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QSO ABSORPTION SYSTEMS AND THE ORIGIN OF THE IONIZING BACKGROUND AT HIGH REDSHIFT

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ABSTRACT

We consider two candidates for the sources of the ionizing background: primeval galaxies and AGN-type objects. The spectrum of the diffuse radiation field is computed taking into account the opacity of intervening Lyα clouds and Lyman limit systems. We assess the possibility that the QSO heavy-element absorption systems are photoionized by a metagalactic flux which is dominated by the UV radiation from hot stars in young galaxies. Grids of photoionization models for metal-line systems are presented, and it is argued that the relative column densities of the most abundant ions predicted by the models are compatible with the observational constraints. We discuss the inferred physical properties of the absorbing clouds. Given that the observed QSOs cannot provide the required number of ionizing photons at high redshift, the results obtained support a scenario in which young, star-forming galaxies are the main sources of the UV radiation background at early epochs.

Subject headings: cosmology — galaxies: intergalactic medium — quasars

1. INTRODUCTION

The absence of an absorption trough on the blue side of the Lyα emission line in the spectra of high-redshift quasars requires the universe to have been highly ionized by $z \gtrsim 4$ (Schneider, Schmidt, & Gunn 1989), in order to satisfy the Gunn-Peterson constraint on the amount of neutral hydrogen in the intergalactic medium (IGM) (Gunn & Peterson 1965). The source of the required metagalactic ionizing flux has been a subject of much recent debate and controversy, as Shapiro & Giroux (1987; see also Donahue & Shull 1987) have argued that the quasars detected in optical surveys cannot provide the required number of photons to ionize the medium by $z \gtrsim 3$. A direct estimate of the intensity of the metagalactic flux at the hydrogen Lyman limit (912 Å), $J_{912} \simeq 10^{-21}$ ergs cm^{-2} s^{-1} sr^{-1} Hz^{-1}, is obtained by measuring the decrease in the counted number of Lyα-absorbing clouds induced by the UV radiation field of a QSO in its vicinity, the so-called "proximity effect" (Murdoch et al. 1986; Bajtlik, Duncan, & Ostriker 1988; Lu, Wolfe, & Turnshek 1991). Lin & Phinney (1991, hereafter LP) have again found that the observed QSOs can account for only $\sim 5\%$ of this limit at $z \simeq 3$. What then generates the ionizing background at high redshift?

The most plausible candidate sources of photoionization are unaccounted-for AGNs and young star-forming galaxies, where high-mass stars produce metals and UV photons (Bechtold et al. 1987; Miralda-Escudé & Ostriker 1990, hereafter MO). The last possibility is intriguing, as an accurate determination of the UV background at high redshift might constrain the history of galaxy formation. However, Steidel & Sargent (1989) and Steidel (1990) have argued that one can rule out young blue galaxies as the main source of ionizing photons because their spectrum is too soft. Indeed, these authors have shown that it is possible to model the ionization structure of the heavy element QSO absorption systems, and discriminate between different spectral shapes by looking at the line strengths of various elements (see also Chaffee et al. 1986 and Bergeron & Stasinska 1986). Specifically, metal-line systems ionized by a stellar spectrum are found to be dominated by low-ionization species, in clear contradiction with the observations. These can best be reproduced by a power-law spectral energy distribution, characteristic of AGN-type sources. In any case, the background continua adopted in Steidel and Sargent represent the intrinsic source spectra, unmodified by intervening absorption and cosmological effects.

In this *Letter* we explore the possibility that the relative column densities of observed ions in metal-line absorbers might still be reproduced by a background stellar spectrum once the attenuation due to intervening Lyα clouds and Lyman limit systems is taken into account. We also reexamine the power-law (AGN) model. To anticipate the conclusions of our analysis, we find that (due to the wavelength dependence of Lyman continuum absorption) the spectrum of the attenuated background is harder than the local (stellar or power-law) emissivity. As a result, the relative column densities of C ions predicted by both photoionization models are found to be in agreement with the observational constraints. The topics discussed here are currently being investigated independently by Giroux & Shapiro (1991).

