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THE PROXIMITY EFFECT AND THE MEAN INTENSITY OF IONIZING RADIATION AT LOW REDSHIFTS

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ABSTRACT

We report the first tentative detection of the proximity effect in the distribution of Lyα forest lines at low redshifts ($z \lesssim 1$). This is based on observations of 13 quasars by Bahcall et al. with the Faint Object Spectrograph on the *Hubble Space Telescope* as part of the Quasar Absorption Line Key Project. We estimate the mean intensity of ionizing radiation on the usual assumption that the proximity effect is caused entirely by the increased photoionization of absorbers near the quasars. The result is $J_L \sim 6 \times 10^{-24}$ ergs s^{-1} cm^{-2} sr^{-1} Hz^{-1} at $z \approx 0.5$. However, the uncertainties are large, and even at the 1 σ level, J_L could be lower by a factor of 3 or higher by a factor of 6. Our estimate could be improved with a larger sample of absorbers and more accurate redshifts of a few of the quasars.

Subject headings: diffuse radiation — intergalactic medium — quasars: absorption lines

1. INTRODUCTION

The density of Lyα forest lines, while generally increasing with redshift, tends to decrease in the immediate vicinity of quasars (Carswell et al. 1982; Murdoch et al. 1986; Tytler 1987b). The standard explanation for this "inverse" or "proximity" effect is that the absorbers near quasars are more highly ionized than those farther away and therefore less likely to exceed the threshold in H I column density needed for detection. In this case, the proximity effect provides a measure of the mean intensity of ionizing radiation from all sources J_ν because the relative importance of photoionization by a given quasar is inversely proportional to J_ν. In a pioneering study, Bajtlik, Duncan, & Ostriker (1988) showed that the predicted and observed proximity effects agreed at high redshifts ($z \approx 3$) for $J_L \sim 1 \times 10^{-21}$ ergs s^{-1} cm^{-2} sr^{-1} Hz^{-1}, where the subscript L denotes the Lyman limit of hydrogen (at a wavelength of 912 Å). This estimate has been confirmed, within the quoted uncertainties of ± 0.5 in log J_L, by Lu, Wolfe, & Turnshek (1991) and Bechtold (1993). The ionizing background and its evolution with redshift play important roles in most models of the intergalactic medium and quasar absorption-line systems. Unfortunately, the ground-based studies of the proximity effect have not yet revealed a significant dependence of J_L on redshift (for $2 \lesssim z \lesssim 4$).

In this *Letter*, we report a tentative detection of the proximity effect at low redshifts and a corresponding estimate of the mean intensity of ionizing radiation. Our study is based on the Lyα forest lines detected in the spectra of 13 quasars by Bahcall et al. (1993) with the Faint Object Spectrograph (FOS) on the *Hubble Space Telescope* (*HST*) as part of the Quasar Absorption Line Key Project. The quasars have redshifts in the range $0.16 \leq z \leq 1.00$, with a mean and median near $z = 0.5$, and apparent magnitudes in the range $12.8 \leq V \leq 16.5$. The FOS spectra cover all or part of the range $1180 \leq \lambda \leq 3270$ Å at resolutions of 1.1, 1.5, or 2.0 Å (depending on the grating used) and have typical signal-to-noise ratios of 20–30. Bahcall et al. identified all absorption lines with equivalent widths greater than a minimum value $W_{\min}(\lambda)$ defined to be 4.5 standard deviations above the noise at the wavelength λ. This procedure resulted in a set of 95 Lyα lines without associated heavy-element systems and nine Lyα lines with associated heavy-element systems. The rest-frame equivalent widths of the former span the range $0.14 \leq W \leq 1.74$ Å, while those of the latter span the range $0.44 \leq W \leq 2.59$ Å.

