Mon. Not. R. Astron. Soc. **289**, 634–644 (1997)

On the source of ionization of the intergalactic medium at $z \sim 2.4$

Shiv K. Sethi★ and Biman B. Nath†

Inter-University Centre for Astronomy and Astrophysics, Post Bag 4, Pune 411007, India

Accepted 1997 March 27. Received 1997 March 27; in original form 1996 June 19

ABSTRACT

We use the recent detection of H II absorption at $z = 2.2$–2.6 in the line of sight of the quasar HS 1700 + 64 to put bounds on the sources of ionization. We find that, given the uncertainty in $\tau_{\rm GP}^{\rm H\,I}$ and the model of absorption in the intergalactic medium (IGM), a wide range of possible sources of ionization is still allowed by the observations. We show that a significant contribution from star-forming galaxies is allowed and is consistent with the proximity effect. In the case of photoionization by the UV background radiation, the contribution of star-forming galaxies to the intensity at 912 Å can be within a range of ~ 1–15 times that of the quasars. We also investigate the case of a collisionally ionized IGM. We show that although collisional ionization can be a dominant source of ionization at $z \sim 2.4$ (taking into account the upper limit on the Compton y-parameter of the microwave background radiation), the thermal state of the IGM cannot yet be determined. We also consider Sciama's model of radiatively decaying neutrinos, and show that the model of decaying neutrinos is consistent with the observations.

Key words: intergalactic medium – quasars: absorption lines – cosmology: miscellaneous.

1 INTRODUCTION

Absorption studies in the line of sight of high-redshift quasars are important sources of our knowledge of the density and state of ionization of the intergalactic medim (IGM). Among various tests, the Gunn–Peterson (GP) test, looking for absorption troughs in the quasar spectra shortward of Lyα emission line, is probably the most important one. The lack of any such absorption trough implies that hydrogen in the IGM has been in a highly ionized state since redshifts as high as $z \sim 5$. The spectra are, however, crowded with numerous discrete absorption lines (Lyα lines) showing the inhomogeneity in the IGM. The existence of a UV background radiation at high redshift is also inferred from the proximity effect – the change in the number density of Lyα lines in the vicinity of quasars (Bajtlik, Duncan & Ostriker 1988). The IGM is usually thought to have been photoionized by the UV background radiation, whose intensity at the Lyman limit (for H I, at 912 Å) has been estimated from the proximity effect. Observations show that the intensity of the background radiation at 912 Å in the redshift range of $z \sim 2$–3 is $J_{912,-21} \sim 10^{\pm 0.5}$, in the standard unit of 10^{-21} erg cm^{-2} s^{-1} sr^{-1} Hz^{-1} (Bechtold 1994; Fernandez-Soto et al. 1995).

The ratio of opacities due to various elements with different ionization thresholds would give us crucial information about the intensity and spectrum of the ionizing background as well as the thermal state of the IGM. Studies of absorption by He II (singly ionized helium) atoms have only been possible with the launch of UV telescopes in space. Jakobsen et al. (1994) detected the absorption due to He II atoms for the first time, but could only put lower bounds on the opacity (of $\tau \gtrsim 1.7$ at $z \sim 3.3$ in the line of sight of Q0302 − 003). From this lower limit, they and others (Madau & Meiksin 1994) put bounds on the shape of the spectrum of the ionizing background. Part of the opacity is possibly due to the He II atoms associated with Lyα lines (from line blanketing), and part of it is from absorption in the diffuse IGM (the H II Gunn–Peterson effect). If one denotes the ratio of the intensity of the background radiation at 912 and 228 Å (the Lyman limit for H I and H II, respectively) as $S_{\rm L} = J_{912}/J_{228}$, then it was shown that $S_{\rm L} \gtrsim 40$, so that the observed lower bound on H II opacity could be explained by a combination of line blanketing and the H II Gunn–Peterson effect.

Madau & Meiksin (1994) showed that such a soft ionizing radiation can be attributed to optically detected quasars, after allowing for continuum absorption by the intervening

★Present address: Institut d'Astrophysique de Paris, 98 bis, Boulevard Arago, 75014 Paris, France.

†Present address: Raman Research Institute, Bangalore 560080, India.

Lyα absorbers, or to a combination of radiation from quasars and star-forming galaxies (Miralda-Escudé & Ostriker 1990). The degree of softness would depend on the combination, and on the degree of absorption. With only a lower limit on $S_{\rm L}$, however, one is still left with a number of possible combinations.

Recently, Davidsen, Kriss & Zheng (1996) have detected an unambiguous trough in the spectrum of HS 1700 + 64, and estimated the opacity due to He II atoms to be $\tau \sim 1 \pm 0.07$ in the redshift range $z \sim 2.2$–2.6. We argue below that this result allows one to put both upper and lower limits on $S_{\rm L}$ – in the case when all of the opacity comes from line blanketing and in the case of partial contribution from the He II Gunn–Peterson effect, respectively. We use these bounds to draw conclusions on the allowed combinations of ionizing radiation from quasars, star-forming galaxies and radiatively decaying neutrinos (Sciama 1990). In addition, we discuss the implications of this observation on the thermal state of the IGM, since a contribution from collisional ionization would also change the ratio of observed values of H I and He II opacity.

The structure of the paper is as follows. Section 2 calculates the bounds on the softness of the UV background radiation, or, more generally, the ratio of the GP opacities for H I and He II, using the He II opacity. We then discuss the implications for various sources of ionization in Section 3. Finally, we summarize the implications of our results in Section 4.

2 BOUNDS ON THE SOFTNESS PARAMETER

The observed He II opacity is partly due to the He II atoms in the Lyα lines, i.e., due to the line blanketing. This contribution to the total opacity can be estimated using a distribution for the Lyα lines, and using the fact that H I and He II column densities are related as $N_{\rm He\,II} = 1.8\, S_{\rm L} N_{\rm H\,I}$. This relation assumes photoionization equilibrium of the gas with the UV background radiation (whose softness parameter is $S_{\rm L}$). For the Lyα lines, we will use the rest equivalent width distribution (Murdoch et al. 1986) (as in Madau & Meiksin 1994),

$$\frac{\partial^2 N}{\partial W \partial z} = 40.7 \exp\left(-\frac{W^{\rm He\,I}}{W_*}\right)(1+z)^{2.46} \quad (0.2 < W^{\rm H\,I} < 2\ \text{Å});$$

$$= 11.4 \left(\frac{W^{\rm H\,I}}{W_*}\right)^{-1.5}(1+z)^{2.46} \quad (W^{\rm H\,I}_{\rm min} < W^{\rm H\,I} < 0.2\ \text{Å}), \tag{1}$$

where $W_* = 0.3$ Å. The opacity due to line blanketing is then given by (Paresce, McKee & Bowyer 1980)

$$\tau_{\rm eff}(z) = \frac{1+z}{\lambda_\alpha}\int_{W_{\rm min}}^{W_{\rm max}} \frac{\partial^2 N}{\partial W \partial z} W\, {\rm d}W, \tag{2}$$

where λ_α is the rest wavelength, and $\partial^2 N/\partial W \partial z$ is the rest-wavelength distribution of the absorbers. We will also use a constant velocity parameter of $b^{\rm H\,I} = 35$ km s^{-1}, as in Madau & Meiksin (1994). This is not very unrealistic, since the observed distribution is fairly peaked around this value of b (see, e.g., Giallongo et al. 1996). For the case where the velocity of the atoms is dominated by hydrodynamical motions, the velocity parameters of He II and H I are related as $b^{\rm He\,II} = \xi\, b^{\rm H\,I}$, where $\xi = 1$. When thermal motions dominate, then $\xi = 0.5$.

