1. INTRODUCTION

Popular cosmological models predict that most of the intergalactic hydrogen was reionized by the first generation of stars or accreting black holes in the universe at a redshift $z \approx 6$. Prior to complete reionization, sources of ultraviolet radiation will be seen behind intervening gas that is still neutral, and their spectra should show the red damping wing of the Gunn-Peterson trough. While this characteristic feature may, in principle, totally suppress the Ly$\alpha$ emission line in the spectra of the first generation of objects in the universe, we show here that the IGM in the vicinity of luminous quasars will be highly photoionized on several megaparsec scales as a result of the source emission of Lyman continuum photons. If the quasar lifetime is shorter than the expansion and gas recombination timescales, the volume ionized will be proportional to the total number of photons produced above 13.6 eV; the effect of this local photoionization is to greatly reduce the scattering opacity between the redshift of the quasar and the boundary of its H II region. We find that the transmission on the red side of the Ly$\alpha$ resonance is always greater than 50% for sources radiating a total of $\approx 10^{60.5}$ ionizing photons into the IGM. The detection of a strong Ly$\alpha$ emission line in the spectra of bright quasi-stellar objects shining for $\approx 10^7$ yr cannot then be used, by itself, as a constraint on the reionization epoch. The first signs of an object radiating prior to the transition from a neutral to an ionized universe may be best searched for in the spectra of luminous sources with a small escape fraction of Lyman continuum photons into the IGM or sources with a short duty cycle.

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

\[ \tau_{\text{GP}}^{\text{blist}}(z) = \frac{1}{1 - \frac{\tau_0}{\bar{n}_H}} \]

\[ \tau_0(z) = \frac{\pi e^2 f \lambda_{\text{em}}}{m_e c H(z)} \bar{n}_H \]

\[ \approx 1.5 \times 10^5 h^{-1} \Omega_{\text{ud}}^{-2} \frac{\Omega_b h^2 (1 + z)^{3/2}}{0.019} \]

is extremely high. Here $f$ is the oscillator strength, $e$ and $m_e$ are the electron charge and mass, $\bar{n}_H$ is the mean density of hydrogen nuclei at redshift $z$, $H_0 = 100$ $h$ km s$^{-1}$ Mpc$^{-1}$ is the present-day Hubble constant, and $(\Omega_{\text{ud}}, \Omega_b)$ are the total matter and baryonic density parameter, respectively. The expression above gives the opacity seen by any photon emitted from a source at $z_{\text{em}}$ on the blue side of the Ly$\alpha$ line, $\lambda_{\text{em}} < \lambda_{\alpha}$, as it is redshifted through the local Ly$\alpha$ resonance at $(1 + z) = (1 + z_{\text{em}}) \lambda_{\text{em}} / \lambda_{\alpha}$. Equation (1) shows that the transmitted quasar flux shortward of Ly$\alpha$ would be reduced to undetectable levels even if 99% of all the cosmic baryons were to fragment at these early epochs into discrete, mildly overdense structures, with only 1% remaining in a diffuse component that was 99% ionized. As such, the detection of a GP trough would not uniquely establish that an object is being observed prior to the reionization epoch (except, perhaps, in the case where reionization occurs extremely rapidly and the GP trough splits into individual Lyman series troughs for a source located at $(1 + z_{\text{em}}) < (1 + z_{\text{em}}) < 32(1 + z_{\text{em}})/27$; Haiman & Loeb 1999). It has been pointed out by Miralda-Escudé (1998), however, that the rest-frame ultraviolet spectra of sources observed prior to complete reionization should show the red damping wing of the GP trough, as they will be seen behind a large column...
density of intervening gas that is still neutral. At \( z \sim 6 \), this characteristic feature extends for more than 1500 km s\(^{-1}\) to the red of the resonance, significantly suppressing the Ly\( \alpha \) emission line. Measuring the shape of the absorption profile of the damping wing could provide a determination of the density of the neutral IGM near the source.

In this Letter we focus on the width of the red damping wing—related to the expected strength of the Ly\( \alpha \) emission line—in the spectra of very distant quasars as a flag of the damping wing in the vicinity of a bright object. The absence in the spectra of luminous quasars of a red damping wing with the predicted absorption profile will not provide then unambiguous evidence of the observation of the IGM after cosmological reionization.