2. METHOD

Our analysis follows that of Bajtlik et al. (1988), with some modifications appropriate for the smaller sample at low redshifts. We begin by defining $f(N, z)dN\,dz$ as the mean number of absorbers with H I column densities between N and $N + dN$ and redshifts between z and $z + dz$ along a random line of sight. The model $f(N, z) = AN^{-\beta}(1 + z)^\gamma$, with $\beta \approx 1.5$ and $\gamma \approx 2$, provides a reasonable fit to the observed distribution at high redshifts but far enough from quasars that the proximity effect can be neglected (Tytler 1987a, b, and references therein). When photoionization by a quasar at a redshift z_q is included, the model becomes

$$f(N, z) = AN^{-\beta}(1 + z)^\gamma[1 + \omega(z)]^{-(\beta - 1)}\,, \tag{1}$$

$$\omega(z) = \frac{F_L^q(z)}{4\pi J_L(z)} = \frac{F_L^q(0)}{4\pi J_L(z)(1 + z_q)}\left[\frac{D(0, z_q)}{D(z, z_q)}\right]^2 . \tag{2}$$

Here, $F_L^q(z)$ is the Lyman-limit flux received at a redshift z from the quasar at z_q, and $D(z, z_q)$ is the luminosity distance between z and z_q. Equations (1) and (2) are based on the simplifying assumptions that the absorbers are highly ionized and that the spectrum of the quasar at z_q has the same shape as the mean spectrum of all other sources of ionizing radiation. The second assumption is not strictly valid even if quasars are the only sources of ionizing radiation because the mean spectrum will be modified by intervening absorbers. This effect, however, is relatively small at low redshifts (Madau 1992).

The approach we take is to convert the rest-frame equivalent width W of each absorber to an H I column density N with the exact curve of growth and an assumed value of the Doppler parameter b. We then compare the model $f(N, z)$ directly with the "observed" distribution in N and z. *Some* assumption about the Doppler parameter is necessary because the Lyα lines are not resolved in the FOS spectra. In a more sophisti-

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cated analysis, $f(N, z)$ would be convolved with a distribution in b before comparison with the observed distribution in W and z. However, this procedure is not warranted at the present time because the distribution of Doppler parameters is not known at low redshifts. Most of our calculations were made with $b = 35$ km s^{-1}, but we also tried $b = 25$ and 45 km s^{-1}. These choices were motivated by the distribution of Doppler parameters at high redshifts, which has a mean near 35 km s^{-1} and a dispersion of about 15 km s^{-1} (Atwood, Baldwin, & Carswell 1985; Carswell et al. 1987; Carswell et al. 1991; Rauch et al. 1992). Fortunately, none of our conclusions depends critically on the adopted values of b.

We estimate the parameters A, β, γ, and $J_{\rm L}$ in the model $f(N, z)$ by the method of maximum likelihood. This is especially suitable for a small sample because it does not require binning of the data. The likelihood function relevant to our problem is

$$L = \prod_a f(N_a, z_a) \prod_q \exp\left[-\int_{z^q_{\rm min}}^{z^q_{\rm max}} dz \int_{N^q_{\rm min}(z)}^{\infty} dN f(N, z)\right], \quad (3)$$

where the first product is over all absorbers in the sample (labeled by a), and the second is over all quasars in the sample (labeled by q). The quantities $N^q_{\rm min}(z)$, $z^q_{\rm min}$, and $z^q_{\rm max}$ are, respectively, the minimum H I column density [corresponding to $W^q_{\rm min}(\lambda)$] and the minimum and maximum redshifts at which absorbers in the foreground of the qth quasar could have been included in the sample. $L(N_1, z_1; N_2, z_2; \ldots)dN_1 dz_1 dN_2 dz_2 \ldots$ is the joint probability, from Poisson statistics, of finding exactly one absorber with an H I column density and a redshift in each of the small intervals $(N_a, N_a + dN_a) \times (z_a, z_a + dz_a)$ and none in any of the other accessible intervals of N and z. The optimum values of A, β, γ, and $J_{\rm L}$ are those that maximize L, and confidence intervals derive from the fact that $-2\ln(L/L_{\rm max})$ is distributed as χ^2 with one degree of freedom for each parameter.

