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 $J_L \approx 1.3 \times 10^{-21} \, (f_{esc}) \, \text{erg cm}^{-2} \, \text{s}^{-1} \, \text{Hz}^{-1} \, \text{sr}^{-1}$ at $z \approx 0.5$, where $(f_{esc})$ is the unknown fraction of stellar Lyman continuum photons that can escape into 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 $\leq 20$ per cent. The background ionizing flux from galaxies can exceed the QSO contribution at $z \approx 0.5$ if $(f_{esc}) > 6$ per cent. 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 OⅢ 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 haloes.

Key words: galaxies: evolution -- intergalactic medium -- quasars: absorption lines -- diffuse radiation -- ultraviolet: general.

1 INTRODUCTION

The integrated ultraviolet flux arising from quasars and hot, massive stars in star-forming galaxies is probably 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 signatures 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 H1 distribution at the edges 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 $\approx 10^{-23} \, \text{erg cm}^{-2} \, \text{s}^{-1} \, \text{Hz}^{-1} \, \text{sr}^{-1}$ at the present epoch to $\approx 5 \times 10^{-22} \, \text{erg cm}^{-2} \, \text{s}^{-1} \, \text{Hz}^{-1} \, \text{sr}^{-1}$ at $z = 2.5$.

The background intensity stays nearly constant in the redshift interval $z = 1.3–3.5$, 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 $z \approx 3$ 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 $\approx 25$ per cent 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 OⅢ 1032-, 1038-Å 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 \( z = 0.9 \).

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 \( T = 20,000 \) K material photoionized by the UVB decreases strongly with cosmic time, and suggest that the recent detection of \( \text{O} \, \text{vi} \) intergalactic absorption lines may provide some clues on the fate of the 'missing' baryons. Throughout this paper, we shall adopt a flat cosmology with \( \Omega_0 = 0.3, \Omega_\Lambda = 0.7, \Omega_{\text{cold dark matter}} = 0.25 \) and \( \sigma_8 = 0.5 \).

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 disentangle the evolution of the luminosity function (LF) from redshift \( z = 0.02 \) to redshift \( z = 1.3 \) of the blue and red galaxy populations separately (Lilly et al. 1995). At variance with that of red objects, the LF of blue galaxies (bluer than present day Sbc galaxies) 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 \( z = 0.3 \) and 0.6 the LF brightens by about 1 mag. 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 colour of the blue population, in the redshift interval considered, is \((U - V) = 0.8\). To estimate the mean number of Lyc photons produced by OB stars, we have modelled the intrinsic UV spectral energy distribution of star-forming galaxies using the Bruzual & Charlot (1993) stellar population synthesis code. We assume a Sàpeter initial mass function with lower and upper cut-offs 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 \( U - V \) colour after convolving with the standard Johnson broad-band filters. Differences greater than 1 Gyr in the age produce changes greater than 0.1 mag in the average colours.

The comoving emissivity at \( h \nu = 1 \) Ryd (1 Ryd = 13.6 eV) of our galaxy sample can then be written as

\[
\epsilon(\nu, z) = \epsilon(\nu) \int_{z_0}^{z} \phi(L, z) \mathrm{d}L, \tag{1}
\]

where \( \epsilon(\nu) \) is the fraction of Lyc photons emitted from stars that can escape into intergalactic space, assumed to be independent of frequency (picket fence type absorption), in analogy with the leakage of ionizing photons from the galactic disc. \( E_\nu \) 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 \( h \nu_{\text{min}} \) corresponding to \( M_B = -17.8 \). The ensuing galaxy emissivity at the Lyman edge is plotted in Fig. 1 as a function of redshift: a strong cosmological evolution is apparent from \( z = 0 \) to \( z = 1 \).

Our procedure yields \( \epsilon(912 \, \text{Å}, 0) \approx 2 \times 10^{25} \langle f_{\text{esc}} \rangle \) erg s\(^{-1}\) Hz\(^{-1}\) Mpc\(^{-3}\). To check for systematic errors, we have re-computed the present-day ionizing emissivity starting from the H\(_\alpha\) luminosity density of the local Universe, \( 1.3 \times 10^{39} \) erg s\(^{-1}\) Mpc\(^{-3}\).
An indirect argument, put forward by Patel & Wilson (1995a,b), suggests a LyC escape fraction from the galactic disc into the halo of greater than 50 per cent. 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 disc. In the presence of ionization balance, the two values should be consistent. In contrast, 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 disc could be relatively high, LyC absorption by cold gas in galaxy haloes 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 3σ upper limit of $J_L < 8 \times 10^{-22} \, \text{erg cm}^{-2} \, \text{s}^{-1} \, \text{Hz}^{-1} \, \text{sr}^{-1}$ 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 per cent 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 Fig. 1. Adding together the galaxy contribution with that estimated from quasars and local active galactic nuclei (AGNs) (Haardt & Madau 1996), we find that a value of $(f_{\text{esc}}) = 15$ per cent, predicted by theoretical models (Dove & Shull 1994), yields a total UVB which is still consistent with the local upper limits. It is interesting to note that, since the opacity of the IGM at $z < 1.5$ is low, galaxies at intermediate redshifts can provide a non-negligible contribution to the local metagalactic flux. The current limits on the UVB from Hα brightness studies in fact provide the most stringent constraints on the total ionizing emissivity at $z \approx 0.5-1$, where the bulk of the blue galaxy evolution is observed.