2. THE RED DAMPING WING

We generalize here the calculation of the absorption profile of the damping wing of the GP trough (Miralda-Escudé 1998) to the case where the IGM in the vicinity of an object at \( z_{\text{em}} \) is photoionized as a result of the source emission of UV photons. When the column density of absorbing atoms is sufficiently large, the width of an absorption line substantially exceeds the value corresponding to the dispersion of particle velocities along the line of sight. In this case, the scattering cross section is determined by the natural width of the Ly\( \alpha \) resonance,

\[
\sigma_a(\nu) = \frac{\pi^2 f}{m_c 4\pi^2 (\nu - \nu_a)^2 + \Delta^2(\nu/\nu_a)^4}/4
\]  

(Peebles 1993), where \( \Delta = (8\pi^2 e^2 f)/(3m_c\epsilon \lambda_\alpha^2) = 6.25 \times 10^6 \) s\(^{-1}\) is the rate of spontaneous radiative decay from the \( 2p \) to 1s energy level. The regions of the line profile for which equation (2) is valid are known as “radiation damping” wings of the line. Equation (2) is unapplicable close to line center, but if damping wings are present the transmitted flux will be essentially zero in the core region anyway. We assume the IGM has a constant H\( \text{ii} \) comoving density \( n_{\text{HI}}(0) \) at all redshifts \( z_{\text{em}} < z < z_{\text{recess}} \), and is highly photoionized between the redshift of the source \( z_{\text{em}} \) and the boundary of its H\( \text{ii} \) region at \( z_\text{r} \).

The scattering optical depth at the observed wavelength \( \lambda_{\text{obs}} > \lambda_\alpha(1 + z_{\text{em}}) \) is

\[
\tau_{\text{GP}}^{\text{red}}(\lambda_{\text{obs}}) = \int_{z_{\text{em}}}^{z_{\text{r}}} dz n_{\text{HII}}(0)(1 + z)^3 \alpha_a [\nu = c(1 + z)/\lambda_{\text{obs}}],
\]

where \( d\lambda/\lambda = c[(1 + z)H(z)]^{-1} \) is the proper cosmological line element. In an Einstein–de Sitter universe, equation (3) can be rewritten as

\[
\tau_{\text{GP}}^{\text{red}}(\lambda_{\text{obs}}) = \tau_{\text{GP}}(\lambda_{\text{em}}) \left[ \frac{\lambda_\alpha(1 + z_{\text{em}})}{\lambda_{\text{obs}}} \right]^{3/2}
\]

\[
\times \int_{x_{\text{recess}}}^{1} dx x^{9/2}/\left(1 - x\right)^3 + R^2 x^8,
\]

where \( R \equiv \Lambda \lambda_\alpha/(4\pi\epsilon) = 2.02 \times 10^{-8} \), \( x_{\text{recess}} = (1 + z_{\text{em}}) \times \lambda_{\text{em}}/\lambda_{\text{obs}} \), and \( x_\text{r} = (1 + z_{\text{r}})\lambda_\alpha/\lambda_{\text{obs}} \). Far from line center (i.e., when \( 0 < x < R^2 x^8 \)), this integral has an analytic solution (Miralda-Escudé 1998). Figure 1 (solid curve) shows the red damping wing in the spectrum of a source at \( z_{\text{em}} = 7 \) assuming \( \tau_{\text{GP}}(\lambda_{\text{em}}) = 3 \times 10^5 \), \( z_{\text{recess}} = 6 \), and \( z_r = z_{\text{em}} \), i.e., in the case when the H\( \text{ii} \) region surrounding the radiation object is very small (because, e.g., the Lyman continuum photons produced cannot escape from the dense sites of star formation into the intergalactic space).

Equation (3) also gives the opacity at wavelengths \( \lambda_\alpha(1 + z_{\text{em}}) > \lambda_{\text{obs}} > \lambda_\alpha(1 + z_{\text{em}}) \), i.e., on the blue side of the quasar Ly\( \alpha \) emission line, due to the damping wing of the fully neutral gas along the line of sight at \( z_{\text{em}} < z < z_r \). We will see in the next section that this must be augmented by the scattering optical depth of the residual H\( \text{ii} \) in the vicinity of the source \( z_r < z < z_{\text{em}} \).

