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CAN QUASARS PHOTOIONIZE THE INTERGALACTIC MEDIUM AT HIGH REDSHIFT?

AVERY MEIKSIN
Canadian Institute for Theoretical Astrophysics, University of Toronto

and

PIERO MADAU
The Johns Hopkins University and Space Telescope Science Institute

ABSTRACT

We discuss the reionization of the intergalactic medium (IGM) by quasar sources at high redshift. We compute the integrated UV background from observed QSOs, taking into account the hydrogen opacity associated with intervening Lyα clouds and Lyman limit systems. We note that the published data appear to indicate a significant underdensity of absorption systems in the Lyα forest with column densities $N_{HI} > 10^{15}\,\mathrm{cm}^{-2}$. This deficit results in a reduction of the opacity of the universe by a factor of 1.5–3 at $z = 3 - 5$ relative to previous estimates. The QSO contribution to the metagalactic flux at the Lyman edge may be as large as $J_{912}(z) \approx 6[(1+z)/4.5]^{0.5} \times 10^{-22}\,\mathrm{erg\,cm^{-2}\,s^{-1}\,Hz^{-1}\,sr^{-1}}$ for $q_0 = 0$, and slightly lower for $q_0 = 1/2$. For a density of the diffuse component of the IGM of $\Omega_D h_{50}^2 < 0.025$, QSOs could photoionize a smooth IGM sufficiently to satisfy the constraints imposed by the Gunn-Peterson effect. The epoch of reionization could be as recent as $z \gtrsim 5$. As a result, neutral patches of IGM would be detectable in the spectra of high redshift quasars. The patches would appear as absorption line systems with typical column densities of $10^{19} - 10^{20}\,\mathrm{cm}^{-2}$, and velocity widths of $100 - 1000\,\mathrm{km\,s^{-1}}$.

SUMMARY

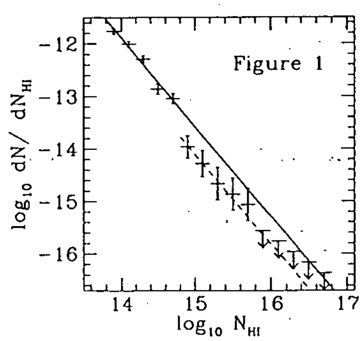
In the past few years, the growing number of observed quasars with $z > 4$ (Schneider, Schmidt, & Gunn 1989) has promoted a renewed interest in the topic of the reionization of the universe. The absence of an absorption trough on the blue side of the Lyα emission line in the spectra of these high redshift QSOs requires the diffuse component of the IGM to have been highly ionized by $z \simeq 5$ (Schneider, Schmidt, & Gunn 1991a). We examine whether QSOs detected in optical surveys can supply the required metagalactic ionizing flux.

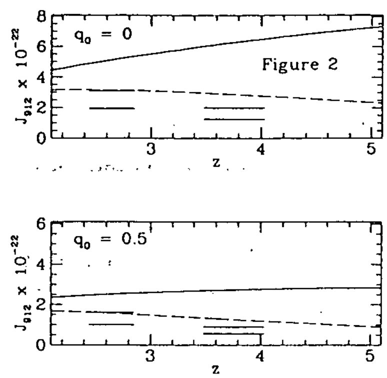
The key quantity here is J_{912}, the *mean* specific intensity of the diffuse radiation field at the observed wavelength $\lambda_{obs} = 912$A, as seen by an observer at redshift z_{obs}:

$$J_{912}(z_{obs}) = \frac{c}{4\pi H_0}\int_{z_{obs}}^{z_{max}} \frac{(1+z_{obs})^3}{(1+z)^3}\frac{\epsilon(\nu,z)\exp\left[-\tau_{eff}(912,z_{obs},z)\right]}{(1+z)^2(1+2q_0 z)^{1/2}}dz, \qquad (1)$$

where $\epsilon(\nu, z)$ is the proper volume emissivity (ergs cm^{-3} s^{-1} Hz^{-1}) of QSOs at frequency $\nu = c(1+z)/[912\mathrm{A}(1+z_{obs})]$ and redshift z, $H_0 = 50h_{50}\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$, and $\exp[-\tau_{eff}(912, z_{obs}, z)]$ is the average transmission over all lines of sight of a clumpy medium. We assess the contribution of quasars to the ultraviolet extragalactic background at high redshift in light of the two major uncertainties: (1) the existence and degree of a controversial decline at the faint end of the QSO luminosity function for $z \gtrsim 3$ (Boyle 1991; Irwin, McMahon, & Hazard 1991; Schmidt, Schneider, & Gunn 1991; Warren, Hewett, & Osmer 1991); and (2) the continuum opacity of intervening absorption systems (e.g., Sargent, Steidel, & Boksenberg 1989; Lanzetta 1991). We use the QSO luminosity function of Boyle (1991), and consider two cases: (1) a population of QSOs with a constant comoving density for $z > 2$ and which turn on at a redshift $z_{on} = 6$ (case CC); (2) a QSO population which declines by a factor of 2 in comoving density per unit redshift for $z > 3$ (case ED). We estimate for the density of the diffuse intercloud medium which must be photoionized $0.02 < \Omega_D < 0.04$ for $H_0 = 50$ and $0.005 < \Omega_D < 0.01$ for $H_0 = 80$, after subtracting observed optically thick absorbers from the estimate of the baryonic density $\Omega_b h_{50}^2 = 0.05 \pm 0.01$ from Walker *et al.* (1991), based on nucleosynthesis constraints. A more complete discussion is presented by Meiksin & Madau (1992).