As shown in Fig. 1, an escape fraction of $(f_{\text{esc}}) = 15$ per cent implies a total UVB of $J_L \approx 10^{-22} \, \text{erg cm}^{-2} \, \text{s}^{-1} \, \text{Hz}^{-1} \, \text{sr}^{-1}$ at $z = 0.15$. If the contribution of the blue galaxies to the metagalactic flux extends to $z \approx 1.5$, 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, $J_L = 2-4 \times 10^{-22} \, \text{erg cm}^{-2} \, \text{s}^{-1} \, \text{Hz}^{-1} \, \text{sr}^{-1}$, from $z = 0.4$ to 4, i.e. for a fraction of 50 per cent of the age of the Universe. Alternatively, QSOs will dominate the metagalactic flux if $(f_{\text{esc}}) \approx 6$ per cent. 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 $2 \times 10^{-22}$ erg cm$^{-2}$ s$^{-1}$ Hz$^{-1}$ sr$^{-1}$ at $z = 2$. The redshift range $2 < z < 5$ 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 $J_L = 6 \pm 1 \times 10^{-22} \, \text{erg cm}^{-2} \, \text{s}^{-1} \, \text{Hz}^{-1} \, \text{sr}^{-1}$.

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 $J_L = 5 \pm 1 \times 10^{-22} \, \text{erg cm}^{-2} \, \text{s}^{-1} \, \text{Hz}^{-1} \, \text{sr}^{-1}$, 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 1.5, to drop by a factor of $\approx 30$ 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 of $\approx 6$ 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 $10^{12}$ to $10^{15}$ cm$^{-2}$ and more, showing a bending below $N_{\text{HI}} \approx 10^{14}$ cm$^{-2}$ where the slope of the power-law distribution flattens from 1.8 to 1.4 at $(z) = 3$ (Giallongo et al. 1996). The density of lines with $N_{\text{HI}} \approx 10^{14}$ cm$^{-2}$, as derived from Hubble Space Telescope (Bahcall et al. 1996) and optical data (Giallongo et al. 1996), stays approximately constant $(dN/dz \approx 25$ from $z \approx 0.15$ to 1.8, to increase rapidly for $z > 2$, $dN/dz \approx 220$ at $z = 3.8$.

The baryon density of photoionized gas can be expressed in units of the critical density $n_{\text{crit}}$ as $\Omega_{\text{IGM}} = n_B n_{\text{HI}}/n_{\text{crit}}$, where $n_B$ is the volume filling factor and $n_{\text{HI}}$ 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), $n_{\text{HI}} = R^{-1/2} N_{\text{HI}}^{-1/2} \rho_{\text{HI}}^{1/2} (\alpha \cos \theta)^{1/2}$. The temperature dependence is very weak for highly photoionized clouds: a value of $T = 2 \times 10^5$ K has been adopted here. The aspect ratio $a = R/l$ generalizes the absorber geometry from spheres to discs of transverse radius $R$ to half-thickness $l$. $\theta$ is the angle between the symmetry axis of the cloud and the line of sight. For $(\alpha \cos \theta) = 1$ the usual limit of spherical clouds is obtained.