3. COSMOLOGICAL H\( \text{II} \) REGIONS AROUND ISOLATED SOURCES

We now assess in detail the impact of a local H\( \text{II} \) region on the shape of the damping wing profile. When an isolated point source of ionizing radiation turns on, the volume of ionized IGM initially grows in size at a rate fixed by the emission of UV photons, and an ionization front separating the H\( \text{II} \) and H\( \text{I} \) regions propagates into the neutral gas. Most photons travel freely in the ionized bubble and are absorbed in a transition layer (the “I-front”), across which the degree of ionization changes sharply on a distance that is small compared to the radius of the ionized zone (this is true even in the case of a
quasi-stellar object [QSO] with a hard spectrum, see Madau & Meiksin 1991). The evolution of an expanding cosmological H II region is governed by the equation

$$\frac{dV_{\text{H}}}{dt} - 3HV_{\text{H}} = \frac{\dot{N}_r}{n_{\text{H}}} - \frac{V_r}{t_{\text{rec}}}$$

(5)

(Shapiro & Giroux 1987; Madau, Haardt, & Rees 1999), where $V_r$ is the proper photoionized volume, $N_r$ is the number of H-ionizing photons emitted by the central source per unit time that escape into the IGM,

$$t_{\text{rec}} = (1.17\alpha_c \alpha_h C^{-1})^{-1}$$

$$\approx 1.3 \text{ Gyr} \left(\frac{\Omega_h h^2}{0.019}\right) \left(\frac{1 + z}{8}\right)^3 C^{-1}$$

(6)

is the volume-averaged recombination time, $\alpha_h$ is the radiative recombination coefficient to the excited states of hydrogen (at an assumed gas temperature of $10^4$ K), and the factor $C = (\langle n_{\text{p}}^2 \rangle/n_{\text{H}} > 1$ takes into account the degree of clumpiness of the photoionized region, with $n_{\text{H}}$ the mean proton density. When the source lifetime $t_s$ is much less than $(t_{\text{rec}})$—as expected, for example, in the case of a quasar shining for an Eddington time scale, $t_s = t_e = 4 \times 10^6 (c/0.1)$ yr with $c$ the radiative accretion efficiency—recombinations can be neglected (this would be true even in the case of a clumpy medium with $C \approx 10$ on megaparsec scales; see eqs. [5] and [6]) and the evolution of the H II region can be decoupled from the expansion of the universe. The volume,

$$V_r = \frac{\dot{N}_r}{n_{\text{H}}} (t_s \ll t_{\text{rec}}, H^{-1})$$

(7)

that is actually ionized becomes then proportional to the total number of Lyman continuum photons emitted over the source lifetime. Note that the I-front initially expands at velocities that are close to the speed of light, i.e., with $n_{\text{p}}(t) = [3V_r(t)/4\pi]^{1/3} \approx ct$. In the case of very luminous, short-lived objects this “relativistic” phase may last a considerable fraction of the source lifetime. Nevertheless, the apparent size of the H II region “seen” by Ly$\alpha$ photons propagating along the line of sight will always be given by equation (7), as these can catch up with the I-front only when it slows down to subluminal velocities.

The known QSOs at $z_{\text{em}} \approx 5$ all have ionizing luminosities that can be estimated to lie in the range $10^{43} - 10^{44}$ s$^{-1}$, the brightest of them being the recently discovered $z_{\text{em}} \approx 5.8$ quasar from the Sloan Digital Sky Survey (SDSS; Fan et al. 2000b). Over a lifetime of, say, $10^7$ yr they would radiate of order $N_r = 10^{75.5} - 10^{22.5}$ photons above 13.6 eV. Placed at $z_{\text{em}} = 7$, sources of similar power would ionize the surrounding IGM out to a proper distance $r_I = 1.5 - 7$ Mpc, corresponding to a Hubble expansion velocity of $\Delta v = H_r t_I = 3300 - 15,800 h \Omega_m^{0.5}$ km s$^{-1}$, or to a redshift difference between the QSO and the boundary of its H II zone of $\Delta z = 3.33 \times 10^{-4} h \Omega_m^{0.5} (1 + z_{\text{em}})^{1/2} (r_I/\text{Mpc}) = 0.088 - 0.42 h \Omega_M^{0.5}$. The effect of these individual H II regions on the flux transmission redward of the Ly$\alpha$ line is shown in Figure 1. The width of the damping wing measures the column density along the line of sight of the fraction of the IGM that is still neutral. The wing nearly completely disappears in the case of a luminous quasar, as there is very little neutral gas in its vicinity. In particular, the transmission is always greater than 50% for $N_r > 10^{50.5}$ photons.

