THE STELLAR UV BACKGROUND AT z<1.5 AND THE BARYON DENSITY OF PHOTOIONIZED GAS

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ABSTRACT

We use new studies of the cosmic evolution of star-forming galaxies to estimate the production rate of ionizing photons from hot, massive stars at low and intermediate redshifts. The luminosity function of blue galaxies in the Canada-France Redshift Survey shows appreciable evolution in the redshift interval z = 0–1.3, and generates a background intensity at 1 ryd of $J_\lambda \approx 1.3 \times 10^{-21} (f_{\text{esc}}) \text{ ergs cm}^{-2} \text{ s}^{-1} \text{ Hz}^{-1} \text{ sr}^{-1}$ at z ≈ 0.5, where $(f_{\text{esc}})$ is the unknown fraction of stellar Lyman-continuum photons which can escape into the intergalactic space, and we have assumed that the absorption is picket fence-type. We argue that recent upper limits on the Hα surface brightness of nearby intergalactic clouds constrain this fraction to be $\lesssim 20\%$. The background ionizing flux from galaxies can exceed the QSO contribution at $z \approx 0.5$ if $(f_{\text{esc}}) \gtrsim 6\%$. We show that, in the general framework of a diffuse background dominated by QSOs and/or star-forming galaxies, the cosmological baryon density associated with photoionized, optically thin gas decreases rapidly with cosmic time. The results of a recent Hubble Space Telescope survey of O vi absorption lines in QSO spectra suggest that most of this evolution may be due to the bulk heating and collisional ionization of the intergalactic medium by supernova events in young galaxy halos.

1 INTRODUCTION

The integrated ultraviolet flux arising from quasars and hot, massive stars in star-forming galaxies is likely responsible for maintaining the high degree of ionization of the intergalactic medium (IGM). The large, low-density intergalactic clouds which produce the Lyman-α forest lines in the absorption spectra of background QSOs represent one of the observational signature of this high level of ionization (Bechtold 1994; Giallongo et al. 1996). Locally, the ultraviolet ionizing background (UVB) may be responsible for the ionization of the hydrogen clouds located in the galactic halo (Ferrara & Field 1994), and for producing the abrupt truncation in the H I distribution at the edge of nearby spiral galaxies (Bochkarev & Sunyaev 1977).

The contribution of QSOs to the UVB is the easiest to assess with some degree of reliability. Madau (1992), and, more recently, Haardt & Madau (1996) have computed the intensity of the UVB as a function of redshift based on the most recent estimates of the quasar luminosity function from $z = 0$ to $z \approx 5$. They included the reprocessing of ultraviolet radiation by intergalactic material, and showed that QSO absorption-line systems are sources, not just sinks of ionizing photons. The resulting metagalactic flux at the Lyman edge is found to increase from $\approx 10^{-23}$ ergs cm$^{-2}$ s$^{-1}$ Hz$^{-1}$ sr$^{-1}$ at the present epoch to $\approx 5 \times 10^{-22}$ ergs cm$^{-2}$ s$^{-1}$ Hz$^{-1}$ sr$^{-1}$ at $z = 2.5$. The background intensity stays nearly constant in the redshift interval $z = 1.5 – 3.5$, to drop rapidly beyond $z = 4$ because of the steep decline of the quasar population.

Hot, massive stars in star-forming galaxies have also been suggested as important contributors to the UVB (Bechtold et al. 1987; Songaila, Cowie, & Lilly 1990; Miralda-Escudé & Ostriker 1990) at early epochs. As the present rate of production of metals in normal galaxies is too low to account for the observed element abundances, there must have been an epoch when the heavy element production rate per unit mass was several times larger than it is today (Madau et al. 1996). Data on the galaxy population at $z \gtrsim 3$ are sparse but are accumulating rapidly (Steidel et al. 1996; Madau et al. 1996). The recent detection by Tytler et al. (1995) and by Cowie et al. (1995) of C IV in the Lyman-α forest clouds has provided the first evidence of widespread chemical enrichment in the IGM at $z \approx 3$. Madau & Shull (1996) have computed the ionizing stellar radiation flux which accompanies the production of metals at high-z, and found that this may be significant, comparable to the QSO contribution if a fraction $\gtrsim 25\%$ of the UV radiation emitted from stars can escape into the intergalactic space. At low and intermediate redshifts, the Canada-France Redshift Survey (Crampton et
al. 1995) has provided new information on the properties and evolution of field galaxies at $z < 1.3$. Finally, the first survey for O vi 1032, 1038Å absorption lines in QSO spectra (Burles & Tytler 1996) has shown the likely presence of a substantial cosmological mass density of hot, collisionally ionized gas at $\langle z \rangle = 0.9$.

