The Lyman continuum radiation escaping from galaxies

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Abstract. The Hα luminosity density of galaxies is used to calculate the local diffuse radiation field at the Lyman limit as resulting from star formation in the universe. The fraction of Lyman continuum radiation leaking out from galaxies through their neutral hydrogen is the most uncertain parameter of the calculation. A comparison of the diffuse radiation predicted from galaxies with that measured from all sources of ionization shows that the average Lyman continuum escape fraction should be lower than 1%. This number is lower than the upper limits reported so far in a few objects. It is also shown that the luminosity density at the Lyman limit resulting from star formation is consistent with the luminosity density and the diffuse background measured in the far (non-ionizing) ultraviolet.

Key words: galaxies: evolution – intergalactic medium – quasars: absorption lines – galaxies: stellar content

1. Introduction

It is thought that massive star formation in the universe may provide a significant fraction of the background radiation that maintains the diffuse intergalactic medium and the Lyman α forest clouds highly ionized (e.g. Bechtold et al. 1987, Songaila et al. 1990, Miralda-Escudé & Ostriker 1990). This contribution would augment that of quasars, especially at high redshift where their number density is observed to decline. The contribution of quasars itself depends on how our picture of their evolution is distorted by dust obscuration (Fall & Pei 1993).

Direct observations of the Lyman continuum (Ly$_c$) radiation escaping from galaxies is however extremely difficult and, so far, only upper limits have been obtained with the Hopkins Ultraviolet Telescope (HUT) in four nearby star-forming galaxies (Leitherer et al. 1995). Attempts to understand how Ly$_c$ radiation leaks out from sites of star formation, ionizes the diffuse interstellar medium around and eventually escapes from a galaxy (e.g. Dove & Shull 1994, Patel & Wilson 1995a,b, Ferguson et al. 1996) have shown that the phenomenon is dominated by patchiness in the distribution of the neutral gas and should be

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highly random. Any quantitative assessment of the contribution of galaxies to the ionizing background would therefore require a large number of observations before a Ly$_c$ luminosity function is established. This uncertainty on the Ly$_c$ escape fraction is also a severe limitation for model predictions even though some of them are reasonably successful in linking the Ly$_c$ radiation produced by star formation to the rate of chemical enrichment in the universe (Cowie 1988, Songaila et al. 1990, Madau & Shull 1996).

In this paper we use the recent determination of the Hα luminosity density of nearby galaxies by Gallego et al. (1995) to estimate the contribution of galaxies to the diffuse radiation background at the Lyman limit and at $z = 0$. As a support to our approach, the Hα luminosity density will be compared with other tracers of the local star formation activity such as the luminosity density and the diffuse background in the far non-ionizing ultraviolet. From the comparison between the diffuse radiation at the Lyman limit predicted from galaxies and that measured from all sources of ionization, we will derive an upper limit to the effective Ly$_c$ escape fraction in the local universe.

2. Basic formulation

Following current formulation (e.g. Bechtold et al. 1987, Meiksin & Madau 1993) the mean specific intensity J_{ν_0} of the diffuse radiation field at frequency ν_0, as seen by an observer at redshift 0 (outside our Galaxy), writes as

$$J_{\nu_0} = \frac{c}{4\pi H_0} \times$$
$$\int_0^\infty \frac{1}{(1+z)^3} \epsilon(\nu, z) \frac{\exp\left[-\tau_{eff}(\nu_0, z)\right]}{(1+z)^2(1+2q_0z)^{1/2}} \, \mathrm{d}z \qquad (1)$$

where $\epsilon(\nu, z)$ is the proper volume emissivity (expressed in erg cm^{-3} s^{-1} Hz^{-1}) at frequency $\nu = \nu_0(1+z)$ and redshift z, and $exp[-\tau_{eff}(\nu_0, z)]$ is the mean transmission of a clumpy medium averaged over all lines of sight. In our application the volume emissivity is the ultraviolet emission resulting from the star formation activity in galaxies. Taking an average over all morphological types and all star formation histories, the luminosity density can be considered continuous with a unique mean spectral shape. In these conditions and following the notations

of Bechtold et al. (1987), $\epsilon(\nu, z)$ can be split into $\epsilon(\nu_0)$ the current local luminosity density of galaxies at frequency ν_0 and $k(\nu/\nu_0)$ the spectral shape normalized to 1 at the frequency ν_0 with a factor $\psi(z)$ accounting for any proper evolution in the luminosity density (the density variation due to expansion is taken into account by a factor $(1+z)^3$). Adopting $q_0 = 0.5$, we get

$$
J_{\nu_0} = \frac{c}{4\pi H_0}\epsilon(\nu_0) \times
$$
$$
\int_0^\infty \psi(z)\, k(\frac{\nu}{\nu_0})\,\frac{1}{(1+z)^{5/2}}\,\exp\left[-\tau_{eff}(\nu_0, z)\right]\mathrm{d}z \qquad (2)
$$