On the blue side of Ly$\alpha$, in the vicinity of the source, the scattering opacity has two contributions, one due to the damping wing of the fully neutral gas beyond the H II region and one due to the ordinary GP trough associated with the residual H I in the photoionized zone. Assuming photoionization equilibrium (this is justified for the highly ionized IGM and the source lifetimes considered here), at every point within the H II bubble the density of neutral hydrogen is given by

$$n_{\text{H}} = \frac{n_r}{t_{\text{rec}}} \left(\int_0^{r_n} F\sigma_r(v)/h_{\nu_p} d\nu\right)^{-1},$$

(8)

where $h_{\nu}$ is the Planck’s constant, $F$ is the incident ionizing flux per unit frequency (to a first approximation simply the radiation emitted by the quasar reduced by geometrical dilution), and the hydrogen photoionization cross section (by photons above the threshold $h_{\nu} n_h = 13.6$ eV) is

$$\sigma_{\text{H}}(v) = \sigma_c \left(\frac{v}{h_{\nu}}\right)^{-3}, \quad \sigma_c = 6.3 \times 10^{-18} \text{ cm}^2.$$

(9)

For a power-law spectrum of the form $F \propto v^{-\alpha}$ near the hydrogen Lyman edge, the neutral hydrogen column through an approximately isothermal H II region can thus be written as

$$N_{\text{HI}} = \frac{3 + \alpha}{\alpha} \sigma_c^{-1} t_{\text{rec}} \left(\frac{r}{r_I}\right)^{3/2},$$

(10)

independently of the source luminosity. Taking $\alpha = 0.5, t_s = 10^7$ yr, and $t_{\text{rec}} = 1.3$ Gyr at $z_{\text{em}} = 7$, one derives $N_{\text{HI}} = 8.6 \times 10^{15}$ cm$^{-2}$. This is too small a column (even in the case of a fast recombing clumpy medium) for the natural width of the line to exceed the thermal broadening. On the other hand, it is straightforward to derive from equations (1), (8), and (9) that the GP optical depth on the blue side of Ly$\alpha$ due to partially ionized gas at a distance $r < r_I$ from the QSO is given by

$$\tau_{\text{GP}}(r) \approx 2 \left(\frac{z_{\text{em}}}{r_I}\right)^2 \frac{t_{\text{rec}}}{t_s} H^{-1} \left(\frac{3 + \alpha}{\alpha}\right).$$

(11)

While the first two terms are of course smaller than unity, the third term is rather large, $cH^{-1}/t_s = 130 h^{-1} \Omega_m^{0.5} r_I$ Mpc at $z_{\text{em}} = 7$, and this means that only the inner parts of the H II region will be optically thin to the classical GP absorption. Note that $\tau_{\text{GP}}$ depends just on the quasar luminosity, not on $t_s$ and $r_I$ separately, and that equations (8), (10), and (11) assume (1) a steady luminosity and (2) a uniform medium at the mean background density. The hydrogen neutral fraction will actually depend on the mean ionizing flux over the last $t_{\text{rec}}(n_r/n_h) \ll t_{\text{rec}}$ yr, while halos having collapsed from, say, $3 \sigma$ fluctuations may actually be sitting in slightly overdense regions.

4. SUMMARY

The lack of a GP trough—i.e., the detection of transmitted flux shortward of the Ly$\alpha$ wavelength—observed in the spectrum of the $z_{\text{em}} = 5.8$ SDSS quasar (Fan et al. 2000b) indicates that the IGM was already highly ionized at that redshift and that sources of ultraviolet photons were present in significant
numbers when the universe was less than 6% of its current age. At the time of writing, three quasars have already been found in the range $5 \leq z_{\text{em}} \leq 5.5$ (Zheng et al. 2000; Stern et al. 2000; Fan et al. 2000a) and two galaxies have been spectroscopically confirmed at $z_{\text{em}} \approx 5.6$ (Hu, McMahon, & Cowie 1999; Weymann et al. 1998). It is estimated that the SDSS could reveal tens of additional sources at these epochs and one QSO at $z_{\text{em}} \approx 6$ about twice as luminous as 3C 273 in every 1500 deg$^2$ of the survey (Fan et al. 2000b).