Using the above distribution, the H I opacity due to lines at a redshift $z \sim 2.4$ is estimated as $\tau^{\rm H\,I}_{\rm Ly\alpha} = 0.235$, for a lower limit of $W_{\rm min} = 0.01$ Å. (The value is not very sensitive to the lower limit of W.) The flux decrement shortward of the Lyα line for HS 1700 + 64 as observed by Davidsen et al. (1996) corresponds to $\tau \sim 0.22$. Obviously, using the average distribution above to calculate the opacity is not accurate to less than 10 per cent. Moreover, since the two opacities (from observation and what is expected from line blanketing) are close, the corresponding $\tau^{\rm H\,I}_{\rm GP}$ is evidently a small number. It is worth recalling here that Steidel & Sargent (1987) put an upper limit on $\tau^{\rm H\,I}_{\rm GP}$ at $z \sim 2.5$ of $\lesssim 0.05$.

In the case where the observed He II opacity stems only from line blanketing the relation between $S_{\rm L}$ and the He II opacity is shown by solid lines in Figs 1(a) and (b). The horizontal lines represent the He II opacity observed by Davidsen et al. (1996). Figs 1(a) and (b) correspond to two values of the minimum H I equivalent width of Lyα lines, $W^{\rm H\,I}_{\rm min} = 0.0025$ and 0.01 Å. The latter value is for H I column density $\sim 2 \times 10^{12}$ cm^{-2}. It is seen that, with $W^{\rm H\,I}_{\rm min} = 0.01$ Å, for velocity broadened lines ($\xi = 1$), $S_{\rm L} \sim 89 \pm 21$, and for thermal broadening ($\xi = 0.5$), $S_{\rm L} = 512 \pm 138$. These are the upper limits on the value of $S_{\rm L}$, for the He II opacity of 1 ± 0.07 (Davidsen et al. 1996). The values of $S_{\rm L}$ are lowered when one adds the possible contribution from the opacity due to diffuse medium. The opacities of He II and H I due to the diffuse IGM are related as $\tau^{\rm He\,II}_{\rm GP} \sim 0.45\, S_{\rm L} \tau^{\rm H\,I}_{\rm GP}$. We will use a value of $\tau^{\rm H\,I}_{\rm GP} \sim 0.05$, corresponding to the upper limit put by Steidel & Sargent (1987). Lower values of $\tau^{\rm H\,I}_{\rm GP}$ will give larger values of $S_{\rm L}$. The dashed lines in Fig. 1 show the dependence of He II opacity on $S_{\rm L}$. For velocity (thermally) broadened lines, we get $S_{\rm L} \sim 18 \pm 2$ ($S_{\rm L} \sim 25 \pm 2$). These are the lower limits on $S_{\rm L}$.

Extending the Lyα distribution below $N_{\rm H\,I} \sim 2 \times 10^{12}$ cm^{-2} down to $W^{\rm H\,I}_{\rm min} = 0.0025$ Å increases the He II opacity for a given value of $S_{\rm L}$, and therefore decreases the bounds on $S_{\rm L}$ for a given opacity. With only line blanketing, for velocity broadened lines, we find $S_{\rm L} \sim 42 \pm 7$, and for thermally broadened lines, $S_{\rm L} \sim 120 \pm 29$. Including a $\tau^{\rm H\,I}_{\rm GP} = 0.05$, we find, for velocity broadening, $S_{\rm L} \sim 16 \pm 2$ and, for thermal broadening, $S_{\rm L} \sim 21 \pm 2$.

In a high-resolution study along the line of sight of Q1331 + 170, Kulkarni et al. (1996) showed that the equivalent width distribution might be steeper than the distribution in equation (1). If confirmed, this will shift the curves in Fig. 1 towards larger values of $S_{\rm L}$.

3 BOUNDS ON SOURCES OF IONIZATION

3.1 Quasars

The proximity effect – the change in the number density of Lyα lines in the vicinity of quasars – shows that the intensity of the UV background radiation at $z \sim 2.4$ at the Lyman limit (912 Å) is $J_{-21} \sim 10^{\pm 0.5}$ (Fernandez-Soto et al. 1995).

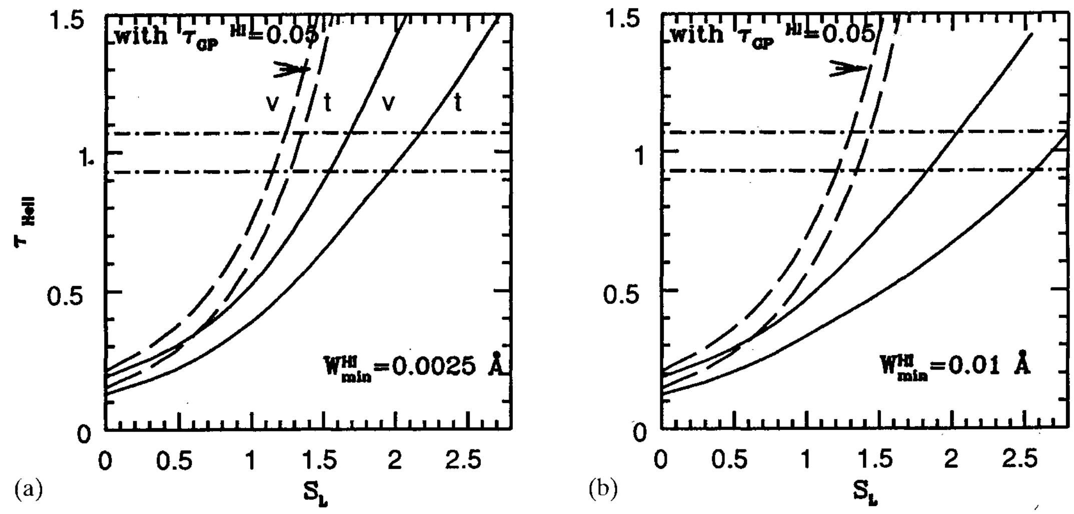

Figure 1. We plot $\tau_{\mathrm{He\,II}}$ against S_{L} for two values of $W_{\mathrm{min}}^{\mathrm{H\,I}}$ (0.0025 and 0.01 Å). Solid lines show the opacity where only line blanketing is included, for velocity and thermally broadened lines, which are labelled 'v' and 't', respectively. Dashed lines show the corresponding opacity when opacity from diffuse IGM is also included, for $\tau_{\mathrm{GP}}^{\mathrm{H\,I}}=0.05$. The horizontal lines correspond to $\tau_{\mathrm{He\,II}}=1.0\pm0.07$, as observed by Davidsen et al. (1996).

Part of the ionizing radiation obviously comes from the quasars, which are the only known source of UV photons at high redshifts, and several authors have derived the intensity due to quasars (Miralda-Escudé & Ostriker 1990; Madau 1992; Meiksin & Madau 1993; Haardt & Madau 1996). We will follow the derivation by Madau (1992) using the quasar luminosity function as given in Boyle (1991). The luminosity function of quasars at redshifts exceeding 3 remains an issue of controversy (for a recent discussion, see Pei 1995, and references therein). As in Madau (1992), we will assume that the comoving number density of quasars is conserved beyond $z\sim3$ (to be precise, z_{c} of Boyle 1991) until $z\sim5$. The spectrum of the quasars is similarly assumed to be $F_\nu\propto\nu^{-0.7}$, for $\lambda>1216$ Å, and $F_\nu\propto\nu^{-1.5}$, for $\lambda<1216$ Å [This value of spectral index is also favoured by recent observations (Tytler et al. 1995)], as in Madau (1992).