2. THE IONIZING RADIATION BACKGROUND

The *mean* specific intensity J_ν (ergs cm^{-2} s^{-1} sr^{-1} Hz^{-1}) of the diffuse radiation field at wavelength $\lambda_{\rm obs}$ as seen by an observer at redshift $z_{\rm obs}$ can be computed as

$$J_\nu(\nu_{\rm obs}, z_{\rm obs}) = \frac{1}{4\pi}\int_{z_{\rm obs}}^{z_{\rm max}} \frac{(1+z_{\rm obs})^3}{(1+z)^3}\,\epsilon(\nu, z) \times \frac{dl}{dz}\exp\left[-\tau(\nu_{\rm obs}, z_{\rm obs}, z)\right]dz \tag{1}$$

(Bechtold et al. 1987), where $\epsilon(\nu, z)$ is the space-averaged, proper volume emissivity (ergs cm^{-3} s^{-1} Hz^{-1}) of the ionizing radiation sources at frequency $\nu = \nu_{\rm obs}(1+z)/(1+z_{\rm obs})$ and redshift z, dl is the proper length increment for the standard Friedmann cosmology, and τ, the effective optical depth of a cloudy IGM, is defined at the observed frequency, $\nu_{\rm obs}$, and is due to the accumulated absorption by H and He in intervening clouds, integrated from the observer redshift z_{obs} to the emitter redshift z. In what follows, we will integrate equation (1) for an Einstein–de Sitter universe, in the simple case of a constant emissivity per comoving volume. We consider two candidates for the sources of ionizing radiation: primeval galaxies and AGN–type objects. In the calculations we normalize J_{912} to equal 10^{-20} ergs cm^{-2} s^{-1} sr^{-1} Hz^{-1} in a perfectly transparent ($\tau = 0$) medium at $z_{obs} = 3$, as it will be found that, to account for the proper intensity inferred from the proximity effect, ~ 10 times more energy must be released at the hydrogen Lyman limit by the candidate ionizing sources. We choose $z_{max} = 7$. Note that the large cumulative opacity of the absorbers will make our results largely "local," thus rather insensitive to the assumptions made above.

2.1. H I *Lyman Continuum Absorption*

Discrete clouds absorb radiation from the background through the ionization of H and He. We will follow MO and LP and calculate the effective optical depth of Poisson distributed clouds due to Lyman continuum accumulated absorption of H I for a photon emitted at redshift z_{em} and observed at redshift z_{obs} with wavelength λ_{obs} as

$$\tau(\lambda_{obs}, z_{obs}, z_{em}) = \int_{z_c}^{z_{em}} \int_0^{\infty} f[N(\text{H I}), z] \times [1 - e^{-\Delta_{\text{H I}}}] dN(\text{H I}) dz\,, \quad (2)$$

where $\Delta_{\text{H I}} = N(\text{H I})\sigma_{\text{H I}}(\lambda_{obs}/912\ \text{Å})^3[(1 + z_{obs})/(1 + z)]^3$ is the optical depth of a cloud with column density N(H I), and $(1 + z_c) = (1 + z_{obs})$ when $\lambda_{obs} \leq 912$ Å, or $(1 + z_c) = (1 + z_{obs})(\lambda_{obs}/912\ \text{Å})$ when $\lambda_{obs} > 912$ Å. Here $\sigma_{\text{H I}}$ is the hydrogen photoionization cross section. We will adopt model A2 from MO for the distribution of Lyα clouds [$N(\text{H I}) < 1.58 \times 10^{17}$ cm^{-2}] and Lyman limit systems in redshift and neutral column density along a given line of sight:

$$f[N(\text{H I}), z] = \begin{cases} 2.0 \times 10^7 N(\text{H I})^{-1.5}(1 + z)^{2.4} \\ \quad (10^{14}\ \text{cm}^{-2} < N(\text{H I}) < 1.58 \times 10^{17}\ \text{cm}^{-2})\,; \\ 2.3 \times 10^8 N(\text{H I})^{-1.5}(1 + z)^{0.5} \\ \quad (1.58 \times 10^{17}\ \text{cm}^{-2} < N(\text{H I}) < 10^{22}\ \text{cm}^{-2})\,. \end{cases} \quad (3)$$