In this paper we estimate the contribution of blue, star-forming galaxies to the UVB, and use some new upper limits to the intensity of the UV diffuse radiation field at the present-epoch to constrain the average escape fraction of Lyman-continuum (Lyc) photons from such systems. We also show that the cosmological gas density of $T \approx 20,000$ K material photoionized by the UVB decreases strongly with cosmic time, and suggest that the recent detection of O vi intergalactic absorption lines may provide some clues on the fate of the “missing” baryons. Throughout this paper, we shall adopt a flat cosmology with $H_0 = 50h_{50}$ km s$^{-1}$ Mpc$^{-1}$ and $q_0 = 0.5$.

2 STAR-FORMING GALAXIES AND THE UVB AT $z < 1.5$

2.1 Blue Galaxy Emissivity

The results of the Canada-France Redshift Survey have made it possible to disantangle the evolution of the luminosity function (LF) from redshift $z = 0.02$ to redshift $z = 1.3$ of the blue and red galaxy population separately (Lilly et al. 1995). At variance with that of red objects, the LF of blue galaxies (bluer than present day Sbc) shows significant cosmological evolution. This evolution can be represented as a brightening of the average luminosity of the blue population as the redshift increases (although density evolution can be present as well). Between $z \approx 0.3$ and $z \approx 0.6$ the LF brightens by about 1 magnitude. Beyond, and up to $z \approx 1.3$ the luminosity evolution of the bright end of the LF levels off. For $z < 0.2$, the new survey shows a significant excess relative to the local LF of Loveday et al. (1992).

In the AB photometric system, the average rest-frame ultraviolet color of the blue population, in the redshift interval considered, is $U − V \approx 0.8$. To estimate the mean number of Lyc photons produced by O-B stars, we have modeled the intrinsic UV spectral energy distribution of star-forming galaxies using the Bruzual & Charlot (1993) stellar population synthesis code. We assume a Salpeter initial mass function with lower and upper cutoffs of 0.1 and 125$M_\odot$, and a constant star formation rate. The fiducial galaxy age is fixed at $\approx 2$ Gyr; this yields the required $U − V$ color after convolving with the standard Johnson broadband filters. Differences greater than 1 Gyr in the age produce changes greater than 0.1 mag in the average colors.

The comoving emissivity at $h\nu_L = 1$ ryd of our galaxy sample can then be written as

$$\epsilon(\nu_L, z) = \langle f_{esc} \rangle \frac{E_{nu}}{E_{nu}} \int_{L_{min}}^{\infty} \phi(L, z) L dL,$$

where $\langle f_{esc} \rangle$ is the fraction of Lyc photons emitted from stars which can escape into the intergalactic space, assumed to be independent of frequency (picket fence-type absorption), in analogy with the leakage of ionizing photons from the galactic disk. $E_{nu}$ is the spectral energy distribution. The luminosity function in the B-band, $\phi$, at various $z$ is taken from Lilly et al. (1995), and we have adopted a constant value of $L_{min}$, corresponding to $M_B = -17.8$. The ensuing galaxy emissivity at the Lyman edge is plotted in Figure 1 as a function of redshift: a strong cosmological evolution is apparent from $z = 0$ to $z \approx 1$.

Our procedure yields $\epsilon(912\AA, 0) = 2 \times 10^{25} \langle f_{esc} \rangle$ ergs s$^{-1}$ Hz$^{-1}$ Mpc$^{-3}$. To check for systematic errors, we have re-computed the present-day ionizing emissivity starting from the Hα luminosity density of the local universe, $1.3 \pm 0.7 \times 10^{39}$ ergs s$^{-1}$ Mpc$^{-3}$ (Gallego et al. 1995). Assuming case-B recombination theory, an escape fraction of 50%, and our fiducial population synthesis galaxy spectrum, this value implies $\epsilon(912\AA, 0) = 1.1 \pm 0.5 \times 10^{25}$ ergs s$^{-1}$ Hz$^{-1}$ Mpc$^{-3}$, in good agreement, within the errors, with the extrapolated value plotted in Figure 1.