To display the proximity effect graphically, it proves convenient to remove the general increase in the density of Lyα forest systems with redshift. With this in mind, we define a "coevolving coordinate" X, similar to the one X_γ introduced by Bajtlik et al. (1988), through the relation

$$dX = (\beta - 1)^{-1}(1 + z)^\gamma N^q_{\rm min}(z)^{-(\beta-1)} dz \,. \quad (4)$$

We then define $g(X)dX$ as the mean number of absorbers with H I column densities above $N^q_{\rm min}(z)$ and coevolving coordinates between X and $X + dX$ along the line of sight to a quasar at X_q. Thus, we have

$$g(X) = (dX/dz)^{-1} \int_{N^q_{\rm min}(z)}^{\infty} dN f(N, z) = A[1 + \omega(X)]^{-(\beta-1)} \,. \quad (5)$$

If $J_{\rm L}$ were very large, and the proximity effect were negligible, $g(X)$ would be independent of X. In general, however, $g(X)$ should decrease as X approaches X_q. Moreover, a plot of $g(X)$ against the Lyman-limit flux $F^q_{\rm L}(X)$ should be the same for all quasars, irrespective of their luminosities, in the approximation that $J_{\rm L}$ is a constant.

In our analysis, the redshifts of the quasars z_q were usually assumed to be the same as the redshifts z_e derived from the Mg II λ2798 emission line. For seven of the quasars, we followed Bahcall et al. (1993) and adopted the redshifts compiled by Véron-Cetty & Véron (1991); these are based primarily but not exclusively on the Mg II emission line. However, for the other six quasars, we found more accurate Mg II emission-line redshifts in the literature (Tytler et al. 1987 for PKS 0044+030, 3C 95, B2 1512+37, and 3C 351; Steidel & Sargent 1991 for PKS 2145+06; Gaskell 1982 for PKS 2251+11). The uncertainties in z_e are typically 300 km s^{-1}, but in a few cases, they could be larger (e.g., 3C 263 and 3C 454.3). The Lyman-limit fluxes of nine of the quasars were taken from the continuum fits to the FOS spectra by Bahcall et al. (1993). According to Schneider et al. (1993), these are accurate to about 20%. For the other four quasars, the FOS spectra did not extend to the Lyman limit, and we adopted the fluxes measured with *International Ultraviolet Explorer* (Kinney et al. 1991 for B2 1512+37; Lanzetta, Turnshek, & Sandoval 1993 for PG 0043+039 and 3C 263) or the Hopkins Ultraviolet Telescope (Davidsen et al. 1993 for 3C 273). These should also be accurate to about 20%. We have corrected the observed fluxes for Galactic extinction using the Burstein & Heiles (1982) reddening maps and the Seaton (1979) extinction curve. No corrections were made for blanketing by Lyα forest lines since this effect is negligible at the low redshifts considered here. The luminosity distances in equation (2) were computed with $q_0 = 0.5$ and $\Lambda = 0$. Again, because the redshifts are low, the cosmological parameters have little effect on our results.

3. RESULTS

We first determine the optimum values of the parameters A, β, and γ in $f(N, z)$ in regions that are relatively free of the proximity effect. For this purpose, we exclude the 15 Lyα lines without associated heavy-element systems and with $F^q_{\rm L} > 8 \times 10^{-24}$ ergs s^{-1} cm^{-2} Hz^{-1}, which corresponds to $\omega > 0.1$ for $J_{\rm L} \approx 6 \times 10^{-24}$ ergs s^{-1} cm^{-2} sr^{-1} Hz^{-1}. For a Doppler parameter of $b = 35$ km s^{-1}, the maximum-likelihood estimates are $\log A = 7.74$, $\beta = 1.48$, and $\gamma = 0.21$. We refer to these as the "standard" values of the parameters. For $b = (25, 45)$ km s^{-1}, we obtain $\log A = (5.21, 10.74)$, $\beta = (1.31, 1.69)$, and $\gamma = (0.19, 0.23)$. The typical uncertainties in these parameters are $\sigma_{\log A} \approx 0.1$, $\sigma_\beta \approx 0.05$, and $\sigma_\gamma \approx 0.6$, with strong correlations between $\log A$ and β and between $\log A$ and γ. The model $f(N, z)$ and the parameters derived here are entirely consistent with the model $f(W, z)$ and the parameters derived by Bahcall et al. (1993) from nearly the same sample of Lyα lines. In particular, we confirm the relatively large amplitude and the weak dependence on redshift. The dependence on H I column density is similar to that found at high redshifts.