We have expanded the exponential in equation (2) to first order when $\Delta_{\text{H I}} < 1$ and neglected it compared to one otherwise. At the Lyman limit this approximation yields:

$$\tau(912, z_{obs}, z_{em}) = 0.244 x_{obs}^3 (x_{em}^{0.4} - x_{obs}^{0.4}) + 2.31 x_{obs}^{1.5} \ln\left(\frac{x_{em}}{x_{obs}}\right) - 0.77 x_{obs}^3 (x_{obs}^{-1.5} - x_{em}^{-1.5}) - 0.0031 (x_{em}^{1.5} - x_{obs}^{1.5})\,, \quad (4)$$

where $x = 1 + z$. Optically thin Lyα clouds provide 50% of the differential optical depth, $d\tau/dz$, at $z = 2.7$. It is instructive to expand τ in z around z_{obs}. At $z_{obs} = 3$, $\tau(912, 3) = 1$ for $\Delta z = 0.2$. Thus the ionizing radiation is produced largely by local sources already at $z \sim 3$, as sources at higher redshift are severely attenuated (LP). For this reason, the computed background at $z \sim 3$ is rather insensitive to uncertainties in the redshift distribution of absorbers at, say, $z \gtrsim 3.7$. Also, due to the wavelength dependence of Lyman continuum absorption, higher energy photons arrive unattenuated from a larger volume, e.g., $\tau(600, 3) = 1$ for $\Delta z = 0.39$. As a consequence, the spectrum of the observed background will be flatter than the local emissivity.

2.2. *Young Galaxy-dominated Model*

To model the spectral distribution of a star-forming galaxy, we used an updated version of the Bruzual (1983) code of stellar population synthesis (Bruzual 1989). The output UV spectrum is displayed in Figure 1*a* (*short-dashed line*) and is nearly independent of the galaxy history as it is produced by short-lived massive stars.

To compute the attenuated diffuse radiation field we need to assess the role of neutral and singly ionized helium associated with absorption-line systems in reducing the intensity of the background radiation at rest-frame wavelengths shortward of the corresponding ionization edges (MO). Consider optically thin, homogeneous clouds in ionization equilibrium with the diffuse field. Case A recombination implies $N(\text{He II})/N(\text{He I}) \simeq 10^{22}(J_{504}/n_{\text{H}})$, where n_{H} is the hydrogen number density of the clouds, and J_{504} is the background intensity at the He I edge. In the popular scenario in which *low-density* absorbers are highly ionized by the intense UV radiation field (Sargent et al. 1980), the fractional abundance of He I is then very small, $N(\text{He}) \simeq N(\text{He II})$, and will be ignored in the following (we estimate that $\lesssim 40\%$ of the total opacity at 504 Å is due to neutral helium). We will also ignore hydrogen and helium recombination radiation, as its estimated contribution in the UV wavelength range is also small.

Figure 1*a* shows the background flux resulting from the numerical integration of equation (1). The attenuation by the intervening clouds produces a significant reduction of the intensity of the metagalactic flux. Between the hydrogen and helium Lyman limit, the attenuated spectral energy distribution (*solid line*) is also much harder than the corresponding spectrum in the limit of a transparent IGM (long-dashed line).

2.3. *AGN-dominated Model*

Consider, on the other hand, the possibility that the absorption systems are photoionized by a metagalactic flux which is dominated by AGN–type sources. For comparison with Steidel and Sargent, we have integrated equation (1) in the simple case of a power-law emissivity $\epsilon(\nu, z) \propto \nu^{-\alpha}$, with $\alpha = 1.5$. In this case, the fractional abundances of He I and He II in low-density clouds are both very small, $N(\text{He}) \simeq N(\text{He III})$. We will only include photoelectric absorption by He II. Case A recombination now implies $N(\text{He II})/N(\text{H I}) = 1.8(J_{912}/J_{228})$, where we have adopted [He/H] = 1/12. When $\lambda \leq 228$ Å, the effective optical depth due to Lyman continuum absorption of He II can again be derived from equation (2), where now $\Delta_{\text{He II}} = 1.8(J_{912}/J_{228})N(\text{H I})\sigma_{\text{He II}}(\lambda_{obs}/228\ \text{Å})^3[(1 + z_{obs})/(1 + z)]^3$. Assuming the ratio J_{912}/J_{228} to be independent of redshift, we derive for $\lambda_{obs} = 228$ Å:

$$\tau(228, z_{obs}, z_{em}) = 0.072\left(\frac{J_{912}}{J_{228}}\right)^{1/2} x_{obs}^{1.5}(x_{em}^{1.9} - x_{obs}^{1.9}) - 0.003\left(\frac{J_{912}}{J_{228}}\right) x_{obs}^3 (x_{em}^{0.4} - x_{obs}^{0.4}) - 0.03(x_{em}^{3.4} - x_{obs}^{3.4}) + 0.77(x_{em}^{1.5} - x_{obs}^{1.5})\,. \quad (5)$$