The effective optical depth $\tau_{eff}(\nu_0, z)$ due to Lyman continuum absorption of HI and HeII by discrete absorption systems is given by (e.g. Paresce et al. 1980, Møller & Jakobsen 1990, Miralda-Escudé & Ostriker 1990)

$$
\tau_{eff}(\nu_0, z) = \int_0^z \mathrm{d}z' \int_0^\infty f(N, z')\,(1 - \exp(-\tau))\,\mathrm{d}N \qquad (3)
$$

where $f(N, z')$ is the redshift and column density distribution of absorbers along the line of sight and τ the optical depth through an individual cloud of column density N.

3. Stellar contribution to the radiation field at the hydrogen Lyman edge

We now use equation (2) to calculate the radiation background at the Lyman limit J_{912}. The luminosity density is assumed to have a proper evolution parameterized as $\psi(z) = (1+z)^\gamma$. Given the severe uncertainties about the spectral energy distribution of Ly_c photons from star formation, the normalized spectral shape is modelled as $k(\nu/\nu_0) = (\nu/\nu_0)^\alpha = (1+z)^\alpha$ while we add a factor for the absorption of stellar Ly_c photons by the neutral hydrogen of each galaxy. In order to account for the ν^{-3} frequency dependence of the absorption of Ly_c photons by neutral hydrogen, we have written the absorption factor as $exp[-6.3\times10^{-18}N_H(1+z)^{-3}]$. The equivalent HI column density term (N_H) is introduced for calculation purpose (we make no assumption as to the geometry and distribution of the gas) and the resulting effective Ly_c escape fraction will be defined as $f = exp[-6.3\times10^{-18}N_H]$. In these conditions the background radiation J_{912} (in erg cm^{-2} s^{-1} Hz^{-1} sr^{-1}) at the Lyman limit writes as

$$
J_{912} = \frac{c}{4\pi H_0}\epsilon(912)\int_0^\infty (1+z)^{\gamma+\alpha-5/2} \times
$$
$$
e^{-6.3\times10^{-18}N_H(1+z)^{-3}}\,e^{-\tau_{\text{eff}}(912, z)}\,\mathrm{d}z \qquad (4)
$$

3.1. Adopted parameters

By comparison with existing models for the Ly_c spectral energy distribution of star-forming population (e.g. Bruzual & Charlot 1993), a value of α in the range -1 to -3 is a realistic approximation. An upper bound to $z = 2$ is also realistic since it cuts any stellar flux contribution below 304 Å. The local luminosity

density of galaxies $\epsilon(912)$ at the Lyman edge can be derived from the total Hα luminosity per unit volume of 1.26×10^{39} ergs s^{-1} Mpc^{-3} evaluated for star-forming galaxies in the local universe by Gallego et al. (1995). Under the current conditions valid in the ionized gas of galaxies (T=10^4K and case B) we get a local density of Ly_c photons of 9.2×10^{50} s^{-1} Mpc^{-3} (Osterbrock 1989). This number can be considered as a lower limit since Ly_c photons in optically thin gas produce fewer Hα photons than those in optically thick gas. The relation between the Ly_c photons density and the luminosity density at 912 Å depends on the value of α. For our average case $\alpha = -2$, we find a luminosity density at 912 Å of 4.8×10^{37} erg s^{-1} Å^{-1} Mpc^{-3} or 1.3×10^{25} erg s^{-1} Hz^{-1} Mpc^{-3}. Incidentally, the relation $\log N_\lambda/L_\lambda = 13.28 \pm 0.16$ (photons Å erg^{-1}) established by Leitherer et al. (1995) would give the same value. This relation was established for starbursts with different star formation histories and initial mass functions while the simplifying assumption of a continuous star formation rate is probably valid at the scale of the local universe.