We evaluate the expected UV background from QSOs using two models for the amount of attenuation by intervening absorption systems. The model used by Madau (1992) gives a moderate amount of attenuation. After examining the H I column density distribution in the spectra of 4 QSOs observed at high resolution, however, we find a significant underdensity of Lyα systems with $\log N_{HI} > 15$ (Figure 1). A deficit by a factor of 3, significant at the 4σ level, occurs in the range $15 < \log N_{HI} < 16$. No Lyα forest lines were detected for $\log N_{HI} > 16$, with a significance of 3σ. We show the best fit line of slope $\beta = 1.7$ determined over the range $13.75 < \log N_{HI} < 14.8$ (*solid line*), and the same fit renormalized to systems in the range $14.8 < \log N_{HI} < 16$ (*dashed line*). The deficit, if real, would result in a decrease in the amount of attenuation by a factor of 1.5-3 from the moderate case. We note that the deficit may be a consequence of a Jeans instability in the Lyα clouds. Spherical clouds of diameter D would be gravitationally unstable for column densities greater than $N_{HI,max} = 3.0 \times 10^{16}(D/200\,\mathrm{kpc})^{-3} J_{-22}^{-1}\,\mathrm{cm}^{-2}$, where J_{-22} is the UV background intensity at the Lyman edge in units of $10^{-22}\,\mathrm{ergs\,cm^{-2}\,s^{-1}\,Hz^{-1}\,sr^{-1}}$.





We show the resulting UV intensity for case CC in Figure 2. The intensity for both the low (*solid line*), and moderate (*dashed line*), attenuation models satisfies the Gunn-Peterson limits on the Lyα optical depth, τ_{GP}, for $\Omega_D h_{50}^2 < 0.025$. The horizontal bars are lower limits to the required intensity based on $\tau_{GP}(\langle z_{abs}\rangle = 2.6) < 0.05$ (Steidel & Sargent 1987), and $\tau_{GP}(\langle z_{abs}\rangle = 3.8) < 0.31$ (Jenkins & Ostriker 1991). In each pair, the upper (lower) bar corresponds to $H_0 = 50\,(80)\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$. We assume $\Omega_D h_{50}^2 = 0.025$ and a temperature of 15,000 K. Case ED succeeds for the low attenuation model, but fails for a moderate amount of attenuation unless $H_0 > 80$.

The Gunn-Peterson limit places a direct constraint on the epoch of reionization, through the porosity parameter $Q(z)$ of the source H II regions, when radiative recombinations in the IGM can be neglected. For case CC, we obtain $\tau_{GP}(z)Q(z)/\Omega_D h_{50}^2 = 0.45 h_{50}^{-1} T_4^{-0.75}[(3+\alpha)/\alpha_S](1+q_0)^{-1}(1+z)^{4-2q_0}[1-(x/x_{on})^{1+q_0}]/\mathcal{J}_{912}(z)$, where $x = 1+z$, α and α_S are the spectral indices of the UV background and the sources, respectively, and T_4 is the IGM temperature in units of 10^4 K. The quantity $\mathcal{J}_{912}$ is a dimensionless integral given by dividing the integrand in eq.(1) by $\epsilon(c/912\mathrm{A}, z_{obs})$. To 15% accuracy, $\mathcal{J}_{912}(z) \simeq 0.65(1+z)^{0.5-q_0}$ for the low attenuation model, and $3.0(1+z)^{-(1+q_0)}$ for the moderate model. For case ED, we obtain, to 15% accuracy for $3 < z < 6$, $\tau_{GP}(z)Q(z)/\Omega_D h_{50}^2 \simeq 0.42 h_{50}^{-1} T_4^{-0.75}[(3+\alpha)/\alpha_S](1+z)^{3-2q_0}/\mathcal{J}_{912}(z)$, where $\mathcal{J}_{912}(z) \simeq 0.35(1+z)^{0.75-q_0}$ for low attenuation, and $1.2(1+z)^{-(0.5+q_0)}$ for moderate. The constraint $\tau_{GP} < 0.05$ at $z = 2.6$ requires $Q(z = 2.6) > 54(25)$ for $q_0 = 0(0.5)$ ($\alpha = 0.5$, $\alpha_S = 0.7$, $T_4 = 1.5$) for case CC. The porosity evolves according to $Q(z) = Q(0)(1+z)^{-(1+q_0)}[1-(x/x_{on})^{1+q_0}]$. The limit on porosity constrains the reionization epoch z_I, when $Q = 1$, to $z_I > 5.9(5.7)$ for $q_0 = 0(0.5)$. For case ED, $Q(z = 2.6) > 40(21)$ for $q_0 = 0(0.5)$. To 15% accuracy, $Q(z) = Q(0)(1+z)^{-(2+q_0)}\exp[-0.69(z-3)]$, for $3 < z < 6$. We then obtain $z_I > 6.2(5.2)$ for $q_0 = 0(0.5)$. Thus the reionization epoch may have been as recent as $z_I \lesssim 6$, and possibly more recent if radiative recombinations are significant. (Note that this conclusion generalizes to any class of radiation sources, depending only on their evolution and spectral shape.) For QSOs, we find $z_I = 5.8(5.6)$ for $q_0 = 0(0.5)$ for case CC. For case ED, we find $z_I = 6.2(5.2)$ for $q_0 = 0(0.5)$.

The epoch of reionization will first reveal itself as absorption lines arising from un-ionized patches of IGM. For $Q(z) \lesssim 1$, the patches will have neutral hydrogen column densities of $10^{19} - 10^{20}\,\mathrm{cm}^{-2}$ and black cores of velocity width $100 - 1000\,\mathrm{km\,s^{-1}}$, determined by the Hubble expansion across a patch. For model ED, the lines would persist over an extended range of $\Delta z \sim 0.5 - 1$, until Q falls below ~ 0.5 and the lines broaden into the Gunn-Peterson absorption trough shortward of the Lyα emission line.