As the opacity is now an explicit function of the background field J, equation (1) must be solved by iteration. Convergence is

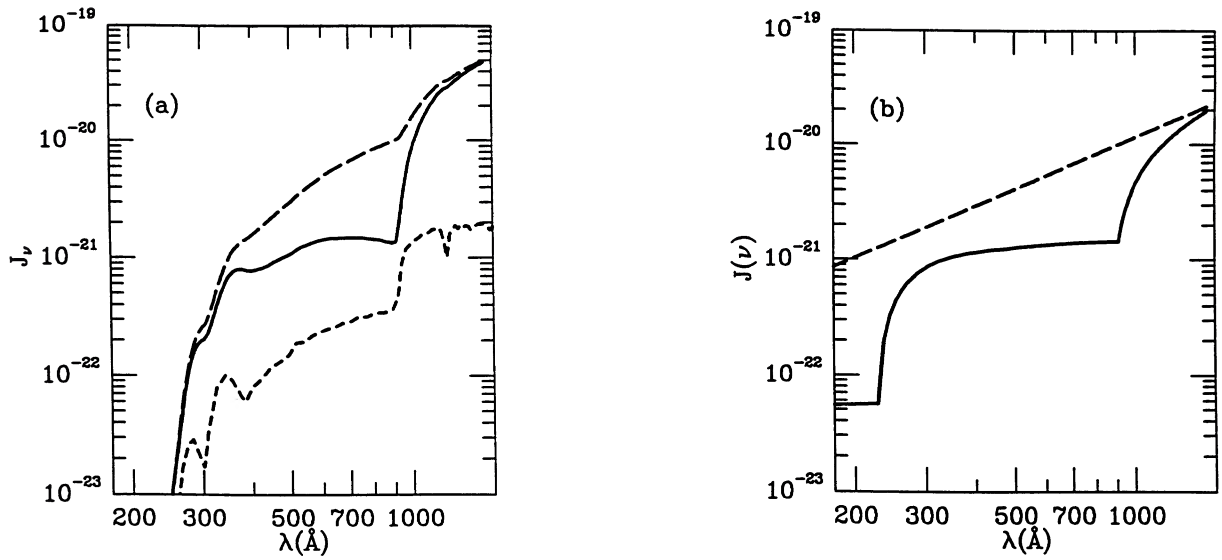

FIG. 1.—Spectrum of the mean background field at $z_{obs} = 3$, in units of ergs cm^{-2} s^{-1} sr^{-1} Hz^{-1}, as modified by the absorption of intervening clouds (*solid line*). The spectrum in the limit of a perfectly transparent ($\tau = 0$) medium is shown for comparison (*long-dashed line*). (*a*) Galaxy-dominated background: also plotted (in arbitrary flux units) is the intrinsic spectrum of a young galaxy (*short-dashed line*) according to Bruzual (1989), for a Salpeter IMF with lower and upper cutoffs of 0.1 $M_\odot$ and 75 $M_\odot$, respectively. (*b*) AGN-dominated background for a power-law emissivity $\epsilon(\nu, z) \propto \nu^{-\alpha}$, with $\alpha = 1.5$.

obtained for $J_{912}/J_{228} = 25.6$, to be compared with the value of 8 valid in the limit of a transparent medium. Note that $\tau(228, 3) = 1$ for $\Delta z = 0.056$. In Figure 1*b* we plot the spectrum of the ionizing background for the power-law AGN case.

