The ultraviolet extragalactic background light: dust extinction and the evolution of the cosmic star formation rate from $z = 0$ to $\sim 0.6$

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ABSTRACT
We show that the accumulated light of galaxies in the ultraviolet can be evaluated from their luminosity density as a function of the evolution of the cosmic star formation rate and dust extinction properties. Constraints on the evolution rate are expected in future. Data available at the moment are consistent with an evolution rate at low $z$ steeper than $(1+z)^{3.5}$. A shallower rate remains possible if the luminosity-weighted dust extinction at 2000 Å, as suggested by some data, is lower than $\sim 1.2$.

Key words: galaxies: evolution – ultraviolet: galaxies – diffuse radiation – dust, extinction.

1 INTRODUCTION
The present-day luminosity density of galaxies and evolution effects are folded into the cumulative emission from galaxies. Disentangling these quantities is known to be difficult because of the need to account for the spectral energy distributions of the galaxies at wavelengths shorter than the window of observation. The cumulative emission from galaxies may be obtained directly from galaxy number counts or isolated within global measurements of the diffuse background radiation (e.g. Bernstein, Freedman & Madore 2002).

In the far-UV wavelength range, the situation is somewhat more simple. The spectral energy distributions are in first approximation dominated by star formation activity, avoiding the need to keep track of too many categories of galaxies and opening the possibility of constraints on the history of stellar birth in galaxies. The Lyman break enters the window of observation at relatively low redshift, reducing the amount of look-back time involved. The accumulated light of galaxies is the dominant source of extragalactic background light which is itself a significant contributor to the total background radiation (e.g. Martin, Hurwitz & Bowyer 1991; Armand, Milliard & Deharveng 1994).

Three factors have recently made a specific examination worth to attempt. First, the luminosity density of galaxies is now available at far-UV wavelengths (Treyer et al. 1998; Sullivan et al. 2000). Second, the galaxy counts in the UV (Gardner, Brown & Ferguson 2000) are now deep enough to provide a reliable evaluation of the background radiation due to galaxies, without the difficulties of subtracting uncertain components from the observations of the total diffuse background radiation. Third, the measurements of the luminosity density of galaxies at Hα (Gallego et al. 1995), can be converted into a luminosity density of ionizing photons, then connected by stellar population models with the luminosity density above the Lyman break and used as a constraint on the average spectral energy distribution of galaxies in the far-UV.

In this paper, our motivation is to evaluate the far-UV integrated light of galaxies with a limited set of parameters and to explore whether useful constraints may be derived on the history of star formation. Despite an explosion in the quantity of faint galaxy data, there are yet significant disagreements in the determinations of the star formation rate (SFR) (e.g. Hopkins et al. 2001; Hogg 2002) that trace the cosmic star formation history. Even in relative terms and at low $z$, the rate of evolution is still a matter of debate, with a parameterization ranging from $(1+z)^{1.5}$ (Cowie, Songaila & Barger 1996; Wilson et al. 2002) to $(1+z)^4$ (e.g. Lilly et al. 1996; Madau et al. 1996; Madau, Pozzetti & Dickinson 1998) for measurements based on UV rest frame data, not to speak of more extreme values (e.g. Hogg 2002) when measurements at other wavelengths are included.

2 FORMULATION
The cosmological radiative transfer equation (Peebles 1993) for sources with proper specific volume emissivity $\epsilon(\nu, z)$ (in
ergs cm$^{-3}$ Hz$^{-1}$ s$^{-1}$) gives a mean specific intensity at observed frequency $\nu_0$ and for an observer at redshift 0 (e.g. Bechtold et al. 1987).