Significant evolution of galaxies is now well established (e.g. Ellis et al. 1996, Lilly et al. 1996, Fall et al. 1996) and we adopt $\gamma = 4$ from $z = 0$ to $z = 1$ as found by Lilly et al. (1996) for the evolution of the luminosity density of the universe at 2800 Åinsofar as the light at this latter UV wavelength is essentially tracing on-going star formation, we think that the same exponent should be valid at our shorter wavelengths. Beyond $z = 1$ the evolution is known to slow down but the situation is less certain. We have adopted $\gamma = 0$, bearing in mind that this choice is not critical since the contribution to the background at $z = 0$ from objects at high redshifts is small as soon as the evolution is not strong. Last, the calculation is independent of the value of H_0 since luminosity densities scale as H_0.

3.2. The intergalactic opacity term

At the Lyman edge and ignoring absorption due to HeII for a line of sight limited to $z = 2$ (HeI absorption is negligible), the effective optical depth $\tau_{eff}(912, z)$ in equation (4) writes as

$$
\tau_{eff}(912, z) = \int_0^z \mathrm{d}z' \int_0^\infty f(N, z') \times
$$
$$
\left(1 - \exp\left[-6.3 \times 10^{-18}(1+z')^{-3}N\right]\right)\mathrm{d}N
$$

Assuming a power-law of exponent -1.5 for the column density distribution (Petitjean et al. 1993, Songaila et al. 1995), and adopting the line densities per unit redshift and the evolution parameters from Boksenberg (1995), $f(N, z')$ writes as $1.07 \times 10^8 N^{-1.5}(1+z')^{0.58}$ for the Lyman α forest clouds, and $5 \times 10^7 N^{-1.5}(1+z')^{1.5}$ for the Lyman limit systems ($N > 1.6 \times 10^{17}$ cm^{-2}). The calculation of the first normalization constant accounts for the detection limit of 0.24 Å rest equivalent width and a velocity width of 30 km s^{-1} as in Miralda-Escudé & Ostriker (1990). The parameters for the Lyman α forest clouds have been obtained for $0 < z < 1.3$ but the plot of their evolution up to $z = 3.7$ (Boksenberg 1995) shows that our parameterization remains appropriate till the adopted

limit at $z = 2$. As a numerical example, we find a transmission from $z = 0$ to $z = 2$ $exp(-\tau_{eff}(912, 2)) = 0.384$. Playing with the error bars given on the line densities per unit redshift and the evolution parameters (Boksenberg 1995) we find that this transmission does not change by more than 40%.

3.3. Results

The background radiation calculated by equation (4) with the average transmission models discussed above is displayed in Fig. 1 as a function of the Ly_c escape fraction. Although our evaluation is based on the measured Ly_c photons density in the local universe and avoids therefore most of the uncertainties inherent to pure model calculations, it still depends on a few parameters, the index α of the average spectral shape in the Lyman continuum, the evolution factor and the opacity of the intergalactic medium. The resulting uncertainties are illustrated in Fig 1. First, the impact of the ill-known index α (values $-1, -2, -3, -4$ are used in Fig 1), is found to be reduced by the relation between α and the luminosity density at the Lyman edge for a given Ly_c photon density. Second, the effect of a larger intergalactic opacity as obtained with the upper limits given by Boksenberg (1995) on the density of Lyman clouds and Lyman limit systems per unit redshift is modest and comparable with a change of one unit of the index α. In contrast, the calculation is sensitive to the amount of evolution as shown with the case of a milder evolution $\gamma = 2$ (till $z = 2$) plotted in Fig 1. Selected as the variable against which the diffuse radiation has been plotted in Fig 1, the Ly_c escape fraction is, as anticipated, the major source of uncertainty. We note, however, that the diffuse radiation does not decrease as fast as the Ly_c escape fraction. The main reason is that galaxies at high redshift contribute to the diffuse radiation and may still be optically thin at $912/(1+z)$ Å while their nearby counterparts are optically thick at 912 Å. The issue of the uncertainty on the luminosity density itself at the Lyman edge will be addressed in the two following sections.