3. PHOTOIONIZATION OF THE METAL-LINE ABSORPTION SYSTEMS

A detailed study of the physical properties of heavy-element QSO absorption systems has been recently completed by Steidel (1990). In particular, the measurements of the column densities of H I and various ionized species of C and Si have been used in conjunction with photoionization models in order to determine which spectrum of the UV background can best explain the dominance of high-ionization species. Following Steidel & Sargent, we have generated a grid of photoionization models using Ferland's code CLOUDY (Ferland 1990). Recent adjustments to the program include a major rewrite of helium treatment and an improved He II Lyα radiation transfer. The observed H I column densities, the gas-phase metal abundances, and the spectral shape (not the intensity) of the incident ionizing continuum are taken as input. The output is an array of the column densities of the heavy-element ionic species as a function of the ionization parameter $\Gamma \equiv n_\gamma/n_H$, where n_γ is the number density of incident ionizing photons. Figure 2 shows the results of the model calculations for a typical cloud with log N(H I) = 17.5. We can now use the observed values of the column densities for C II and C IV, and the upper limits on N(C III), to constrain the value of Γ and to test the starlight spectral distribution hypothesis. The ratio N(C IV)/N(C II) is

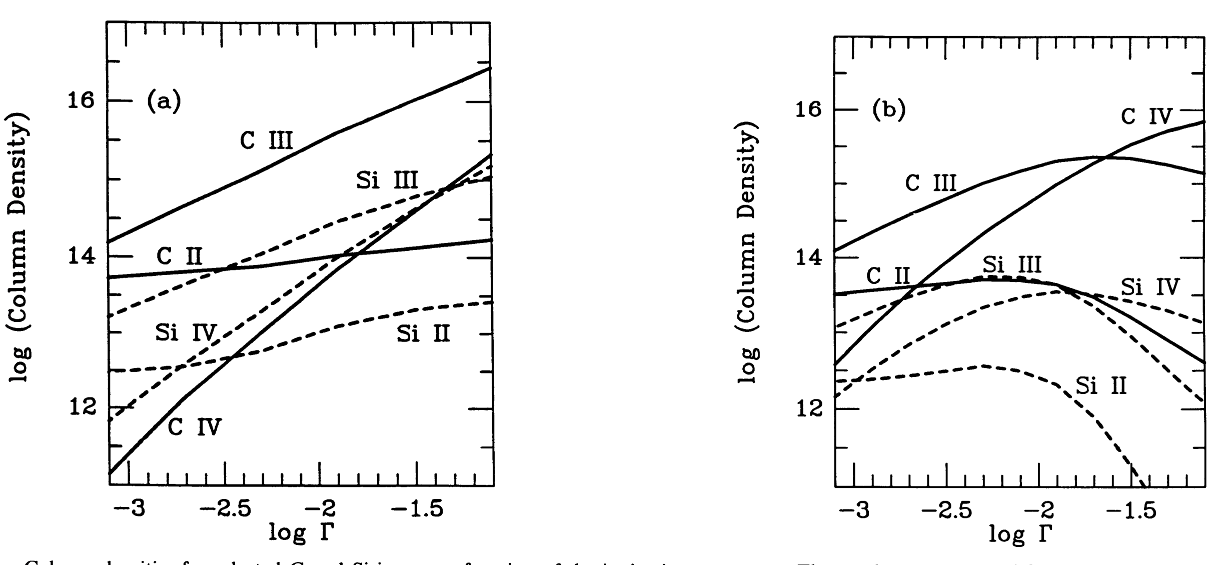

FIG. 2.—Column densities for selected C and Si ions as a function of the ionization parameter. The results are presented for a plane-parallel slab with log N(H I) = 17.5. The metal abundances are 1/100 solar. The photoionization code input spectra are (*a*) background radiation field with Bruzual galaxy emissivity as modified by the absorption of intervening clouds; (*b*) power-law (AGN) spectrum as modified by the absorption of intervening clouds.

found to be particularly sensitive to variations of the ionization parameter. The relative column densities of the silicon ions Si III and Si IV, also plotted in Figure 2, are not as useful as carbon because their photoionization balance, affected by the He II Lyα transport within the cloud, is very uncertain (Netzer & Ferland 1984; Steidel 1990). Constraints can, however, be placed on the sum N(S III) + N(Si IV). From the comparison of our Figure 2 with Figure 1 of Steidel and Sargent, it is clear that the model cloud ionized by a radiation field which has been modified by the absorption of intervening material is very different from the one photoionized in the limit of a transparent IGM. In the AGN power-law model, the main effect of the cloud opacity is a large enhancement of the N(C IV)/N(C II) and N(C IV)/N(Si II) ratios for log $\Gamma > -2$. Based on this model, the observed column densities of C II, C III, and C IV require log $\Gamma \geq -2.6$, implying a total hydrogen column density $N(\mathrm{H}) \geq 10^{20}$ cm^{-2} (this is correct, strictly speaking, only in the limit of an optically thin cloud).