$$I_{\nu} = \frac{1}{4\pi} \int_{0}^{\infty} \frac{dI}{dz} \frac{1}{(1+z)^{3}} \epsilon(\nu, z) \, dz$$

where $\nu = \nu_0(1+z)$ and the opacity of the intergalactic medium is neglected for our application in the non-ionizing ultraviolet and at relatively low redshift. The relation between the proper length increment and the redshift increment is given by

$$\frac{dl}{dz} = \frac{c}{H_0}(1+z)^{-1} (\Omega_M (1+z)^3 + \Omega_\Lambda)^{-0.5}$$

where the cosmological parameters and $c$ have their usual meanings. In our case the volume emissivity is the ultraviolet emission resulting from the star formation activity in galaxies. Following the notations of Bechtold et al. (1987), we assume that it can be written as

$$\epsilon(\nu, z) = \epsilon(\nu_0)(1+z)^{\psi(z) - \beta}$$

where $\epsilon(\nu_0)$ is the current local luminosity density of galaxies at frequency $\nu_0$, $s(\nu/\nu_0)$ represents the spectral shape normalized to 1 at the frequency $\nu_0$ and $\psi(z)$ accounts for any proper evolution in the luminosity density. We take $\nu_0$ as corresponding to 1595 Å, the pivot wavelength of the far-UV galaxy counts of Gardner et al. (2000). The evolution $\psi(z)$ is currently parameterized as $(1+z)^{\beta}$. For the purpose of simplification and according to models of star-forming galaxies (continuous star formation), we assume that $s(\nu/\nu_0)$ can be parameterized as $(\nu/\nu_0)^{\alpha}$ between our window of observation and the Lyman break.

In these conditions the integrated light from galaxies at 1595 Å is given by

$$L_{\nu}(1595) = \frac{c}{4\pi H_0}(1595) \int_{0}^{\infty} \frac{(1+z)^{\alpha + \beta - 1}}{(\Omega_M (1+z)^3 + \Omega_\Lambda)^{0.5}} \, dz$$

In practice the upper bound in equation (4) will be approximately limited to the redshift at which the Lyman break reaches the pivot wavelength of the observations of the integrated light of galaxies (Gardner et al. 2001).

### 3 EVALUATION OF THE UV BACKGROUND RADIATION DUE TO GALAXIES

We first discuss the two quantities $\alpha$ and $\epsilon(1595)$ that, in addition to the evolution factor $\gamma$, enter the equation (4) for the calculation of the background radiation due to galaxies.

The normalized spectral shape $s(\nu/\nu_0)$ is written as $(\nu/\nu_0)^{\alpha} = (1+z)^{\alpha}$ under the assumption that the spectral energy distribution results from continuous star formation and dust extinction. This assumption is justified by the fact that the luminosity density is averaged over a large volume. According to models (Leitherer et al. 1999), the unreddened s.e.d. can be reasonably approximated in the range 1200 Å - 2000 Å by a power-law of slope $\alpha = -0.1$ with current values of IMF and metallicity. Such a slope ($-2.1$ for s.e.d. per unit wavelength) is observed in star-forming galaxies with low extinction (Calzetti et al. 1994). Models also show that this slope can be extrapolated shortward of 1200 Å but recent observations in the range 900 Å - 1200 Å (Leitherer et al. 1999) lead us to stop our extrapolation to $\sim 1000$ Å because of the many absorption features that depress the flux before the Lyman break is effectively reached. In these conditions, the effective slope $\alpha$ is defined by the slope between 2000 Å and 1000 Å. Accounting for the differential dust extinction, the effective slope can be written as

$$\alpha = -0.1 + \frac{0.4(A_{1000} - A_{2000})}{(\log(2000) - \log(1000))}$$

with $A_{1000}$ and $A_{2000}$ being the amount of extinction at 1000 Å and 2000 Å, respectively. It is finally found to depend on $A_{2000}$ and the ratio of the reddening law at 1000 Å and 2000 Å, $k(1000)/k(2000)$

$$\alpha = -0.1 + 1.328 A_{2000} k(1000)/k(2000) - 1$$

Following the prescriptions of Calzetti et al. (2000) and their extrapolation shortward of 1200 Å by Leitherer et al. (2001), we have $k(1000)/k(2000) = 13.88/8.87 = 1.565$

The value of $\epsilon(1595)$ is derived from the luminosity density of galaxies observed at 2000 Å by Sullivan et al. (2000), taken as $8.4 \times 10^{78}$ ergs s$^{-1}$ Å$^{-1}$ Mpc$^{-3}$ for $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$. It is then scaled from $z = 0.15$ to $z = 0$ using the factor $1/(1.15)^{0.5}$, and from 2000 Å to 1595 Å using the slope $\alpha$ determined as a function of $A_{2000}$.