The spectrum of the UV background radiation will be determined by the intrinsic spectra of the quasars and absorption of the photons by the intervening Lyα absorption systems (the spectrum is also affected by the uniformly distributed hydrogen and helium, but this effect is negligible). We use models A2 from Miralda-Escudé & Ostriker (1990) and LA from Meiksin & Madau (1993) for the H I column density distribution of the Lyα lines. The second of these models (LA) is based on the fact that there exists a deficit of Lyα systems with column densities $\gtrsim10^{15}$ cm^{-2}, and so the real opacity of the universe at high redshifts might be lower than that predicted by A2. For a recent discussion of possible models of absorption by Lyα clouds, see Giroux & Shapiro (1996). Most allowed models of Lyα absorption fall between models A2 and LA. We show in Fig. 2 the resulting spectrum of the UV background at $z\sim2.4$ due to quasars. The strong break at 228 Å is due to absorption at the Lyman limit for He II atoms (for details, see Appendix A). It is seen that the value of S_{L} of the ionizing background for quasars alone is 10–20, depending on the absorption model. We have neglected the contribution of recombination photons from the Lyα systems to be background flux. This contribution, as shown by Haardt & Madau (1996), makes an insignificant difference to the value of S_{L} at $z\simeq2.4$. We note here that the intensity at 912 Å for radiation from only quasars falls short of the inferred value from proximity effect.

Comparing with the bounds on S_{L} from Fig. 1, it is seen that radiation from only quasars is consistent with a value of $\tau_{\mathrm{GP}}^{\mathrm{H\,I}}\simeq0.05$.

3.2 Star-forming galaxies

It is possible that young galaxies which are forming stars at high redshift emit a large number of UV photons. Several authors have discussed the effect of such star-forming young galaxies on the background radiation (Bechtold et al. 1987; Miralda-Escudé & Ostriker 1990). The effect will depend on the intrinsic spectrum of the young galaxies, their number density and evolution in redshift, and the absorption by the intervening Lyα absorption systems. Miralda-Escudé & Ostriker (1990) used the UV spectrum from Bruzual (1983) (their fig. 2), and we also use the same analytical fit.

The intensity of the ionizing flux depends both on the history of galaxy formation and on the time-scales of star formation in the young galaxies. We use the model 'G2' for galaxy formation and the model 'S1' for star formation history (Miralda-Escudé & Ostriker 1990). The model 'G2' assumes a Gaussian model of galaxy formation with a formation redshift of $z_{\mathrm{f}}=4.5$ with a span in redshift $w=2$. The normalization of the ionizing flux, which also includes the uncertainty of the absorption by dust inside the galaxies, is then varied to change the contribution of young galaxies to the ionizing flux. The ionizing flux is most sensitive to the intrinsic spectrum of the young galaxies. For a Bruzual-type intrinsic spectrum, the ionizing flux at redshift $z\sim2.5$ receives contributions from photons emitted at redshifts $z\lesssim2.6$–3, depending on the absorption model and the normalization. So the ionizing flux from young galaxies does

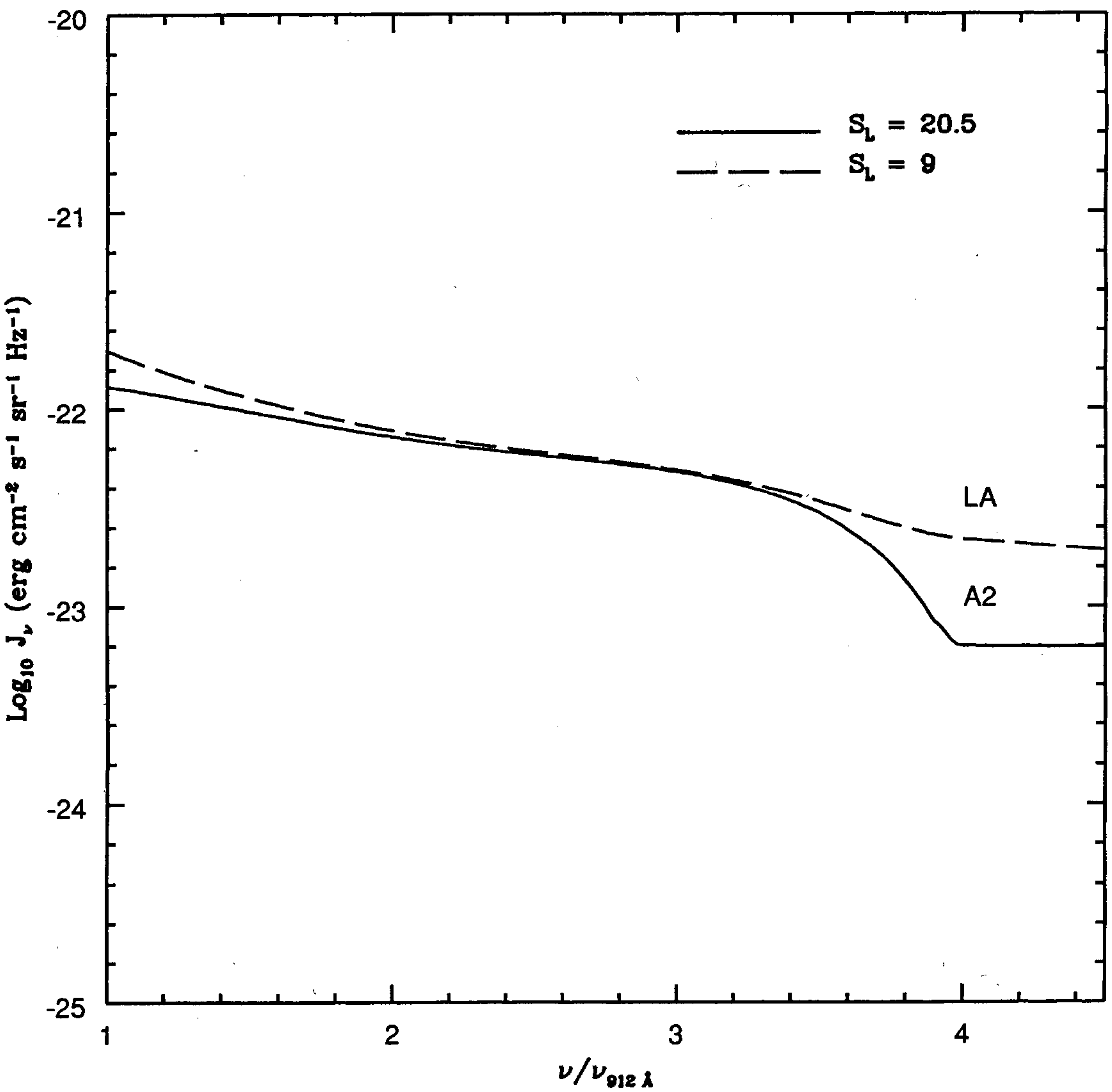

Figure 2. The spectrum of the UV background radiation at $z = 2.4$ due to quasars is shown for two absorption models, A2 and LA. The corresponding values of the softness parameter S_L are also shown.

not depend strongly on the redshift evolution of galaxies, but only on the intrinsic spectrum and the normalization (relative to the quasars). We show typical spectra of the ionizing flux from young galaxies and quasars, with two models of absorptions discussed in the last section, in Fig. 3.

We show the effect of adding UV photons from young galaxies to that from quasars in Fig. 4. It plots the value of S_L as a function of the ratio of intensities from young galaxies to that from quasars at 912 Å. As expected, S_L increases with the ratio, i.e., the addition of UV photons from young galaxies makes the spectrum of the background radiation softer. There are two reasons for this. First, the intrinsic spectrum of star-forming galaxies is softer than that of quasars. Secondly, the absorption at the He II Lyman limit has a non-linear effect on the softness parameter. The softer the spectrum is, the more abundant are the singly ionized helium atoms in the Lyα absorption systems, and the greater is the absorption, thereby further increasing the softness parameter (Miralda-Escudé & Ostriker 1990). The horizontal lines correspond to the values of S_L inferred from the discussion in Section 2.