2.2 Ionizing Background Intensity

The mean specific intensity $J_\nu$ of the UV background at the observed frequency $\nu_0$, as seen by an observer at redshift $z_0$, is given by

$$J(\nu_0, z_0) = \frac{1}{4\pi} \int_{z_0}^{\infty} \frac{df}{dz} \left(\frac{(1 + z_0)^3}{(1 + z)}\right)^2 \epsilon(\nu, z) \exp[-\tau_{eff}(\nu_0, z_0, z)] dz,$$

where $\tau_{eff}$ is the effective photoelectric optical depth of a cloudy intergalactic medium following Madau (1992), $\epsilon(\nu, z)$ is the proper volume emissivity at frequency $\nu = \nu_0(1 +
z)/(1 + z_o), and dℓ/dz is the line element in a Friedmann cosmology.

The main uncertainty in the estimate of the UVB generated by star-forming galaxies is the escape fraction of Lyc photons (<f_esc> into the IGM. While theoretical models of the structure of H I regions in a vertically stratified disk suggest an escape fraction of ~15% through the H I layers into the halo (Dove & Shull 1994), the recent data obtained by the Hopkins Ultraviolet Telescope show that less than 3% of the stellar UV radiation can escape from the four, low-redshift starburst galaxies observed by Leitherer et al. (1995). Given the peculiar nature of the selected targets, however, it is conceivable that the escape fraction might be significantly reduced in these objects by the presence of dust absorption. From a reevaluation of the same data Hurwitz et al. (1997) suggest less restrictive upper limits with an average value closer to 19%.

An indirect argument, put forward by Patel & Wilson (1995a, b), suggests a Lyc escape fraction from the galactic disk into the halo greater than 50%. From their observations of Hα emission in nearby galaxies, these authors were able to estimate the total star formation rate and compare it with the value derived from the distribution of OB stars in the galactic disk. In the presence of ionization balance, the two values should be consistent. On the contrary, heavy losses of ionizing photons appear to be taking place in the field. In this respect, it is important to note that, although the fraction of ionizing photons leaking from the galactic disk could be relatively high, Lyc absorption by cold gas in galaxy halos may be quite common, as suggested by the identification of the galaxies associated with the Lyman-limit systems observed in quasar spectra (e.g., Steidel 1995).

The study of nearby isolated intergalactic clouds where no sign of stellar activity is detected can provide a stringent upper limit to the local UVB and hence to the mean escape fraction. In particular, by looking at the Hα radiation that should escape from these optically thick clouds due to the reprocessing of the incident Lyc photons, Vogel et al. (1995) (see also Donahue, Aldering & Stocke 1995) have recently set a 3-σ upper limit of J_L < 8 × 10^{-23} ergs cm^{-2} s^{-1} Hz^{-1} sr^{-1} at z = 0. Given the constraints on the luminosity function and the average spectral shape of the blue galaxies, the local UVB limit implies that no more than 20% of Lyc photons can escape into the IGM from star-forming regions. The evolution of a galaxy-dominated UVB is shown as a function of redshift in Figure 1. Adding together the galaxy contribution with the one estimated from quasars and local AGNs (Haardt & Madau 1996), we find that a value of <f_esc> = 15%, predicted by theoretical models (Dove & Shull 1994), yields a total UVB which is still consistent with the local upper limits. It is interesting to notice that, since the opacity of the IGM at z < 1.5 is low, galaxies at intermediate redshifts can provide a negligible contribution to the local metagalactic flux. The current limits on the UVB from Hα-brightness studies in fact provide the most stringent constraints to the total ionizing emissivity at z ≈ 0.5 – 1, where the bulk of the blue galaxy evolution is observed.