We next consider several different samples that include Lyα lines near the quasars. These are defined as follows: Sample 1 consists of all Lyα lines without associated heavy-element systems and with redshifts less than the emission-line redshifts of the quasars; the latter condition removes one Lyα line with $z > z_e$ in the spectrum of 3C 351. Sample 2 is the same as sample 1 except that the only broad absorption line (BAL) quasar, PG 0043+039, is excluded, which removes one more Lyα line. BAL quasars were specifically excluded from the studies of the proximity effect at high redshifts by Lu et al. (1991) and Bechtold (1993) on the grounds that BAL activity might influence the ionization or redshifts of nearby absorbers. Samples 3 and 4 also exclude the BAL quasar, but the redshifts of the other quasars are taken to be 500 km s^{-1} lower or higher than the emission-line redshifts. Thus, we set $z_q = z_e \mp \Delta z$ with $\Delta z = (1 + z_e)(\Delta v/c)$ and $\Delta v = 500$ km s^{-1}. While the true redshifts of individual quasars might differ from the Mg II emission-line redshifts by 500 km s^{-1} or more, it is very unlikely that the mean difference for the whole sample is this large (Gaskell 1982; Espey et al. 1989). Finally, sample 5 is the

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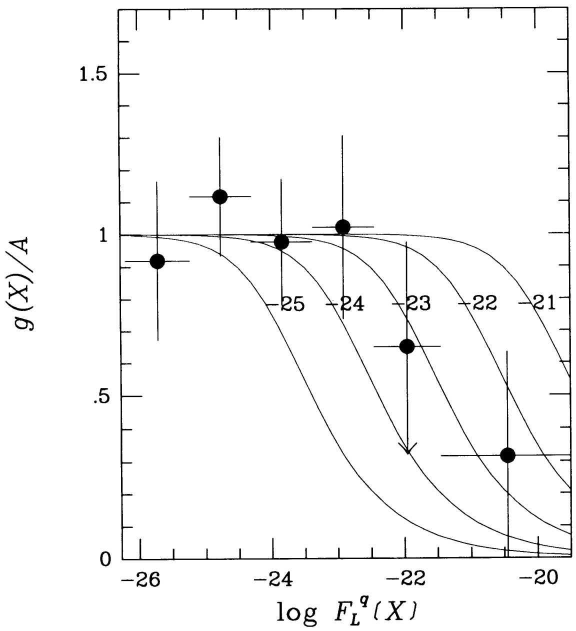

FIG. 1.—Mean number of Lyα forest lines $g(X)$ per unit coevolving coordinate X as a function of the logarithm of the Lyman-limit flux from a quasar $F_L^q(X)$ (in ergs s^{-1} cm^{-2} Hz^{-1}) for sample 1 with the standard values of b, A, β, and γ. The filled circles represent our estimates; the vertical bars, 1 σ uncertainties; and the horizontal bars, the extent of the bins. The downward-pointing arrow indicates that $g(X)$ would be lower for sample 2 (which excludes the BAL quasar). The solid curves are the predictions of the photoionization model with the indicated values of log J_L (in ergs s^{-1} cm^{-2} sr^{-1} Hz^{-1}).