The integrated light from galaxies, calculated from equation (4), is displayed in Fig. 1 as a function of $A_{2000}$ for three values of the evolution rate. It has been converted into units of photons cm$^{-2}$ s$^{-1}$ Å$^{-1}$ ster$^{-1}$ for comparison with the range of values 144 – 195 photons cm$^{-2}$ s$^{-1}$ Å$^{-1}$ ster$^{-1}$ reported by Gardner et al. (2000). An upper bound of $z = 0.6$ has been used in equation (4) but the integrated light of galaxies would be increased by any flux shortward of the Lyman break. The increase has been found to be less than $\sim 10\%$ (even in the case of the evolution rate of $(1+z)^{\beta}$ for an upper limit to the Lyman continuum escape fraction of $\sim 6\%$ in the nearby star-forming galaxies (e.g. Hurwitz et al. 1997; Heckman et al. 2001; Deharveng et al. 2002)).

### 4 LYMAN DISCONTINUITY

A possible constraint on the parameter $\alpha$ is the need for the luminosity density at 900 Å derived from the observed H$_0$ luminosity density to be compatible with that observed at 2000 Å. The Lyman discontinuity predicted by stellar population models is a key element in such a comparison. As it is current practice (Bruzual & Charlot 1993; Leitherer et al. 1999), the Lyman discontinuity is evaluated between 1000 Å and 900 Å in order to avoid the influence of the severe line-blanking by hydrogen towards the series limit at 912 Å. The luminosity density at 1000 Å is directly related to that observed at 2000 Å by Sullivan et al. (2000), through the intrinsic slope of $-2.1$ (per wavelength unit) and the extinction adopted $A_{2000}$. Under current conditions, the H$_0$ luminosity density observed and corrected for extinction by Gallego et al. (1995) (taken as $1.76 \times 10^{59}$ ergs s$^{-1}$ Mpc$^{-3}$ for $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$) implies a density of $1.3 \times 10^{51}$ s$^{-1}$ Mpc$^{-3}$ ionizing photons, and in turn a luminosity density of $0.67 \times 10^{59}$ ergs s$^{-1}$ Å$^{-1}$ Mpc$^{-3}$ at 900 Å (assuming
5 DISCUSSION AND DUST EXTINCTION

If the constraint from the Lyman discontinuity is ignored or assumed to be solved by the effects listed above, the predictions of the integrated light from galaxies are compatible with the observations for a large range, but relatively low values of the $A_{2000}$ extinction (Fig. 1). Most of these values are lower than the extinction of 1.3 reported by Sullivan et al. (2000) as affecting their luminosity density. Taken at face value, the extinction $A_{2000} = 1.3$ would imply an evolution rate $\gamma \geq 3.5$; a significant adjustment for the Lyman discontinuity and the lower bound of the UV integrated light would be required if $\gamma \sim 3.5 - 4$. Such a definite conclusion ($\gamma \geq 3.5$), however, is mitigated by a number of arguments.

(i) The $A_{2000} = 1.3$ extinction compares well with the average UV extinction estimated in starburst galaxies by a number of authors (e.g., Buat & Burgarella 1998; Meurer, Heckman & Calzetti 1996; Calzetti 2001; Bell & Kennicutt 2001). When it comes to UV selected samples of nearby galaxies, lower average extinction has been reported, especially when this extinction is evaluated from the dust emission of the galaxies. UV selected samples are expected to contain normal, quiescent star-forming galaxies in addition to starburst galaxies as should be the case for the UV luminosity density discussed here. The average UV extinctions reported range from 0.6 to $\sim 1$ (Buat et al. 1999).