The bounds on the sources of photoionizing background radiation from Figs 1 and 4 are summarized in Table 1. The column for A2 for the case of $\tau_{GP}^{HI} = 0.05$ is left blank, as the ratio $J_{912,YG}/J_{912,QSO}$ is too small ($\ll 0.5$) to be relevant. It is seen from Table 1 that a wide range of values (~ 1–15) of $J_{912,YG}/J_{912,QSO}$ is possible, given the uncertainty in the absorption model and in the value of τ_{GP}^{HI}. We note here that the total intensity is $J_{-21} = 1$ for $J_{912,YG}/J_{912,QSO} = 6.7$ (A2) and 4.1 (LA). This fact, and the values of Table 1, imply that only values of $\tau_{GP}^{HI} < 0.05$ are consistent with the proximity effect results, especially for model A2.

3.3 Collisional ionization

It is also possible that the IGM is warm ($T_{IGM} \sim 10^6$ K), and that it is collisionally ionized to a large extent. Several authors have pursued the models of reionizing the IGM by collisional ionization, with various heating sources. For

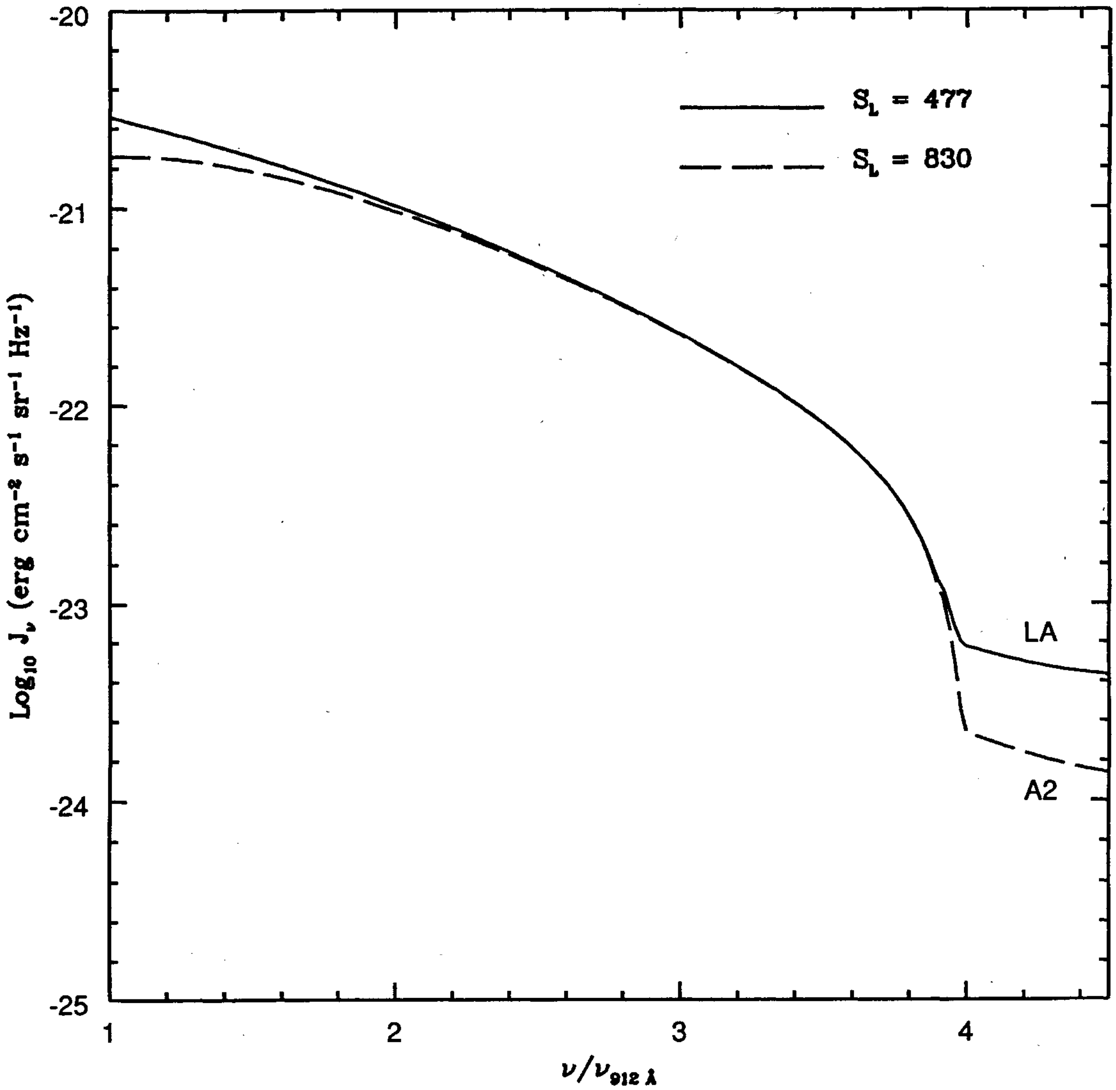

Figure 3. A typical spectrum of the UV background radiation at $z=2.4$ due to quasars and young galaxies is shown for two absorption models, A2 and LA. The corresponding values of the softness parameter S_L are also shown.

example, Tegmark, Silk & Evrard (1993) showed that galactic winds from low-mass galaxies can heat the Universe to the extent that the IGM is collisionally ionized, and Nath & Biermann (1993) showed that cosmic rays from galaxies could also be a source of heating. A warm IGM has also been invoked to inhibit the formation of small-scale structure in the Universe (Blanchard, Valls-Gabaud & Mamon 1992). For a temperature $T_{\rm IGM} \gtrsim 10^5$ K, the hot electrons will ionize H I and He II atoms to a varying degree, depending on the temperature and the number density of the atoms. The ratio of the Gunn–Peterson opacities of H I and He II atoms will therefore depend on the temperature. The final effect on the opacities will depend both on the temperature and the softness of the photoionization background radiation which exists in any case.

We show in Fig. 5 the effect of adding collisional ionization. We define $S_L^{\rm eff}$ as the ratio $\tau_{\rm GP}^{\rm He\,II}/(0.45\tau_{\rm GP}^{\rm H\,I})$ for the case including collisional ionization. Note that for a photoionized IGM, $S_L = \tau_{\rm GP}^{\rm He\,II}/(4.45\tau_{\rm GP}^{\rm H\,I})$. In other words, an IGM with both collisional and photoionization mimics a photoionized IGM with the inferred value of S_L (from the observations of $\tau_{\rm GP}^{\rm He\,II}$ and $\tau_{\rm GP}^{\rm H\,I}$) equal to $S_L^{\rm eff}$. The value of $S_L^{\rm eff}$ first decreases at the ionization threshold of He II because, in the absence of collisional ionization, the intensity of J at 228 Å is small, with a low photoionization rate. Including a high temperature makes collisional ionization more dominant and ionizes He II abundantly. Collisional ionization does not make a large difference at the ionization threshold of H I, as the photoionization rate there is already high. This explains the decrease of $S_L^{\rm eff}$ at the ionization threshold of He II in Fig. 5. The decrease is larger for the case of UV radiation from quasars and young galaxies. This is because in the case of radiation from only quasars, the intensity of J is larger at 228 Å than in the case of radiation from quasars and young galaxies (see Figs 2 and 3). This is why collisional ionization makes a large difference in the latter case. The value of $S_L^{\rm eff}$ increases at higher temperatures when collisional ionization becomes the dominant source of ionization for hydrogen also. At very high temperatures, the rates of collisional ionization and recombination of both H I and He II have similar