In the galaxy model, opacity effects increase the N(C IV)/N(C II) ratio by a factor of less than ~ 10, and decrease the N(C III)/N(C IV) ratio by a factor ~ 3. Also, the C IV column density is found to increase by 50%–100% relative to Si IV. From the observed column densities of log N(H I) ≈ 17.5 metal-line absorbers, it is always N(C IV)/N(C II) ≥ 1, and N(C III)/N(C IV) < 80 (Steidel 1990). For a stellar background spectrum attenuated by intervening clouds, this requires that log $\Gamma \geq -1.8$, implying $N(\mathrm{H}) \geq 10^{21}$ cm^{-2}, a lower bound ~ 8 times smaller than that derived by Steidel and Sargent. In addition, no contradiction with the observed upper limits on N(C III)/N(C IV) is found (see, e.g., Steidel & Sargent), as this ratio is less than ~ 45 for log $\Gamma > -1.8$. (A small depletion onto dust grains could take care of a marginal inconsistency of N(Si III) + N(Si IV) relative to N(C IV).)

4. CONCLUSIONS

In view of the above discussion, our main conclusion is that it is possible to reproduce the relative column densities of the observed C ions with a model in which the heavy element absorbers are photoionized by a metagalactic flux dominated by the UV radiation from hot stars in young galaxies. In particular, the predicted N(C IV)/N(C II) and N(C III)/N(C IV) ratios are found to be compatible with the observational constraints if we take into account the effective opacity of the universe to ionizing photons due to intervening H I associated with Lyα clouds and Lyman limit systems. Although we agree with Steidel and Sargent that the ionizing spectrum must be hard, we find that, due to the effect of absorption by intervening systems, the underlying spectrum of the radiation sources may be as soft as that of the starlight of a young galaxy. If we now take $J_{912} = 10^{-21}$ ergs cm^{-2} s^{-1} sr^{-1} Hz^{-1}, the lower bound on Γ required in the galaxy-dominated model implies $n_{\mathrm{H}} \leq 0.004$ cm^{-3} in the absorbing systems, and a typical cloud size and mass $D \gtrsim 100$ kpc, and $M \gtrsim 10^{10.7}\ M_{\odot}$. The derived cloud properties would be expected on theoretical grounds for individual protogalaxies, and are compatible with the size limits suggested by the observations of correlated absorption in the spectra of closely spaced QSOs (Shaver & Robertson 1982). Note, however, that $D \propto J_{912}^{-1}$ and $M \propto J_{912}^{-2}$ at a constant Γ, and thus the values obtained are only indicative. The estimated sizes and masses are found to be much larger than the ones derived in the limit of an AGN-dominated background (Steidel 1990), even after the attenuation of intervening material is taken into account: in this case we infer $n_{\mathrm{H}} \leq 0.03$ cm^{-3}, $D \gtrsim 1$ kpc, and $M \gtrsim 10^6\ M_{\odot}$. At this point, it is only fair to caution that the computed effective opacity is sensitive to uncertainties in the column density distribution of absorption clouds given in equation (3). Metal-line systems are believed to be associated with the halos of intervening galaxies: the incident ionizing flux may then be dominated by local sources of radiation, rather than by a background field. More importantly, the increased Opacity Project photoionization cross sections of C and Si ions might affect the results of our models, possibly allowing for lower ionization parameters (Donahue & Shull 1991). This would reduce the inferred intervening masses. One further complication is that the far-UV spectra of primeval galaxies might be affected by additional sources of ionizing photons, such as H II regions and supernova remnants (Shull & Silk 1979), the inclusion of which is beyond the scope of this *Letter*. With these caveats in mind, it is worth mentioning that the derived properties of metal-line absorbers may provide an important clue for further investigation of the galactic halo hypothesis for their origin.

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