Near-future studies of the rest-frame UV spectra of high-redshift quasars and star-forming galaxies could then conceivably provide important probes of the formative early stages of cosmic evolution. In this Letter we have discussed one of the first signs of an object radiating prior to the transition from a neutral to an ionized universe: the red damping wing of the GP trough. We have shown that the local photoionized zones which will inevitably surround luminous quasars at early epochs will greatly reduce the scattering opacity between the redshift of the source and the boundary of its megaparsec-size H II region, thus increasing the transmission of photons on the red side of the Ly$\alpha$ resonance. To better gauge this effect on real data, we have plotted in Figure 2 the Keck/Low-Resolution Imaging Spectrograph (LRIS) spectrum of the faint $z_{\text{em}} = 5.5$ quasar RD J0301117+002025 (Stern et al. 2000), redshifted to $z_{\text{em}} = 7$. The figure depicts the same 800 A-wide region of the observed spectrum around the Ly$\alpha$ resonance, together with the transmission $\exp(-t_{\text{em}})$ assuming the QSO is being observed prior to the reionization epoch at $z_{\text{reion}} = 6$.

This should be taken just as an illustrative example, as in some numerical simulations (e.g., Ciardi et al. 2000) reionization was already well in progress prior to redshift 6 and the form of the damping profile would be different in the case of patchy ionization along the line of sight. Four cases are shown as the emission rate of UV photons which ionize the IGM in the vicinity of the quasar is increased from $N_e = 0$ to $N_e = 10^{56}$, 10$^{57}$, and 10$^{58}$ s$^{-1}$. The calculations assume a quasar lifetime of $t_q = 10^7$ yr, a power-law spectrum of the form $F_v \propto v^{-\alpha}$ with $\alpha = 0.5$ near the hydrogen Lyman edge, a recombination timescale of $t_{\text{em}} = 1.3$ Gyr, and an Einstein-de Sitter universe with $\Omega = 0.5$.
this case, large H \textsc{ii} regions may still be expected if these early galaxies were highly clustered on megaparsec scales.

Support for this work was provided by NASA through ATP grant NAG5-4236 (P. M.), by a B. Rossi Visiting Fellowship at the Observatory of Arcetri (P. M.), and by the Royal Society (M. J. R.). We are indebted to D. Stern and H. Spinrad for providing the spectrum of quasar RD J030117+002025. Results similar to the ones presented here have been reached independently by Cen & Haiman (2000).

REFERENCES

Cen, R., & Haiman, Z. 2000, ApJ, 542, L75
Ciardi, B., Ferrara, A., Governato, F., & Jenkins, A. 2000, MNRAS, 314, 611
Fan, X., et al. 2000a, AJ, 119, 1
———. 2000b, AJ, submitted (astro-ph/0005414)
Gnedin, N. Y., & Ostriker, J. P. 1997, ApJ, 486, 581
Gunn, J. E., & Peterson, B. A. 1965, ApJ, 142, 1633 (GP)
Haiman, Z., & Loeb, A. 1997, ApJ, 483, 21
———. 1999, ApJ, 519, 479
Hu, E. M., McMahon, R. G., & Cowie, L. L. 1999, ApJ, 522, L9
Madau, P., Haardt, F., & Rees, M. J. 1999, ApJ, 514, 648
Madau, P., & Meiksin, A. 1991, ApJ, 374, 6
Miralda-Escudé, J. 1998, ApJ, 501, 15
Peebles, P. J. E. 1993, Principles of Physical Cosmology (Princeton: Princeton Univ. Press)
Shapiro, P. R., & Giroux, M. L. 1987, ApJ, 321, L107
Stern, D., Spinrad, H., Eisenhardt, P., Bunker, A. J., Dawson, S., Stanford, S. A., & Elston, R. 2000, ApJ, 533, L75
Weymann, R. J., Stern, D., Bunker, A., Spinrad, H., Chaffee, F. H., Thompson, R. I., & Storrie-Lombardi, L. 1998, ApJ, 505, L95
Zheng, W., et al. 2000, AJ, submitted (astro-ph/0005247)