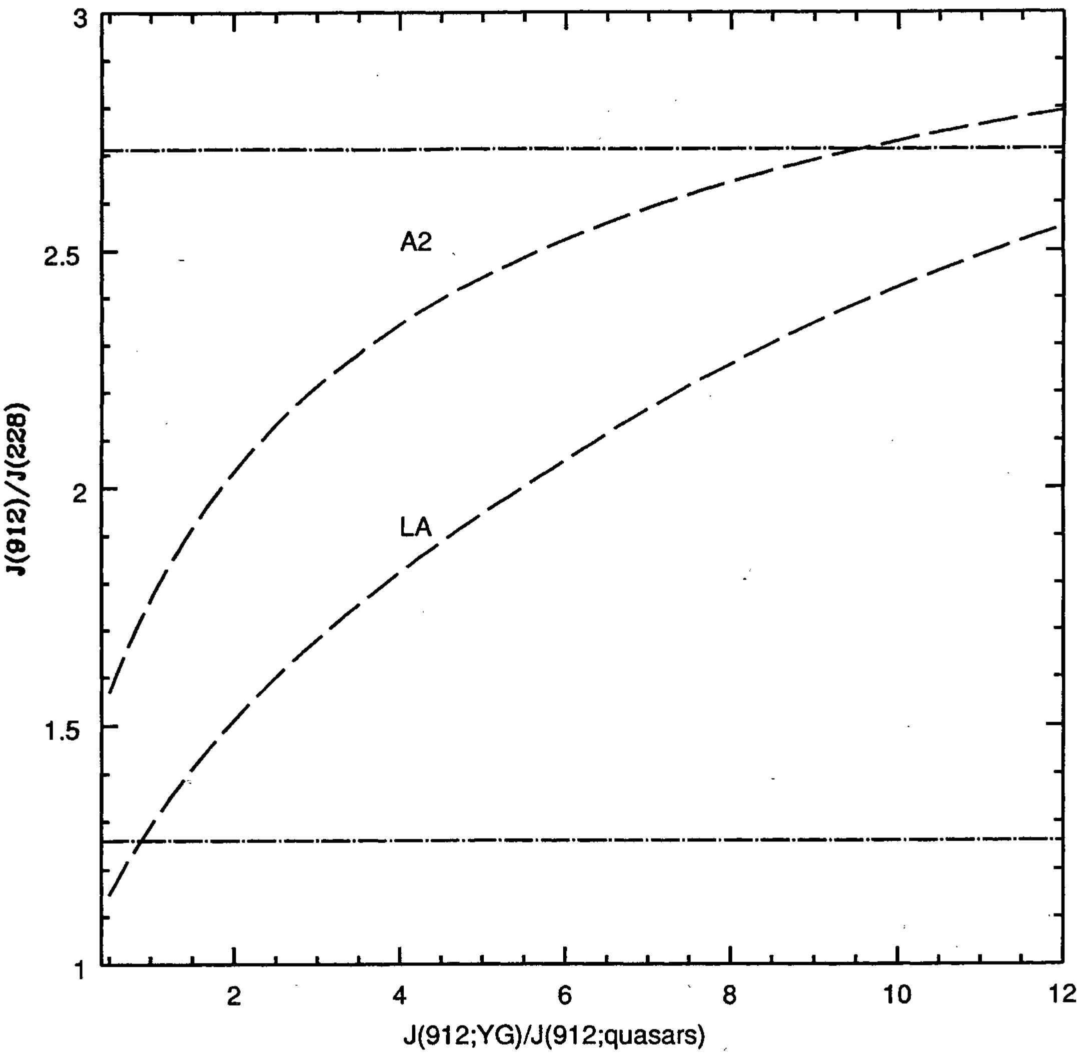

Figure 4. S_L is plotted against the ratio of contributions to the UV background radiation from young galaxies to that from quasars, $J_{912,\,YG}/J_{912,\,QSO}$, for two absorption models, A2 and LA. Constraints on the softness parameter S_L from Section 2 are shown as horizontal lines.

Table 1. Allowed values of $J_{912,\,YG}/J_{912,\,QSO}$ from $\tau_{He\,II}(z=2.4)=1.\pm 0.07$ (Fig. 1). 'vel' and 'th' correspond to velocity and thermally broadened lines as in Fig. 1.

		J_{912}(YG)/J_{912}(QSO) for	
		A2	LA
Line blanketing	(vel)	1.65 ± 0.45	$5. \pm 1.$
	(th)	$9.5 \pm 3.$	14.7 ± 2.25
With $\tau_{GP}^{H\,I} = 0.05$	(vel)	-	0.85 ± 0.15
	(th)	-	1.45 ± 0.15

dependences on the temperature (for the dependence of recombination coefficients on temperature, see Cen 1992). This explains the levelling off of the ratio at high temperatures.

We have assumed here that collisional ionization in the IGM does not change the internal structures of the Lyα absorption systems. This is justified because the temperature of Lyα absorption systems is of the order 10^4–10^5 K, as inferred from the b parameter of the Lyα lines, whose distribution has a peak around 35 km s^{-1} (Giallongo et al. 1996). This means that photoionization is the dominant process of ionization inside the clouds.

We also calculate the limit on the temperature of the IGM from the *COBE* limits on the Compton y-parameter, $y \lesssim 1.5 \times 10^{-5}$ (Fixsen et al. 1996). If the hot electrons in the IGM lose energy to the microwave background photons through inverse Compton scattering at $z \sim 2.4$, then the temperature of the IGM is bounded as $T \lesssim 1420$ eV (Fig. 5).

It is not yet possible to put limits on the temperature of the IGM gas based on the analysis of $S_L^{\rm eff}$, since the relative contributions of quasars and young galaxies in the UV background radiation and the value of J_{-21} are unknown. However, if J_{-21} is determined in the future with better accuracy at this redshift, and the value of $\tau_{GP}^{H\,I}$ for this line of sight is determined (in other words, the value of $S_L^{\rm eff}$ is determined), then such an analysis as described above will lead to limits on the temperature.

