Star Formation at High Redshift: A Population of Early Dwarfs?

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Abstract
The history of the transition from a neutral intergalactic medium (IGM) to one that is almost fully ionized can reveal the character of cosmological ionizing sources and set important constraints on the stellar birthrate at high redshifts. The hydrogen component in a highly inhomogeneous universe is completely reionized when the number of photons emitted above 1 ryd in one recombination time equals the mean number of hydrogen atoms. If stellar sources are responsible for photoionizing the IGM at \( z = 5 \), the rate of star formation at this epoch must be comparable or greater than the one inferred from optical observations of galaxies at \( z \approx 3 \), and the mean metallicity per baryon in the universe \( \sim > 1/500 \) solar. In hierarchical clustering scenarios, high-z dwarfs (i.e. an early generation of stars in dark matter halos with circular velocities \( v_{\text{circ}} \approx 50 \text{ km s}^{-1} \)) are expected to be one of the main sources of UV photons and heavy elements at early epochs. They would be very numerous, \( > 0.2 \text{ arcsec}^{-2} \), and faint, \( I_{\text{AB}} > 29.5 \text{ mag} \): their detection may have to wait for the Next Generation Space Telescope.

1 Introduction
What keeps the universe ionized at \( z = 5 \)? The existence of a filamentary, low-density intergalactic medium (IGM), which contains the bulk of the hydrogen and helium in the universe, is predicted as a product of primordial nucleosynthesis [5] and of hierarchical models of gravitational instability with “cold dark matter” (CDM) [1], [7], [17]. The application of the Gunn-Peterson [10] constraint on the amount of smoothly distributed neutral material along the line of sight to distant objects requires the hydrogen component of the diffuse IGM to have been highly ionized by \( z \approx 5 \) [37], and the helium component by \( z \approx 2.5 \) [8]. The plethora of discrete absorption systems which give origin to the Ly\( \alpha \) forest in the spectra of background quasars are also inferred to be strongly photoionized. From QSO absorption studies we also know that neutral hydrogen accounts for only a small fraction, \( \sim 10\% \), of the nucleosynthetic baryons at early epochs [19]. It thus appears that substantial sources of ultraviolet photons were present at \( z > 5 \), perhaps low-luminosity quasars [13] or a first generation of stars in virialized dark matter halos with \( T_{\text{vir}} \sim 10^4 – 10^5 \text{ K} \) [1], [2], [14], [29]: early star formation provides a possible explanation for the widespread existence of heavy elements in the IGM [7]. More in general, establishing the character of cosmological ionizing sources is an efficient way to constrain competing models for structure formation in the universe, and to study the collapse and cooling of small mass objects at early epochs.

In this talk I will focus on the candidate sources of photoionization at early times and on the time-dependent reionization problem, i.e. on the history of the transition from a neutral
Figure 1: Comoving space density of bright QSOs as a function of redshift. The data points with error bars are taken from [15] (filled dots), [15] (filled squares), [36] (crosses), and [18] (filled pentagon). The points have been normalized to the $z = 2.5$ space density of quasars with $M_B < -26$ ($M_B < -27$ in the case of [18]). The empty triangles show the space density (normalized to the peak) of the Parkes flat-spectrum radio-loud quasars with $P > 7.2 \times 10^{26}$ W Hz$^{-1}$ sr$^{-1}$ [16].

IGM to one that is almost fully ionized. Throughout this paper I will adopt an Einstein-de Sitter universe ($q_0 = 0.5$) with $H_0 = 50h_{50}$ km s$^{-1}$ Mpc$^{-1}$. The ideas described below have been developed in collaboration with F. Haardt and M. J. Rees [25].

2 Sources of Ionizing Radiation at High Redshifts

2.1 Quasars

The existence of a decline in the space density of bright quasars at redshifts beyond $\sim 3$ was first suggested by [31], and has been since then the subject of a long-standing debate. In recent years, several optical surveys have consistently provided new evidence for a turnover in the QSO counts [15], [15], [36], [18]. The interpretation of the drop-off observed in optically selected samples is equivocal, however, because of the possible bias introduced by dust obscuration arising from intervening systems [33]. Radio emission, on the other hand, is unaffected by dust, and it has recently been shown [39] that the space density of radio-loud quasars also decreases strongly for $z > 3$, demonstrating that the turnover is indeed real and that dust along the line of sight has a minimal effect on optically-selected QSOs (Figure 1).