4. Comparison with the ionizing background: constraints on the Ly_c escape fraction

We have compared the predictions of Fig. 1 with the measurements of the ionizing background (at $z \approx 0$) at the Lyman edge. These measurements are only indirect and include the contribution of all ionizing sources, chief among them the quasars. They are therefore upper limits, possibly very generous, to the contribution of galaxies. The measurements have been obtained so far through a variety of methods (Bechtold 1993, for a review), such as the Hα emission from 21-cm emitting clouds, the modeling of the sharp edges of H I clouds and, the proximity effect (Kulkarni & Fall 1993), following the observations of the Lyman α forest at low redshift with the HST. From the recent works of Dove & Shull (1994), Vogel et al. (1995) and Donahue et al. (1995) and review of previous determinations therein, we conclude that the ionizing background at 900 Å should lie in the range $0.06 - 1 \times 10^{-22}$ erg cm^{-2} s^{-1} Hz^{-1} sr^{-1}. At its lower bound the ionizing background is comparable to the evalua-

tions currently made for the contribution of quasars (e.g. Madau 1992), indicating a possible negligible role of the galaxies.

Fig 1 shows that, under most of the conditions, the Ly_c escape fraction is smaller than 1%. This is smaller than the upper limits in the four star-forming galaxies observed by Leitherer et al. (1995), especially after the modifications advocated by Hurwitz et al. (1997) on the basis of unaccounted absorption by H I gas in our Galaxy. Our upper limit would be less restrictive than 1% if the spectral index α is lower than -4, or the evolution milder ($\gamma < 4$) than found by Lilly et al. (1996). Insofar as our comparison was made with the intergalactic radiation field of all origin, our upper limit is probably generous but, even if small, does not exclude that galaxies make most of the ionizing intergalactic radiation field.

Our conclusion also depends crucially on the value of the total Hα luminosity density of the local universe in the sense that the larger the Hα luminosity density (or the associated number of Ly_c photons), the stronger is the upper limit for the Ly_c escape fraction. Our limit of 1% seems firm for two reasons. First, the Hα luminosity function built by Gallego et al. (1995) is based on star-forming galaxies with Hα+N[II] equivalent widths larger than 10 Å and therefore should more likely lead to an underestimation of the total Hα luminosity density. Second, our conversion of the Hα luminosity density into a Ly_c photon density under case B assumptions provides, as previously said, a lower limit on the latter quantity.

5. Consistency with the non-ionizing far UV radiation

As the Hα luminosity density of the local universe is a key input in our calculation, we have tried to evaluate how this quantity and the associated number of Ly_c photons compare with other measured quantities tracing the star formation activity in the universe such as the far-UV luminosity density as determined from surveys of galaxies or the far-UV (non ionizing) background as measured by in-orbit experiments.

The former quantity is related to the luminosity density emitted at 900 Å by star formation activity through two parameters, the Lyman break of a pure star-forming population and the extinction at far-UV wavelengths due to dust mixed with the young stars in each galaxy. The far-UV spectral energy distribution (from longward of the Lyman break to ≈ 2000 Å) of a pure (without dust) and continuous star-forming population can be assumed to be flat in energy per frequency unit as shown by the models of Bruzual & Charlot (1993) and the observations of star-forming galaxies with little extinction by Calzetti et al. (1994). In the case of a continuous rate as we expect for the average star formation in the local universe, the Lyman break factor should be of the order of 4 according to Bruzual & Charlot (1993) and possibly between 6 and 20 depending on the initial mass function for massive stars according to Leitherer & Heckman (1995). With an average far-UV extinction of the order of 1 mag as discussed by Deharveng et al. (1994), we get a far-UV (observed) to 900 Å (emitted) luminosity density ratio between 1.6 and 8. For comparison, the 1600 Å (observed) to 900 Å (emitted) flux ratios in the four galaxies observed by
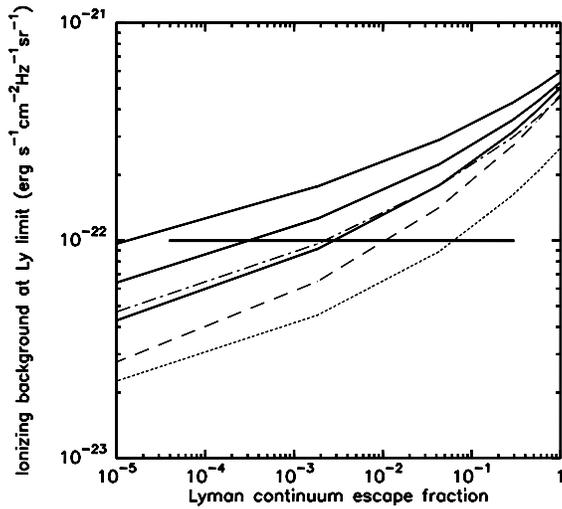
Fig. 1. Background radiation due to star formation in galaxies predicted at the Lyman limit and $z = 0$ as a function of the Ly_c escape fraction. Solid lines: spectral index (ν^α, see text) $\alpha = -1, -2, -3$ respectively from top to bottom. Long-dashed line: $\alpha = -4$. Dot-dashed line: $\alpha = -2$ and intergalactic opacity higher than nominal with a density per unit redshift $(dN/dz)_0 = 30.9$ instead of 24.3 for the Ly forest clouds and a density per unit redshift $(dN/dz)_0 = 0.42$ instead of 0.25 for the Lyman limit systems. Short-dashed line: $\alpha = -2$ and $(1 + z)^2$ evolution from $z = 0$ to $z = 2$ instead of $(1 + z)^4$ from $z = 0$ to $z = 1$ and no evolution from $z = 1$ to $z = 2$ in all other cases. The horizontal thick line is the upper limit to current measurements of the diffuse background radiation at the Lyman limit and $z = 0$.