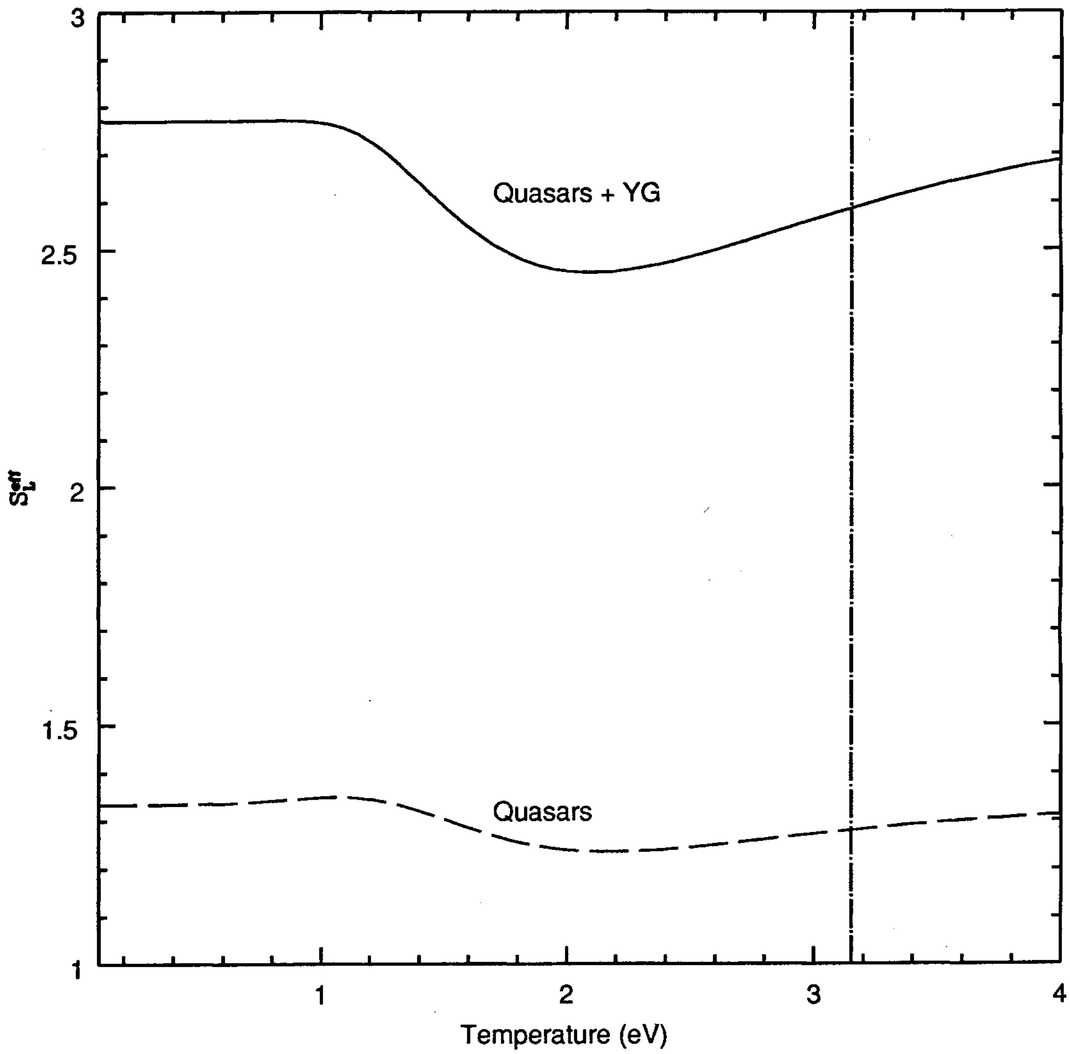

Figure 5. The effective value of S_L is plotted as a function of the temperature of the IGM for two cases. The dashed curve is for the case where only UV photons from quasars are considered. The solid curve is for UV photons from quasars and young galaxies, where $J_{-21}=1$ (at $z=2.4$). Both curves use the absorption model A2. The dot–dashed line shows the upper limit from the Compton y-parameter bound.

3.4 Decaying neutrinos

Another possible source of photoionization of the AGM at high redshifts is radiatively decaying neutrinos (Sciama 1990; for details and relevant references of Sciama's model, see Sciama 1994b and Sethi 1997). In this paper, we consider the model of radiatively decaying neutrinos proposed by Sciama. In this model, massive neutrinos of mass $m_\nu \sim 30$ eV decay into a massless neutrino and a photon with a decay lifetime $\tau \sim 10^{23}$ s. Observation of the hydrogen-ionizing photon flux at the present epoch fixes the parameters m_ν and τ (Sciama 1995). We use $\rho = 2\times 10^{23}$ s and $m_\nu = 27.4$ eV, as in Sciama (1995). The resulting spectrum of the ionizing flux, at $z=2.4$, with the quasars and radiatively decaying neutrinos as the two sources, is shown in Fig. 6. The value of $J_{-21}(912)$ is $\sim\{0.72, 0.64\}$ for the model of absorption {LA, A2}. Depending on the value of model of absorption, the resulting value of S_L lies between 32 and 5856. These values are consistent with those in Fig. 1, and indicate a value of $\tau_{GP}^{HI} < 0.05$.

The feature that distinguishes radiatively decaying neutrinos from other soft sources of photoionization like the young galaxies is the relative suppression of neutral helium-ionizing flux. The observation of neutral helium resonant lines in four Lyman-limit systems along the line of sight to HS 1700 − 64 can indicate the nature of ionizing background at that redshift (Reimers & Vogel 1993; Sciama 1994a; Sethi 1997). However, unlike the GP tests which probe the ionization state of the IGM averaged over length-scales $\sim$ a few × 10 Mpc, and are therefore insensitive to the local sources of ionization, the state of ionization inside the Lyman-limit systems could be caused by sources inside the cloud (Viegas & Friaça 1995). Therefore, for studying the nature of background ionizing flux, we do not discuss the consequences of this observation.

3.5 He I GP test

HS 1700 + 6416 has also been observed for He I GP (Reimers et al. 1992); the reported upper limit on the number

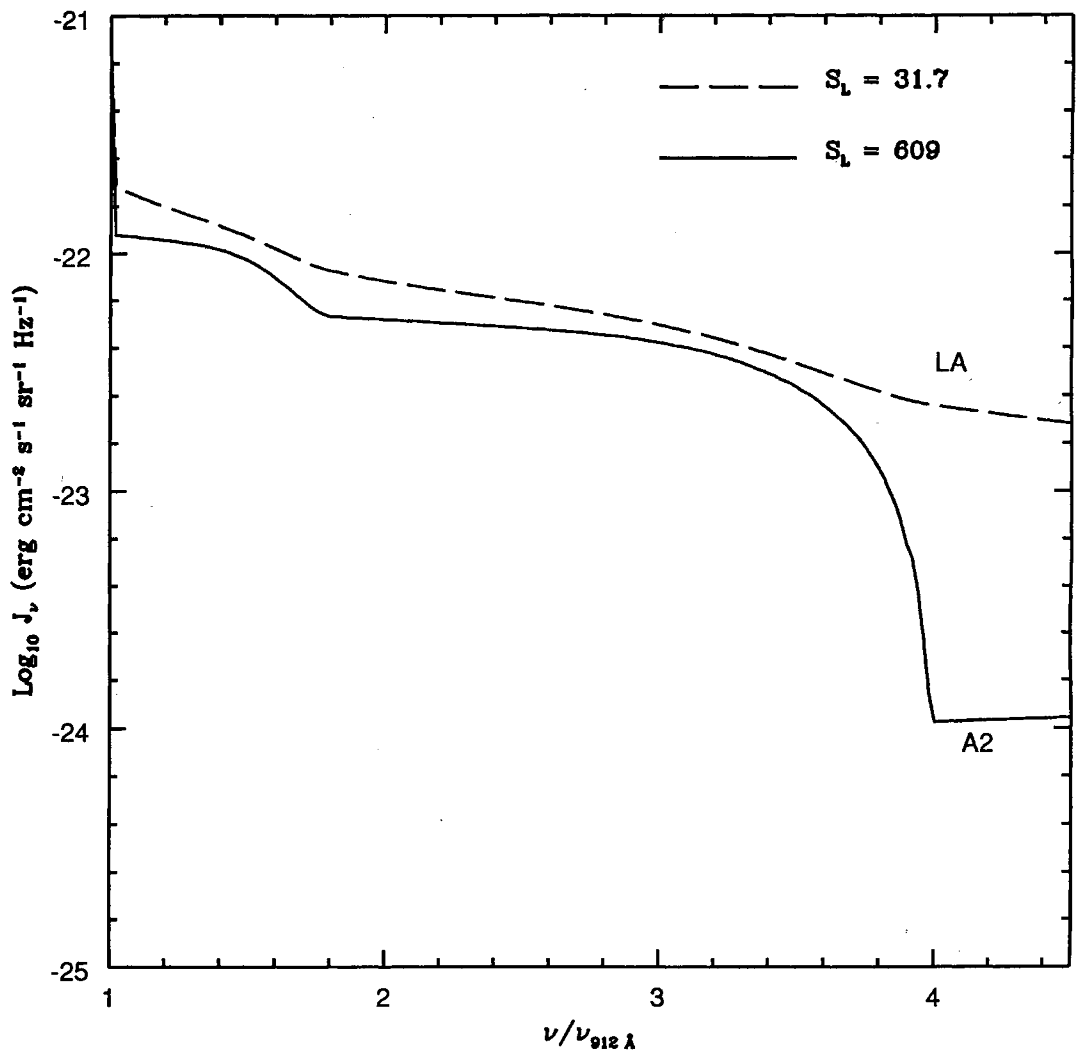

Figure 6. The spectrum of the UV background radiation from quasars and decaying neutrinos is shown for two absorption models, A2 and LA.

