1990), and $I_\alpha < 1.6 \times 10^{-16}$ ergs s^{-1} cm^{-2} arcsec^{-2} at about the 1.3 σ level for the absorber toward Q0216+080 (Deharveng et al. 1990). These are weaker than the limits included in Table 1 and consequently provide only loose constraints on the star formation rates.

TABLE 1

UPPER LIMITS ON STAR FORMATION RATES IN DAMPED LYMAN-ALPHA SYSTEMS

						$\dot{\mu}_S(\theta = 0°)$		$\dot{\mu}_S(\theta = 60°)$	
Quasar	$z_{\rm abs}$	$N_{\rm H\,I}/10^{21}$	Reference	$I_\alpha/10^{-18}$	Reference	$k\delta = 0.1$	$k\delta = 0.3$	$k\delta = 0.1$	$k\delta = 0.3$
PHL 957	2.31	2.5	1	<6.5	4	9.3–48	21–900	6.2–14	13–86
Q0458−020	2.04	5.0	2	<6.8	5	14–380	32–40000	8.7–45	20–840
Q0528−250	2.81	1.3	3	<9.8	4	14–31	29–210	11–15	19–49
Q0836+113	2.47	0.4	2	11	6	5.3–6.3	8.1–14	5.4–5.7	6.9–8.7
Q1337+113	2.80	0.8	2	<4.9	4	4.7–7.6	9.1–29	4.2–5.1	6.5–11
Q2348−011	2.62	1.8	2	<3.3	4	5.0–16	11–170	3.6–6.1	7.0–27

NOTES.—$N_{\rm H\,I}$ in cm^{-2}; I_α in ergs s^{-1} cm^{-2} arcsec^{-2}; $\dot{\mu}_S$ in $M_\odot$ Gyr^{-1} pc^{-2}. Except for Q0836+113, the entries under $\dot{\mu}_S$ are all upper limits. The lower end of each range is for distributed sources (weakest attenuation), and the upper end is for midplane sources (strongest attenuation).

REFERENCES.—(1) Black, Chaffee, & Foltz 1987; (2) Turnshek et al. 1989; (3) Foltz, Chaffee, & Black 1988; (4) Smith et al. 1989 (3 σ upper limit in an area of 3".5 × 3".5 from narrow-band imaging); (5) Wolfe 1989 (4 σ upper limit in an area of 4".0 × 4".0 from narrow-band imaging); (6) Hunstead, Pettini, & Fletcher 1990 (4 σ detection in an area of 1".2 × 2".2 from long-slit spectroscopy).

The surface brightness of Lyα photons reflected by a damped Lyα system at a redshift z can be approximated by

$$I_\alpha^R \approx \frac{0.68 h\nu_\alpha}{(1+z)^4} \int_{\nu_L}^{\infty} d\nu \, \frac{J_\nu(z)}{h\nu} \,, \tag{11}$$

where $J_\nu(z)$ is the mean intensity of the UV background and ν_L is the frequency at the Lyman limit.[4] We ignore the possible dependence of I_α^R on the viewing angle because the limb darkening has not been calculated for reflected Lyα photons. We assume that the spectrum of the UV background is a power law, $J_\nu(z) = J_{\nu_L}(z)(\nu_L/\nu)^\alpha$, with the mean index $\alpha = 0.64$ appropriate for unreddened quasars (Pei et al. 1991). Inserting this into equation (11) gives

$$I_\alpha^R \approx 6 \times 10^{-17}(1+z)^{-4} J_{-21} \text{ ergs s}^{-1} \text{ cm}^{-2} \text{ arcsec}^{-2} \,, \tag{12}$$

where, by definition, $J_{-21} \equiv J_{\nu_L}(z)/10^{-21}$ ergs s^{-1} cm^{-2} sr^{-1} Hz^{-1}. The "proximity effect" in the distribution of Lyα forest clouds near bright quasars implies $J_{-21} \sim 1$ for $1.7 \lesssim z \lesssim 3.8$ (Bajtlik, Duncan, & Ostriker 1988; Lu, Wolfe, & Turnshek 1991). This is probably a lower bound because the proximity effect might be a combination of photoionization and other processes. However, unless J_{-21} has been seriously underestimated, the surface brightness of the reflected Lyα photons at $2 \lesssim z \lesssim 3$ is about one order of magnitude below current observational limits.

5. CONCLUSIONS

Our main conclusion is that, with the typical dust-to-gas ratio inferred from the reddening of background quasars, many damped Lyα systems could have star formation rates of 10–100 $M_\odot$ Gyr^{-1} pc^{-2} and still not be detected in the searches for Lyα emission. The corresponding lower limits on the time scale for gas consumption, $\tau_G = 1.3 m_p N_{\rm H\,I\perp}/\dot{\mu}_S$, are roughly 0.1–1 Gyr. It is possible, therefore, that the damped Lyα systems would qualify as "starburst" galaxies. The large uncertainties in the star formation rates, especially for systems with high H I column densities, are caused by the unknown orientations and distributions of the stars, gas, and dust. Constraints on chemical enrichment would be just as weak because the same stars that produce heavy elements also produce Lyα photons. Our results are conservative in the sense that the IMF slope was assumed to be the same in all damped Lyα systems and the dust-to-gas ratio was confined to a relatively narrow range. In reality, the values of these parameters in individual systems could deviate from the typical values adopted here. The unknown topology of the H II regions in the damped Lyα systems is another source of uncertainty in the attenuation of Lyα emission. Measurements of continuum or Balmer-line radiation, while difficult, would provide more reliable estimates of the star formation rates.

The conclusions reached here should not be taken to imply that the searches for Lyα emission are futile. Strong Lyα emission appears to be a common feature of radio galaxies and quasars at high redshifts (Spinrad 1989; Heckman et al. 1991; Hu et al. 1991), but how much of this is induced by stellar ionizing radiation is not at all clear. The detection of Lyα emission from a large number of damped Lyα systems would provide valuable information about their sizes and shapes. At present, we have only a lower limit on the size of one damped Lyα system, from the 21 cm absorption of an extended background radio source (Briggs et al. 1989). Future searches for Lyα emission should probably be directed toward systems with $N_{\rm H\,I} \lesssim 5 \times 10^{20}$ cm^{-2} (corresponding to $\Delta \lesssim 3$), where the attenuation by dust is expected to be relatively weak. It may be more than a coincidence that the only damped Lyα system detected so far in Lyα emission has an H I column density in this range.

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[4] Songaila et al. (1990) considered the scattering of only half the Lyα photons back into intergalactic space, resulting in the factor of $\frac{1}{2}$ in their analog of eq. (11).

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