Hence the cosmological mass density produced by the Lyman α clouds is equal to

$$\Omega_{\text{IGM}} = 1.3 \times 10^{-11} \left(\frac{\alpha + 3}{4.5}\right)^{-1/2} \left(\frac{J_{L,22} R_{100}}{\alpha \cos \theta}\right)^{1/2} T_{0.363}^{-1/3},$$

where $J_{L,22} = \int J_{L,22} \, dN_{\text{HI}}$. We include the contribution from Lyman α 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 $\beta_1 = 1.8$, and the contribution to $\Omega_{\text{IGM}}$ becomes progressively smaller. For $N_{\text{HI}} < 10^{14}$ cm$^{-2}$, $\beta_1 = 1.4$ and the contribution to the mass density parameter increases slowly with decreasing $N_{\text{HI}}$. We have adopted a lower $N_{\text{HI}}$, cut-off 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 $z \approx 1.8$ (Bechtold et al. 1994; Dinshaw et al. 1994) have shown that the Lyman $\alpha$ sizes are of the order of $R \approx 2 \times 10^6 h_0^{-1}$ kpc, much larger than previously thought. Observations at lower redshifts, $z \approx 0.5$, show even larger sizes, $R \approx 3 \times 10^6 h_0^{-1}$ 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 cold dark matter (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 $R = 2 \times 10^6 h_0^{-1}$ 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 Fig. 2 from $z = 0$ to $z = 4$ as a function of cosmic time. The redshift dependence of the baryon density of photoionized gas is associated with the product $(J/\tau)^{1/2} d\Omega/dz$ 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 Fig. 2(a) $\Omega_{\text{igm}}(z)$ has been computed for a QSO-dominated UVB. In Fig. 2(b) both galaxies and QSOs contribute to the metagalactic flux. In the redshift interval $1.7 < z < 4.1$, the UVB assumes the constant value $J_{912} \sim 5 \times 10^{-22}$ erg cm$^{-2}$ s$^{-1}$ Hz$^{-1}$ ster$^{-1}$, 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, $\Omega_b h_0^2 = 0.05 \pm 1$ (Walker et al. 1991). Note that a large aspect ratio, $a \geq 10$, 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 per cent at $z \approx 1.8$ (i.e. $t \approx 3$ 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 $\Omega_{\text{igm}} = 0.007$ 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, $\Omega_c = 0.004e^{0.13}$ (e.g. Peebles 1993).

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 that can escape from individual galaxies into the IGM is not negligible. We have shown in Section 2 that $(J/\tau)$ is constrained to be $< 20$ per cent, in order to satisfy the upper limit on the intensity of the local UVB. If we adopt $(J/\tau) \sim 15$ per cent 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 4.

We have also shown that the baryon fraction which is associated with the photoionized Lyman $\alpha$ 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 Section 3, the mass density parameter depends only weakly on the intensity, $I_{\alpha}$, of the UVB, with $\Omega_{\text{igm}} \propto J^{1/2}$. 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, $\Omega_{\text{igm}} \propto \langle R/\alpha \rangle^{1/2} = \langle J/\tau \rangle^{1/2}$. Moreover, in CDM scenarios, lines with $N_{\text{HI}} < 10^{15}$ cm$^{-2}$ have typical sizes which appear essentially uncorrelated with the HI 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 $2l \approx 100 - 300$ 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 in the cases of both spherical and disc-like geometry.

We can parametrize 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 Fig. 2, this yields two characteristic e-folding time-scales, $\tau \approx 1$ Gyr for $t < 3$ Gyr and $\tau \approx 8$ Gyr at later epochs. Thus roughly 60 per cent of the photoionized gas in the Universe ‘disappears’ at early epochs over a time-scale 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 Lyman $\alpha$ line population must mainly reflect either a dilution of the photoionized gas clouds in a general diffuse intergalactic medium or an
in the neutral column density of clouds were present following the
Thus the strong evolution derived in the redshift interval
4 cannot
be
mainly due to a decrease (with decreasing redshift) of
the lower cut-off of the N\textsubscript{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 \approx 10^5 K by the gravitational
accretion into progressively more massive haloes, with higher
velocity dispersions, or by collisional ionization from supernova
winds. The easiest way to find collisionally ionized, cosmologically
distributed material at T \approx 10^5 K is to search for O\textsubscript{VI} absorption.
O\textsubscript{VI} is most prevalent at these temperatures, while O\textsubscript{VII} lines are
stronger than those of C\textsubscript{IV} for T \approx 10^6 K. The recent results of the
first survey for O\textsubscript{VI} at 1032-, 1038-Å 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 supernova
explosions in spheroidal systems, as suggested by recent numerical
simulations (e.g. Miralda-Escudé et al. 1996), the strong evolution of
Q_{\text{QSO}} observed between z = 2 and 4 could be triggered by the star
formation activity in galaxies at high redshift. Note that, while an
e-folding time-scale of only 1 Gyr is much shorter than the decay
time of star formation, \approx 4-7 Gyr, characteristic of late-type spirals,
it is comparable to 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 10^5 K may be
quickly heated to temperatures 10 times larger (Gioux & Shapiro
1996). If this scenario is confirmed by new observational
constraints on R and J\textsubscript{s} 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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