density of neutral helium $n_{\mathrm{He\,I}} \lesssim 7\times10^{-12}$ cm^{-3} (for $q_0=0$, $h_0=0.5$) translates to $\tau_{\mathrm{GP}}^{\mathrm{He\,I}} \lesssim 0.05$ (for $q_0=0.5$, $h_0=0.5$). For photoionization models the GP optical depth can be related to the background ionizing photons as:

$$\tau_{\mathrm{GP}}^{\mathrm{He\,I}}(z)=\frac{1.6\times10^{-3}h_0^3\Omega_{\mathrm{IGM}}^2(3+\alpha)(1+z)^{4.5}}{J_{-21}(504)}y_2. \tag{3}$$

Here $\alpha\simeq0.5$ is the local index of the spectrum of ionizing photons near the ionization threshold of He I; $y_2=n_{\mathrm{He\,II}}/n_{\mathrm{He}}$ in the fraction of He II. For $\tau_{\mathrm{GP}}^{\mathrm{He\,II}}\simeq1$ at $z\simeq2.7$, one gets $y_2=5\times10^{-4}$ (for $\Omega_{\mathrm{IGM}}=0.05$, $h_0=0.5$, $q_0=0.5$). Noting that $J_{-21}(504)\simeq0.1$–1 for all the models we have studied (Figs 2, 3 and 6) and inserting the value of y_2 in equation (3), one sees that the He I GP test is easily satisfied for HS 1700+6416. [It should be pointed out that as different models of photoionization give quite different values for He II ionizing flux (Figs 2, 3 and 6), the fiducial values of Ω_{IGM}, h_0 and q_0 we use for the estimate given above will not satisfy the He II GP test for all the models; however, a scatter in these values does not change our conclusion.]

4 SUMMARY AND DISCUSSION

The proximity effect suggests that $J_{-21}(912)\simeq1$ at $z\simeq2.4$. As is seen from Fig. 2, quasars contribute only a fraction of this flux. If one assumes that the remaining flux is contributed by the star-forming galaxies, then, for model A2 (LA), one needs $J_{912,\mathrm{YG}}/J_{912,\mathrm{QSO}}=6.7(4.1)$. Fig. 4 gives the corresponding values of the softness parameter. For A2 (LA), we find that $S_{\mathrm{L}}=367\,(68)$.

In Fig. 7 we show the value of $\tau_{\mathrm{GP}}^{\mathrm{H\,I}}$ necessary to explain $\tau_{\mathrm{He\,II}}=1$, including line blanketing with $W_{\mathrm{min}}^{\mathrm{H\,I}}=0.01$ Å, for velocity and thermally broadened lines. It is seen that for the large values of S_{L} implied by the proximity effect, the required $\tau_{\mathrm{GP}}^{\mathrm{H\,I}}$ is very small. For $S_{\mathrm{L}}=68$, for themally (velocity) broadened lines $\tau_{\mathrm{GP}}^{\mathrm{H\,I}}\sim0.015\,(0.002)$, which implies $\Omega_{\mathrm{IGM}}h^{3/2}=0.015\,(0.006)$. For $S_{\mathrm{L}}=367$, for thermally broadened lines, $\tau_{\mathrm{GP}}^{\mathrm{H\,I}}\sim0.0005$, implying $\Omega_{\mathrm{IGM}}h^{3/2}=0.002$. A note of caution is in order here. We have used an average column density distribution of Lyα lines to calculate the line-blanketing opacity. To rely on such small values as $\tau_{\mathrm{GP}}^{\mathrm{H\,I}}\sim0.0005$, however, one should use the column density distribution of Lyα lines in the particular line of sight.

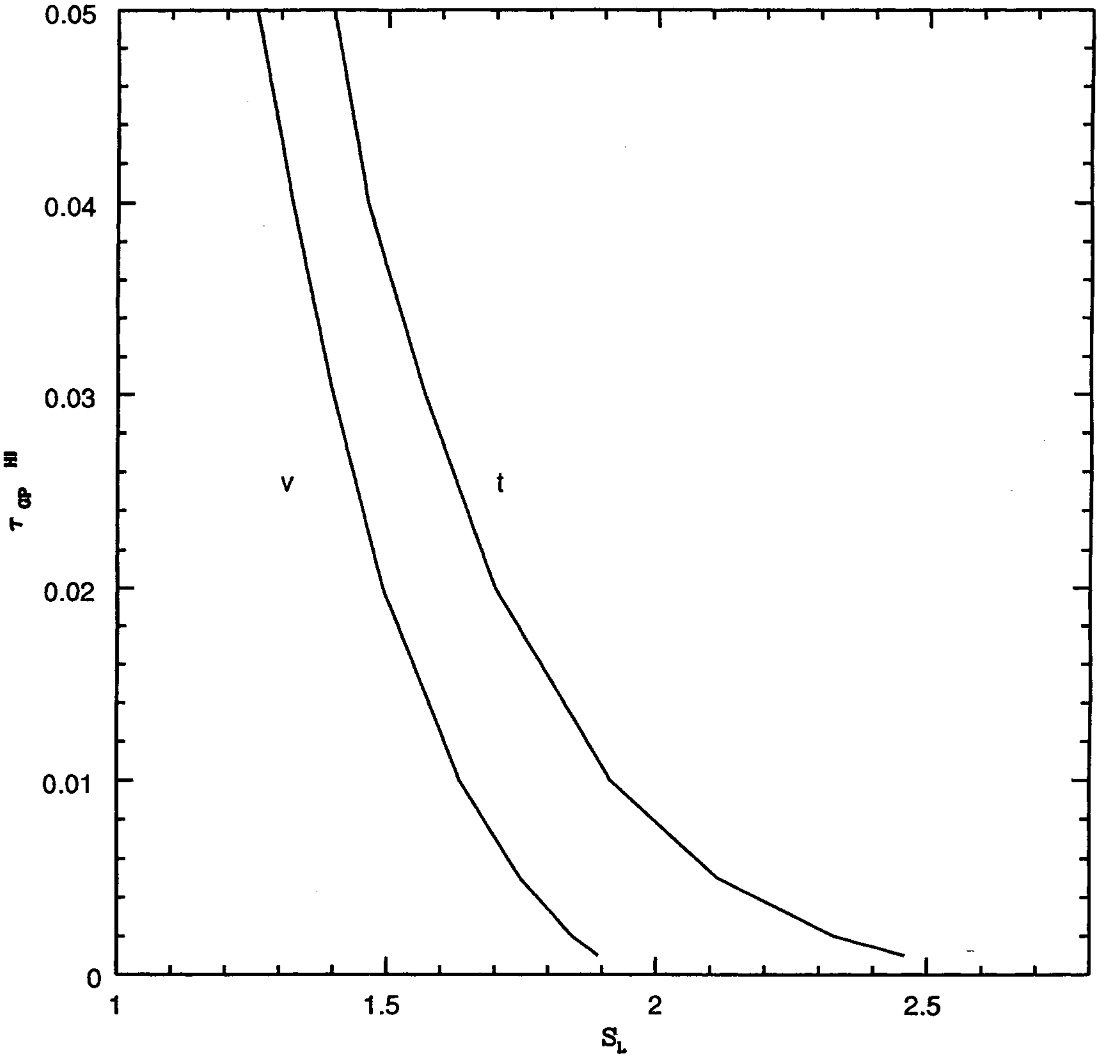

Figure 7. The value of $\tau_{\rm GP}^{\rm H\,I}$ that is necessary to explain $\tau_{\rm He\,II}(z=2.4)=1$, where the He II opacity includes the contribution from line blanketing, is shown as a function of S_L. Curves due to velocity and thermally broadened lines are labelled 'v' and 't', respectively.