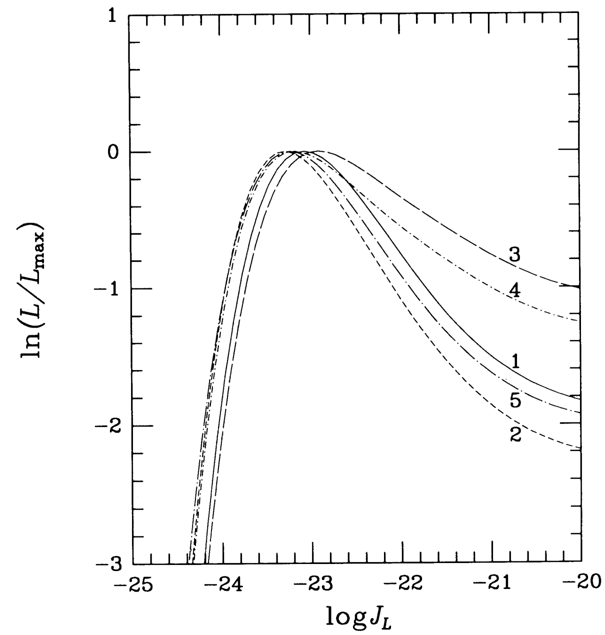

FIG. 2.—Natural logarithm of the likelihood L as a function of the logarithm of the mean intensity of Lyman-limit radiation J_L (in ergs s^{-1} cm^{-2} sr^{-1} Hz^{-1}) at $z \approx 0.5$. The curves pertain to samples 1–5, as indicated, with the standard values of b, A, β, and γ.

same as sample 2 except that it includes the six Lyα lines with associated heavy-element systems and $z < z_e$. In this case, the standard values of the parameters, determined as above for $b = 35$ km s^{-1}, are log $A = 6.98$, $\beta = 1.43$, and $\gamma = 0.27$.

Figure 1 shows our estimates of $g(X)$ as a function of $F_L^q(X)$ for sample 1 with the standard values of b, A, β, and γ. Following the studies at high redshifts, we have approximated $g(X)$ by $\Sigma \Delta N_q / \Sigma \Delta X_q$, where ΔN_q and ΔX_q are, respectively, the number of Lyα lines and the interval of coevolving coordinate for each quasar in the bin defined by $\Delta F_L^q(X)$, and the sums are over all quasars in the sample. Evidently, there is a deficiency of Lyα lines with respect to the relation $g(X) = A$ for $F_L^q \gtrsim 3 \times 10^{-23}$ ergs s^{-1} cm^{-2} Hz^{-1}. The statistical significance of this deficiency—the proximity effect—is 2.4 σ. For sample 2 (which excludes the BAL quasar), one Lyα line would be removed from the next-to-last bin, and the significance of the deficiency would increase to 3.0 σ. Thus, we are reasonably confident that the proximity effect has been detected at low redshifts. Figure 1 also shows the predicted dependence of $g(X)$ on $F_L^q(X)$ from equations (2) and (5) for several values of the mean intensity of ionizing radiation. The best fit occurs for log $J_L \approx -23$ and has a reduced χ^2 of 0.2.

To obtain more reliable estimates of J_L, we now return to the method of maximum likelihood. Figure 2 shows the likelihood L as a function of J_L for samples 1–5 with the standard values of b, A, β, and γ. The curves are all quite similar except that L declines less rapidly at high J_L for the two samples in which the redshifts of the quasars have been perturbed. The maximum-likelihood estimates of log J_L and the corresponding 1 σ uncertainties, given by $\ln(L/L_{max}) = -0.5$, are listed in Table 1. Here, we have also included the results of some calculations with $b = 25$ and 45 km s^{-1} and with values of β and γ that differ from the standard values by 1 σ (with A adjusted so that the expected number of absorbers remains nearly

TABLE 1

MAXIMUM-LIKELIHOOD ESTIMATES OF J_L

Sample	b (km s^{-1})	log A (cm$^{2(1-\beta)}$)	β	γ	log J_L (ergs s^{-1} cm^{-2} sr^{-1} Hz^{-1})
1..........	35	7.74	1.48	0.21	$-23.1^{+0.8}_{-0.5}$
2..........	35	7.74	1.48	0.21	$-23.3^{+0.7}_{-0.5}$
3..........	35	7.74	1.48	0.21	$-22.9^{+1.3}_{-0.6}$
4..........	35	7.74	1.48	0.21	$-23.2^{+1.1}_{-0.5}$
5..........	35	6.98	1.43	0.27	$-23.2^{+0.8}_{-0.6}$
2..........	25	5.21	1.31	0.19	$-23.6^{+0.9}_{-0.5}$
2..........	45	10.74	1.69	0.23	$-23.1^{+0.6}_{-0.5}$
2..........	35	7.83	1.48	−0.39	$-23.1^{+0.8}_{-0.6}$
2..........	35	7.65	1.48	0.81	$-23.4^{+0.6}_{-0.5}$
2..........	35	7.00	1.43	0.21	$-23.3^{+0.8}_{-0.5}$
2..........	35	8.48	1.53	0.21	$-23.3^{+0.7}_{-0.4}$