As shown in Figure 1, an escape fraction of <f_esc> = 15% implies a total UVB of J_L ~ 10^{-22} ergs cm^{-2} s^{-1} Hz^{-1} sr^{-1} at z ≈ 0.15. If the contribution of the blue galaxies to the metagalactic flux extends to z < 1.5, i.e., if the escape fraction of Lyc photons into the IGM is significant even at early epochs, it is possible to envisage a scenario where the background intensity remains nearly constant, J_L = 2 – 4 × 10^{-22} ergs cm^{-2} s^{-1} Hz^{-1} sr^{-1}, from z = 0.4 to z = 4, i.e., for a fraction of 50% of the age of the universe. Alternatively, QSOs will dominate the metagalactic flux if <f_esc> < 6%.

The intensity, spectrum, and evolutionary history of a QSO-dominated UVB have been recently computed by Haardt & Madau (1996) on the basis of our current knowledge of the QSO luminosity function. The integrated diffuse flux at the Lyman edge is found to increase from 2 × 10^{-20} at z = 0 to ≈ 5 × 10^{-22} ergs cm^{-2} s^{-1} Hz^{-1} sr^{-1} at z ≈ 2. Over the redshift range z = 2 - 3.5, J_L remains roughly constant, to decrease to 2 × 10^{-23} ergs cm^{-2} s^{-1} Hz^{-1} sr^{-1} at z ≈ 5.

Since the luminosity function of star forming galaxies at z > 1 is poorly known it is difficult to estimate the galaxy contribution to the UVB in the redshift interval 2 < z < 5. However an extrapolation of the z ≈ 1 luminosity function at higher z would imply a total UVB at z ≈ 3.5 of the order of J_L = 6 ± 1 × 10^{-22} ergs cm^{-2} s^{-1} Hz^{-1} sr^{-1}.

An independent estimate of J_L at high redshifts comes from the statistical study of the proximity effect in the spectra of QSOs (Bajtlik, Duncan, & Ostriker 1988; Bechtold 1994). The value recently derived from a large high resolution sample of Lyman-α forest lines is J_L = 5 ± 1 × 10^{-22} ergs cm^{-2} s^{-1} Hz^{-1} sr^{-1}, constant in the redshift range 1.7 < z < 4.1 (Giallongo et al. 1996). As a direct consequence, while in a QSO-dominated background model the photoionization rate will remain approximately constant from z ~ 3.5 to z ~ 1.5, to drop by a factor of ~ 30 by the present epoch, in a universe in which star-forming galaxies contribute significantly to the metagalactic flux, J_L may only decrease by a factor ~ 6 from z = 2 to the present epoch.

### 3 THE BARYON DENSITY OF PHOTOIONIZED GAS

A simple estimate of the cosmological density of the baryons hidden in the Lyman-α forest clouds can be obtained from the following quantities: the intensity J_L of the UVB, the number density of lines along the line of sight dN/dz, the typical cloud radius R, and the observed H I column. The latter spans a large range of values, from 10^{14} cm^{-2} to 10^{15} cm^{-2} and more, showing a bending below N_H ~ 10^{14} cm^{-2} where the slope of the power-law distribution flattens from 1.8 to 1.4 at ≈ 3 (Giallongo et al. 1996). The density of lines with N_H ~ 10^{15} cm^{-2}, as derived from Hubble Space Telescope (Bahcall et al. 1996) and optical data (Giallongo et al. 1996), stays approximately constant ~ dN/dz ~ 25 – from z ~ 0.15 to z ~ 1.8, to increase rapidly for z > 2, dN/dz ~ 220 at z ≈ 3.8.

The baryon density of photoionized gas can be expressed in units of the critical value n_{crit} as Ω_{IGM} = f_V n_H/n_{crit} where f_V is the volume filling factor and n_H is the typical hydrogen gas density of individual clouds. The volume filling factor is proportional to the number of systems along the line of sight and depends on the cloud geometry, while the gas density is a measure of the photoionization state of the absorbers (Madau & Shull 1996), n_H ∝ R^{-1/2} N_H^{1/2} T^{-0.363} J_L^{-1/2} (a cosθ)^{1/2}. The temperature dependence is very weak for highly photoionized clouds: a

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value of $T = 2 \times 10^4$ K has been adopted here. The aspect ratio $a \equiv R/l$ generalizes the absorber geometry from spheres to disks of transverse radii $R$ to half-thickness $l$. For $(a \cos \theta) = 1$ the usual limit of spherical clouds is obtained.