The fact that $\tau_{\rm GP}^{\rm H\,I}$ is not determined in the same lines of sight in which He II absorption has been detected is an obstacle in the study of the physical condition of the IGM. Although Davidsen et al. (1996) have determined the decrement D_A in the spectrum of HS 1700 + 64, it is not enough for the purpose of studying the background radiation and the IGM gas. It is important to know the contribution from Lyα lines and the diffuse IGM to this decrement. Using an average distribution of Lyα lines to determine this, or using the value of $\tau_{\rm GP}^{\rm H\,I}$ from other lines of sight, is not a useful procedure. It is now thought that the IGM is probably not homogeneous, and there is a probability distribution for the value of $\tau_{\rm GP}^{\rm H\,I}$ at a given redshift (Reisenegger & Miralda-Escudé 1995). We here note that the absence of a determination of $\tau_{\rm GP}^{\rm H\,I}$ in the line of sight of Q0302 − 003 also makes the study of the IGM in the vicinity of that quasar and the UV background radiation very uncertain (Giroux, Fardal & Shull 1995; Nath & Sethi 1996).

The quasar HS 1700 + 64 has been studied in the past in various contexts. Various elements in high ionization states (N V and O VI) were observed in the Lyman-limit systems along this line of sight (Reimers et al. 1992). If these states of ionization were to be attributed to the background radiation, it would imply a hard background source (with spectrum like $\nu^{-0.6}$) (Vogel & Reimers 1993). Although it is not clear that these ionization states are caused by background radiation, the consistency of such an assumption with our analysis would require $\tau_{\rm GP}^{\rm H\,I} > 0.05$ (Fig. 1).

A large contribution from young galaxies to the UV background radiation will be accompanied by the production of metals. According to the calculations of Giroux & Shapiro (1996), the metallicity of the Universe at $z\sim 3$ can be larger than that of Population II stars. However, their calculation is based on continuous metal production. They have suggested that if metals were ejected from the galaxies, this problem will be alleviated (see also Madau & Shull 1996).

To summarize, the observation of Davidsen et al. (1996) brings us closer to the source of ionization at $z=2.4$. Unlike the previous studies based on the detection of He II in Q0302 − 003, which permitted only a lower limit on the softness parameter (S_L), this new observation allows us to put an upper bound on S_L. Our study shows that this rules out sources with very soft spectra (e.g., $S_L \gtrsim 650$, see Fig. 1), irrespective of the value of $\tau_{GP}^{H\,I}$ in this line of sight. However, as we have shown in the previous sections, it is difficult to pinpoint the exact nature of the ionizing source, because S_L has a large range of allowed values ($16 \lesssim S_L \lesssim 650$). Among other things, determination of $\tau_{GP}^{H\,I}$ along this line of sight and high-resolution observation of Lyα lines would help resolve some of these issues.

ACKNOWLEDGMENTS

We thank R. Srianand for several stimulating discussions, and the anonymous referee for comments.

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APPENDIX A

The specific intensity (in units of erg cm^{-2} s^{-1} Hz^{-1} sr^{-1}) of background photons observed at a frequency ν_0 and redshift z_0 is given by

$$J(\nu_{\rm obs}, z_0) = \frac{cH_0^{-1}}{4\pi} \int_{z_0}^{\infty} {\rm d}z \, \frac{(1+z_0)^3}{(1+z)^5(1+\Omega_0 z)^{1/2}} \, \epsilon(\nu, z) \exp[-\tau(\nu_{\rm obs}, z_{\rm obs}, z)],$$

where $\epsilon(\nu, z)$ is the cumulative proper volume emissivity (in units of erg cm^{-3} s^{-1} Hz^{-1}) of all the sources of photoionization (QSO, young galaxy, decaying neutrino, etc.) at frequency $\nu = \nu_{\rm obs}(1+z)/(1+z_{\rm obs})$ and redshift z. $\tau(\nu_{\rm obs}, z_{\rm obs}, z)$ measures the optical depth suffered by a photon emitted at redshift z and observed at redshift $z_{\rm obs}$ with frequency $\nu_{\rm obs}$.

We consider two sources of absorption: diffuse IGM and Lyα systems. Thus

$$\tau(\nu_{\rm obs}, z_{\rm obs}, z) = \tau_{\rm diffuse}(\nu_{\rm obs}, z_{\rm obs}, z) + \tau_{\rm cloud}(\nu_{\rm obs}, z_{\rm obs}, z). \tag{A1}$$

The optical depth due to diffuse IGM is

$$\tau_{\rm diffuse}(\nu_{\rm obs}, z_{\rm obs}, z) \simeq \int_{z_{\rm obs}}^{z} {\rm d}z \left|\frac{{\rm d}t}{{\rm d}z}\right| [n_{\rm H}\sigma_{\rm H\,I}(\nu) y + n_{\rm He}\sigma_{\rm He\,I}(\nu) y_1 + n_{\rm He}\sigma_{\rm He\,II}(\nu) y_2]. \tag{A2}$$

Here, $y = n_{\rm H\,I}/n_{\rm H}$, $y_1 = n_{\rm He\,I}/n_{\rm He}$, and $y_2 = n_{\rm He\,II}/n_{\rm He}$, and σ is the photoionization cross-section for various species. $\tau_{\rm cloud}$, the average attenuation of photon flux due to Poisson-distributed clouds, is given by

$$\tau_{\rm cloud}(\nu_{\rm obs}, z_{\rm obs}, z) \simeq \int_{z_{\rm obs}}^{z} \int_0^{\infty} {\rm d}z \, {\rm d}N_{\rm H\,I} \mathscr{P}(N_{\rm H\,I}, z) [\![1 - \exp\{-[N_{\rm H\,I}\sigma_{\rm H\,I}(\nu) + N_{\rm He\,I}\sigma_{\rm He\,I}(\nu) + N_{\rm He\,II}\sigma_{\rm He\,II}(\nu)]\}]\!]. \tag{A3}$$

Here, $N_{\rm H\,I}$, $N_{\rm He\,I}$ and $N_{\rm He\,II}$ correspond to column densities of neutral hydrogen, neutral helium and singly ionized helium in the clouds, and $\mathscr{P}(N_{\rm H\,I}, z)$ is the observed column density and redshift distribution of the Lyα clouds along an average line of sight. In ionization equilibrium, $N_{\rm He\,I}$ and $N_{\rm He\,II}$ can be inferred from known column densities of neutral hydrogen $N_{\rm H\,I}$:

$$N_{\mathrm{He\,II}} = N_{\mathrm{H\,I}} \times 1.8 \frac{J_{912}}{J_{228}}\ \mathrm{cm}^{-2}; \qquad N_{\mathrm{He\,I}} = N_{\mathrm{H\,I}} \times 0.044 \frac{J_{912}}{J_{504}} y_2\ \mathrm{cm}^{-2}. \tag{A4}$$

The absorption due to neutral helium is important only for the case of radiatively decaying neutrinos, as seen in Fig. 6. We consider two models: model A2 of Miralda-Escudé & Ostriker (1990) (the same as model MA of Meiksin & Madau 1993 and model 3 of Giroux & Shapiro 1996), and model LA of Meiksin & Madau (1993) of absorption due to Lyα systems. Most realistic models of absorption due to Lyα systems fall between these two models (for a detailed discussion, see Giroux & Shapiro 1996).

The rates of photoionization and collisional ionization, and the recombination coefficients are taken from Cen (1992).