(ii) The evaluation of the Lyman discontinuity would be reduced if the value adopted from Gallego et al. (1995) underestimates the H$\alpha$ luminosity density. Arguments have been given in that sense by Jones & Bland-Hawthorn (2001) and higher values have been reported (Gronwall 1999; Glazebrook et al. 2003); recently the value of Gallego et al. (1995) has been revised upward by a factor of 1.6 (Pérez-González et al. 2003). The evaluation of the Lyman discontinuity would be divided by the same factor and would be brought closer to the prediction.

(iii) The possibility of an increase of the value predicted by models has also been examined. The amplitude of the stellar Lyman discontinuity is rather independent of metallicity and only decreases at very low metallicity (Schaerer 2003). Recent models including non-LTE effects (Schaerer 1998; Smith, Norris & Crowther 2003) tend to produce smaller discontinuities. In contrast, a relative content in massive stars reduced with respect to the current IMF would increase the discontinuity (Leitherer et al. 1999). By far, a departure from the assumption of a continuous star formation would be the most radical way for increasing the stellar Lyman discontinuity; we have no possibility to exclude an aging burst contribution in the composite population that would make the stellar Lyman discontinuity larger and consistent with the evaluation.

### Table 1. Values of the Lyman discontinuity resulting from observations as a function of the adopted $A_{2000}$ extinction.

| $A_{2000}$ | $\gamma = 1.5$ | $\gamma = 2.5$ | $\gamma = 4$ |
|-----------|--------------|--------------|--------------|
| 0         | 4.3          | 3.8          | 3.1          |
| 0.2       | 5.2          | 4.5          | 3.7          |
| 0.4       | 6.3          | 5.5          | 4.4          |
| 0.6       | 7.6          | 6.6          | 5.3          |
| 0.8       | 9.1          | 7.9          | 6.4          |
| 1.0       | 11.0         | 9.5          | 7.7          |
| 1.2       | 13.0         | 11.0         | 9.3          |

Values of the Lyman discontinuity are dependent on the evolution rate because the UV luminosity density had to be scaled back to $z \sim 0$ (with the factor $1/(1.15)^\gamma$) for comparison with the H$\alpha$ luminosity density.
Such values would be compatible with evolution rate $\gamma < 3.5$.

(ii) The extinction of 1.3 found by Sullivan et al. (2000) for their luminosity density is surprisingly close to the average performed on the individual extinctions, whereas a lower value is expected from a luminosity-weighted average.

(iii) In addition to the $A_{2000}$ extinction itself and the issue of the universality of the starburst obscuration curve (Bell 2002), the ratio $k(1000)/k(2000)$ is a factor in the calculation of the integrated light from galaxies (cf equation 5). Given the uncertainties on the absorption curve, especially below 1200 Å, a value lower than the adopted 1.565 cannot be ruled out; this would raise the series of curves in Fig. 1 in the domain of large extinction and would make again the data compatible with a lower evolution rate.

6 CONCLUSION

We have tried to put together three quantities deduced from independent measurements, the accumulated far-UV light of galaxies (at $\sim 1595$ Å), the luminosity density of galaxies in the far-UV (at 2000 Å) and at H\alpha. As the star formation is likely to be continuous over large volume, we assume that the cosmic spectrum, i.e. the luminosity-scaled spectra summed over all galaxies, can be written in the far-UV as a simple cosmic spectrum, i.e. the luminosity-scaled spectra summed over all galaxies, and that the extinction are less extreme in the UV than those based on starburst galaxies. The latter possibility, with an average extinction $A_{2000} < 1.2$ and/or a reddening law shallower at short wavelengths than predicted by Leitherer et al. (2002), cannot be ruled out and is supported by recent trends found in normal galaxies.

The comparison between the luminosity density of galaxies in the far-UV (at 2000 Å) and at H\alpha is compatible with the stellar Lyman discontinuity predicted by evolutionary synthesis models if a fraction of the ionizing photons are trapped by dust before ionization and/or the H\alpha luminosity density of Gallego et al. (1993) is underestimated.

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