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constant). In all cases, we find $-23.6 \leq \log J_L \leq -22.9$. This range is smaller than the typical 1 σ uncertainties of -0.5 and $+0.8$ in each estimate of $\log J_L$. As a best estimate, we adopt $J_L \sim 6 \times 10^{-24}$ ergs s^{-1} cm^{-2} sr^{-1} Hz^{-1}, the mean for samples 1 and 2 with the standard values of b, A, β, and γ. Had we relied exclusively on the Véron-Cetty & Véron (1991) catalog for the redshifts of the quasars, our estimates of J_L would be similar but the uncertainties would be even larger.

4. DISCUSSION

It is interesting to compare our estimate of J_L with other indications of the mean intensity of ionizing radiation at low redshifts. The probable detections of Hα emission from two high-velocity clouds in the halo of the Milky Way imply $J_L \lesssim 2 \times 10^{-22}$ ergs s^{-1} cm^{-2} sr^{-1} Hz^{-1} (Kutyrev & Reynolds 1989; Songaila, Bryant, & Cowie 1989). This is an upper limit because some of the Hα emission could be induced by shocks or ionizing radiation from local sources. A search for Hα emission from a large cloud associated with the nearby galaxy NGC 3067 gives a similar limit on J_L (Stocke et al. 1991). Another indication follows from the observed edges in the outer H I disks of nearby galaxies at $N \approx$ few $\times 10^{19}$ cm^{-2}, which imply $J_L \sim (1\text{–}10) \times 10^{-23}$ ergs s^{-1} cm^{-2} sr^{-1} Hz^{-1} (Bochkarev & Sunyaev 1977; Corbelli & Salpeter 1993; Maloney 1993). The range quoted here mainly reflects different assumptions about the spectrum of the ionizing radiation and the vertical structure of the outer H I disks. Recent calculations of the expected contribution by quasars to the mean intensity of ionizing radiation give $J_L \sim (2\text{–}8) \times 10^{-23}$ ergs s^{-1} cm^{-2} sr^{-1} Hz^{-1} at $z \approx 0.5$ (Miralda-Escudé & Ostriker 1990; Madau 1992; Zuo & Phinney 1993). Our estimate lies below this range, but the difference is not statistically significant.

In summary, we have made a tentative detection of the proximity effect in the distribution of Lyα forest lines at low redshifts. The statistical significance of the detection is 2.4–3 σ, depending on whether the BAL quasar is included. We have also made a provisional estimate of the mean intensity of ionizing radiation at $z \approx 0.5$ on the usual assumption that the proximity effect is caused entirely by the increased photoionization of absorbers near the quasars: $J_L \sim 6 \times 10^{-24}$ ergs s^{-1} cm^{-2} sr^{-1} Hz^{-1}. The 1 σ uncertainties are such that J_L could be lower by a factor of 3 or higher by a factor of 6. Thus, our estimate is at least one and probably two orders of magnitude smaller than the estimate $J_L \sim 1 \times 10^{-21}$ ergs s^{-1} cm^{-2} sr^{-1} Hz^{-1} from the proximity effect at $z \approx 3$ (Bajtlik et al. 1988; Lu et al. 1991; Bechtold 1993). The results presented here could be improved and extended to intermediate redshifts ($1 \lesssim z \lesssim 2$) as more observations from the Quasar Absorption Line Key Project and other *HST* programs become available. It would also help to have more accurate redshifts of a few of the quasars.

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