Hence, the cosmological mass density produced by the Ly$\alpha$ clouds is proportional to

$$\Omega_{\text{IGM}} = 1.3 \times 10^{-11} \left( \frac{a+1}{a} \right)^{-1/2} \left( \frac{J_{\text{Ly}\alpha}}{10^{-22}} \right)^{1/2} \frac{R_{\text{HI}}}{T^{0.363}}$$

where $J \equiv J_{\text{Ly}\alpha} 10^{-22}$ ergs s$^{-1}$ cm$^{-2}$ Hz$^{-1}$ sr$^{-1}$, $R = R_{\text{HI}} h_{50}^{-1}$ kpc, $T = T_{4.3} 3 \times 10^4$ K, $a = 1.5$ is the spectral slope of the ionizing UVB and $B(z)$ is the number of lines per unit $N_{\text{HI}}$ and unit redshift interval derived at given redshifts from the observed spectra as in Giallongo et al. (1996). Thus, $dN/dz = B(z) \int N_{\text{HI}}^2 dN_{\text{HI}}$. We include the contribution from Ly$\alpha$ lines of various column densities on the basis of the known shape of the column density distribution. For $N_{\text{HI}} > 10^{14}$ cm$^{-2}$ this distribution is fairly steep, with $\beta \sim 1.8$, and the contribution to $\Omega_{\text{IGM}}$ becomes progressively small. For $N_{\text{HI}} < 10^{14}$ cm$^{-2}$, $\beta_f \sim 1.4$ and the contribution to the mass density parameter increases slowly with decreasing $N_{\text{HI}}$. We have adopted a lower $N_{\text{HI}}$ cutoff of $10^{12}$ cm$^{-2}$ as derived from high resolution data (Webb et al. 1992, Giallongo et al. 1995, Hu et al. 1995).

The cloud size and geometry are subject to substantial uncertainties. An estimate of the characteristic size of absorbers is provided by the statistical coincidence of absorption lines in closely separated quasar pairs. Recent observations of the quasar pair 1343+264A/B at $z \sim 1.8$ (Bechtold et al. 1994, Dinshaw et al. 1994) have shown that the Ly$\alpha$ sizes are of the order of $R \sim 200 h_{50}^{-1}$ kpc, much larger than previously thought. Observations at lower redshifts, $z \sim 0.5$, show even larger sizes, $R \gtrsim 300 h_{50}^{-1}$ kpc, independently of the cloud structure or geometry (Dinshaw et al. 1995). The mild redshift evolution implied by these preliminary measurements is consistent with the expectations of the standard CDM cosmological scenarios. As outlined by the numerical simulations of Miralda-Escudé et al. (1996), although the gas moves on average to regions of higher overdensity, the dominant effect for the evolution of the average cloud properties appears to be the Hubble expansion.

For these reasons, we have assumed a typical radius $R = 200 h_{50}^{-1}$ kpc at $z = 1.8$ which evolves in time following the Hubble expansion as $R \propto (1+z)^{-1}$.

The ensuing cosmological baryon density due to Lyman-\(\alpha\) clouds is shown in Figure 2 from $z = 0$ to $z \approx 4$ as a function of cosmic time. The redshift dependence of the baryon density of photoionized gas is associated with the product $(JR)^{1/2} dN/dz$ where the dominant factor is the number density evolution of the clouds.

Two different evolutionary scenarios can be envisaged at this point, depending on the sources of the ionizing background. In Figure 2a, $\Omega_{\text{IGM}}(z)$ has been computed for a QSO-dominated UVB. In Figure 2b both galaxies and QSOs contribute to the metagalactic flux. In the redshift interval $1.7 < z < 4.1$, the UVB assumes the constant value $J_{\beta 12} \approx 5 \times 10^{-22}$ ergs cm$^{-2}$ s$^{-1}$ Hz$^{-1}$ sr$^{-1}$, as derived from the proximity effect. The increase of the baryon density at higher redshifts is due to the increase of the number density of Lyman-\(\alpha\) lines, which is partly compensated by the decrease of the average cloud sizes. Lyman-\(\alpha\) absorbers at $z \approx 4$ can easily account for all the baryons in the universe predicted by nucleosynthesis, $\Omega_b h^2 = 0.05 \pm 1$ (Walker et al. 1991). Note that a large aspect ratio, $a \gtrsim 10$, must be adopted to avoid $\Omega_{\text{IGM}}$ values significantly in excess of the nucleosynthesis constraints, as outlined by Rauch & Haehnelt (1995).