Leitherer et al. (1995) are found to be 0.3, 1.5, 1.6 and 6. With the ratio above and our local luminosity density $\epsilon(912)$ at the Lyman edge of 1.3×10^{25} erg s^{-1} Hz^{-1} Mpc^{-3} we get a far-UV luminosity density of $2 - 10 \times 10^{25}$ erg s^{-1} Hz^{-1} Mpc^{-3}. This is in agreement with the local luminosity density of 3×10^{18} W Hz^{-1} Mpc^{-3} (H_0=50 km s^{-1} Mpc^{-1}) evaluated at 2800 Å by Lilly et al. (1996) and of 6×10^{18} W Hz^{-1} Mpc^{-3} (H_0=50 km s^{-1} Mpc^{-1}) evaluated at 2000 Å by Milliard et al. (1997).

Although the far-ultraviolet background is rich of several possible components, some of them of galactic origin, various arguments have established the accumulation of galaxy light along the line of sight as the dominant extragalactic contributor (e.g. Bowyer 1991, Jakobsen 1995, for a review) with an intensity in the range $50 - 150$ photon cm^{-2} s^{-1} Å^{-1} sr^{-1}(or $0.7 - 2 \times 10^{-21}$ erg cm^{-2} s^{-1} Hz^{-1} sr^{-1} at say 2000 Å). This background radiation can be converted back into a local luminosity density $\epsilon(2000)$ according to equation (2) which, with the same assumptions as above but without the neutral gas absorption term and the intergalactic opacity term, writes as

$$J_{2000} = \frac{c}{4\pi H_0} \epsilon(2000) \int_0^{1.2} (1 + z)^{\gamma + \alpha - 5/2} \, dz \qquad (5)$$

The integral upper bound is now 1.2, the value which shifts the Lyman break at 2000 Å. Assuming $\gamma = 4$ and α in the range -1

to -3 (the case $\alpha = 0$ is observed for galaxies with little extinction and is not appropriate for the average spectral shape) the upper limit background of 2×10^{-21} erg cm^{-2} s^{-1} Hz^{-1} sr^{-1} gives a far-UV luminosity density in the range $2.6 - 6 \times 10^{18}$ W Hz^{-1} Mpc^{-3}, again in satisfying agreement with the range of values that we have derived above.

6. Conclusion

We have used the Hα luminosity density of galaxies in the local universe for estimating the contribution of galaxies to the ionizing background at $z = 0$. This approach reduces the number of theoretical assumptions entering this type of evaluation and is therefore expected to narrow the range of predicted values. Of the remaining parameters needed for the evaluation, the fraction of Ly_c radiation leaking out from galaxies is the most uncertain. From a comparison between the ionizing photons predicted by on-going star formation in galaxies and those measured in the intergalactic radiation field, it is found that the Ly_c escape fraction is smaller than 1% in the local universe. This average upper limit is more restrictive than the upper limits reported in four galaxies by Leitherer et al. (1995) and re-analyzed by Hurwitz et al. (1997).

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