The residual baryon density is already about 30% at $z \sim 1.8$ (i.e., $t \sim 3$ Gyr). By contrast, for $z < 1.7$ the number density of Lyman-\(\alpha\) clouds stays nearly constant and the evolution of the density parameter depends mainly on the evolution of the ionizing sources contributing to the UVB and of the cloud size. In any case, a further decrease of $\Omega_{\text{IGM}}$ is present in the redshift interval $z = 0.3$–$1.7$. This evolution is stronger in the case of a QSO-dominated UVB where a value of $\Omega_{\text{IGM}} \geq 0.007$ is found at $z = 0.3$. In a galaxy-dominated UVB the evolution is slower and $\Omega_{\text{IGM}} \approx 0.01$ at the same redshift. These values are larger than the baryonic “visible” mass density of galaxies, $\Omega_* = 0.004 h^{\pm 0.3}$ (e.g., Peebles 1993).

![Figure 2](image-url)  
**Figure 2.** Mass density parameter of photoionized intergalactic gas as a function of cosmic time. a) QSO-dominated UVB. b) Same including a contribution from star-forming galaxies. Points are derived from the Lyman-\(\alpha\) sample described in the text. Two exponential curves are shown simply for comparison (see sect. 4), with e-folding timescales equal to 1 and 8 Gyr. Again, the galaxy contribution has been computed assuming an escape fraction of ionizing photons into the IGM of $(f_{\text{esc}}) = 15\%$.

4 DISCUSSION

We have presented here two main results. First, we have computed the integrated emission of ionizing photons from the observed population of star-forming galaxies at $z < 1.3$, and shown that it may equal or even exceed the overall QSO contribution to the UVB in this redshift range if the mean fraction of UV photons which can escape from individual galaxies into the IGM is not negligible. We have shown in $\S$ 2 that $(f_{\text{esc}})$ is constrained to be $< 20\%$, in order to satisfy the upper limit on the intensity of the local UVB. If we adopt $(f_{\text{esc}}) \sim 15\%$ as a fiducial value for the escape fraction, the
ensuing UVB is found to evolve little in the redshift interval between \( z = 0.4 \) and \( z = 4 \).

We have also shown that the baryon fraction which is associated with the photoionized Ly\( \alpha \) clouds appears to decrease rapidly with cosmic time. At \( z \approx 4 \), \( \Omega_{\text{IGM}} \) may account for all of the nucleosynthesis baryons of the universe. As shown in § 3, the mass density parameter depends only weakly on the intensity, \( J_{\text{L}} \), of the UVB, with \( \Omega_{\text{IGM}} \propto J^{3/2} \). Hence tighter constraints on the escape fraction from galaxies are unlikely to change qualitatively the evolution of \( \Omega_{\text{IGM}} \) (see Fig. 2). The dependence of \( \Omega_{\text{IGM}} \) on the typical cloud radius and geometry is also relatively weak, \( \Omega_{\text{IGM}} \propto (R/a)^{1/2} \equiv t^{1/2} \). Moreover, in CDM scenarios, lines with \( N_{\text{HI}} < 10^{15} \text{ cm}^{-2} \) have typical sizes which appear essentially uncorrelated with the H\( \alpha \) column (Miralda-Escudé et al. 1996). Thus, while the exact normalization of \( \Omega_{\text{IGM}} \) depends on these values, it is difficult to explain the strong evolution inferred in the redshift interval \( z = 1.7 - 4 \) as a simple geometrical effect. Note that photoionization models and the statistics of coincident absorptions in QSO pairs suggest a typical cloud thickness in the range 2\( \approx \) 100 – 300 kpc, independently of the assumed aspect ratio (Fang et al. 1996). At \( z \approx 4 \), the baryon content of the Lyman-\( \alpha \) forest clouds may then be significant both in the case of spherical or disk-like geometry.

We can parameterize the cosmological evolution of \( \Omega_{\text{IGM}} \) as an exponentially decreasing function with cosmic time, \( \Omega_{\text{IGM}} \propto \exp(-t/\tau) \). As shown in Figure 2, this yields two characteristic e-folding timescales, \( \tau \approx 1 \text{ Gyr} \) for \( t < 3 \text{ Gyr} \) and \( \tau \approx 8 \text{ Gyr} \) at later epochs. Thus, roughly 60% of the photoionized gas in the universe “disappears” at early epochs over a timescale which is much shorter than the Hubble time. What is the fate of these “missing” baryons? They are unlikely to fragment into stars, as the baryonic visible mass density of galaxies today is known to be only a small fraction of the value derived from cosmological nucleosynthesis. The decrease of \( \Omega_{\text{IGM}} \) observed in the Ly\( \alpha \) line population must mainly reflect either a dilution of the photoionized gas clouds in a general diffuse intergalactic medium or an increase of the fraction of the IGM which is collisionally ionized at temperatures \( T \gtrsim 10^6 \text{ K} \) by supernovae shocks. If a strong evolution in the neutral column density of clouds were present following the Hubble flow, it would produce at \( z = 1.7 \) lines ten times weaker (\( \log N_{\text{HI}} \sim 11 \)) than at \( z \approx 3.8 \). However, since the contribution to \( \Omega_{\text{IGM}} \) increases slowly for decreasing \( N_{\text{HI}} \) (\( \Omega_{\text{IGM}} \propto N_{\text{HI}}^{0.1} \) for \( \beta \approx 1.4 \)), lines ten times weaker in \( N_{\text{HI}} \) increase \( \Omega \) only by \( \sim 0.005 \) when \( z \) decreases from \( z \approx 3.8 \) to \( z \approx 1.7 \) (i.e. from \( t \approx 1 \text{ Gyr} \) to \( t \approx 3 \text{ Gyr} \)). Thus the strong \( \Omega \) evolution derived in the redshift interval \( z = 1.7 - 4 \) can not be mainly due to a decrease (with decreasing redshift) of the lower cutoff of the \( N_{\text{HI}} \) distribution unless the sizes evolved much faster than assumed in this simple model.

A plausible possibility appears to be the additional heating of the absorbing gas at temperatures \( T \sim 10^6 \text{ K} \) by the gravitational accretion into progressively more massive halos, with higher velocity dispersions, or by collisional ionization from supernovae winds. The easiest way for finding collisionally ionized, cosmologically distributed material at \( T \gtrsim 10^6 \text{ K} \) is to search for O \( \text{vi} \) absorption. O \( \text{vi} \) is most prevalent at these temperatures, while O \( \text{vi} \) lines are stronger than those of C \( \text{iv} \) for \( T \gtrsim 10^6 \text{ K} \). The recent results of the first survey for O \( \text{vi} \) 1032, 1038\AA absorption lines in QSO spectra (Burles & Tytler 1996) suggest the presence of a substantial cosmological mass density of hot, collisionally ionized gas at \( z = 0.9 \). If the bulk heating were mainly due to supernovae explosions in spheroidal systems, as suggested by recent numerical simulations (e.g., Miralda-Escudé et al. 1996), the strong evolution of \( \Omega_{\text{IGM}} \) observed between \( z = 2 \) and \( z = 4 \) could be triggered by the star-formation activity in galaxies at high redshift. Note that, while an e-folding timescale of only 1 Gyr is much shorter than the decay time of star formation, \( 4 - 7 \text{ Gyr} \), characteristic of late type spirals, it is comparable with the decay time of star formation characteristic of “average” quiescent elliptical galaxies (e.g., Bruzual & Charlot 1993). Various authors have argued in favour of a significant contribution to the UVB by star-forming galaxies (Bechtold et al. 1987; Miralda-Escudé & Ostriker 1990; Madau 1991; Madau & Shull 1996). Order-of-magnitude arguments suggest that the overall kinetic energy released in supernova explosions can be about one-third of the radiative UV power (Miralda-Escudé & Ostriker 1990).

In this case a highly photoionized IGM at \( T \approx 10^4 \text{ K} \) may be quickly heated to temperatures 10 times larger (Giroux & Shapiro 1996). If this scenario will be confirmed by new observational constraints on \( R \) and \( J_\beta \) and by detailed theoretical models, then the evolution of the Lyman-\( \alpha \) forest clouds may be used as a probe of the cosmic star formation rate as a function of time.

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