The QSO emission rate of hydrogen ionizing photons per unit comoving volume can be
written as 20

$$\dot{N}_Q(z) = (1.45 \times 10^{30} \text{ s}^{-1} \text{ Mpc}^{-3})(1 + z)^{α_s - 1} \frac{e^{εz}(1 + e^{εz})(1 - 4^{-α_s})}{e^{εz} + e^{εz}} (\frac{4400}{912})^{-α_s},$$

where $α_s$ is the slope of the quasar spectral energy distribution, and the best-fit parameters are $z_s = 1.9$, $ζ = 2.58$, and $ζ = 3.16$. It is important to notice that the procedure adopted to derive this quantity implies a large correction for incompleteness at high-z. With a fit to the quasar luminosity function (LF) which goes as $φ(L) \propto L^{-1.64}$ at the faint end [34], the contribution to the emissivity converges rather slowly, as $L^{0.36}$. At $z = 4$, for example, the blue magnitude at the break of the LF is $M_κ ≈ -25.4$, comparable or slightly fainter than the limits of current high-z QSO surveys. A large fraction, about 90% at $z = 4$ and even higher at earlier epochs, of the ionizing emissivity in our model is therefore produced by quasars that have not been actually observed, and are assumed to be present based on an extrapolation from lower redshifts. The value of $\dot{N}_Q$ obtained by including the contribution from observed quasars only would be much smaller at high redshifts than shown in Figure 2. While it is also possible that an excess of low-luminosity QSOs, relative to the best-fit LF, could actually boost the estimated ionizing emissivity at early epochs, the observed lack of red, unresolved faint objects in the Hubble Deep Field seems to argue against models where the quasar LF steepens significantly with lookback time [14].

2.2 Star-forming Galaxies

Galaxies with ongoing star-formation are another obvious source of Lyman continuum photons. The tremendous progress in our understanding of faint galaxy data made possible by the recent identification of star-forming galaxies at $2 ≲ z ≲ 4$ in ground-based surveys [42] and in the Hubble Deep Field (HDF) [11, 24, 22] has provided new clues to the long-standing issue of whether galaxies at high redshifts can provide a significant contribution to the ionizing background flux. Since the rest-frame UV continuum at 1500 Å (redshifted into the visible band for a source at $z ≈ 3$) is dominated by the same short-lived, massive stars which are responsible for the emission of photons shortward of the Lyman edge, the needed conversion factor, about one ionizing photon every 10 photons at 1500 Å, is fairly insensitive to the assumed IMF and is independent of the galaxy history for $t ≳ 10^{7.3}$ yr. A composite ultraviolet luminosity function of Lyman-break galaxies at $z ≈ 3$ has been recently derived by [3]. It is based on spectroscopically (about 375 objects) and photometrically selected galaxies from the ground-based and HDF samples, and spans about a factor 50 in luminosity from the faint to the bright end. Because of the uncertainties that still remain in the rescaling of the HDF data points to the ground-based data, the comoving luminosity density at 1500 Å is estimated to vary within the range 1.6 to $3.5 \times 10^{38}$ erg s$^{-1}$ Hz$^{-1}$ Mpc$^{-3}$. The “best guess” Schechter fit gives log ($φ_*/$Gpc$^{-3}$) = 6.1, $α = 1.38$, and $M_κ^*$ (1500) = −20.95 [3], the magnitude at the “break” corresponding to a star-formation rate slightly in excess of $10 M_⊙$ yr$^{-1}$ (Salpeter IMF).

Figure 3 shows the Lyman continuum luminosity function of galaxies at $z ≈ 3$ (at all ages $> 0.1$ Gyr one has $L(1500)/L(912) ≈ 6$ for a Salpeter mass function and constant star formation rate [2]), compared to the distribution of QSO luminosities at the same redshift. The comoving ionizing emissivity due to Lyman-break galaxies is $4.2 \pm 1.5 \times 10^{25}$ erg s$^{-1}$ Hz$^{-1}$ Mpc$^{-3}$, between 2 and 4 times higher than the estimated quasar contribution at $z = 3$.

This number neglects any correction for dust extinction and intrinsic H I absorption. While it has been pointed out by many authors [28, 33, 3] that the colors of Lyman-break galaxies are redder than expected in the case of dust-free star-forming objects, the prescription for a “correct” de-reddening is still unknown at present (note that redder spectra may also results
Figure 2: Comoving emission rate of hydrogen Lyman continuum photons (solid line) from QSOs, compared with the minimum rate (dashed line) which is needed to fully ionize a fast recombining (with clumping factor $C = 30$) Einstein–de Sitter universe with $h_{50} = 1$ and $\Omega_b = 0.08$. Models based on photoionization by quasar sources appear to fall short at $z = 5$. See [25] for details on the assumed quasar luminosity function and spectral energy distribution. The data points with error bars show the estimated contribution of star-forming galaxies at $z \approx 3$ and, with significantly larger uncertainties, at $z \approx 4$. The fraction of Lyman continuum photons which escapes the galaxy H I layers into the intergalactic medium is taken to be $f_{\text{esc}} = 0.5$.

from an aging population or an IMF which is rather poor in massive stars). A Salpeter IMF, $E_{B-V} = 0.1$ model with SMC-type dust in a foreground screen, for example, has been found to reproduce quite well the rest-frame ultraviolet colors of the HDF “UV dropouts” [25]. In this model the color excess $E_{912-1500} = 1.64E_{B-V}$ is rather small and can be safely neglected in correcting from observed rest-frame far-UV to the Lyman edge. For typical dust-to-gas ratios, however, it is the H I associated with dust that would greatly reduce the flux of Lyman continuum photons able to escape into the intergalactic space. The data points plotted in Figure 2 assume a value of $f_{\text{esc}} = 0.5$ for the unknown fraction of ionizing photons which escapes the galaxy H I layers into the intergalactic medium [27]. The possible existence of a numerous population of galaxies below the detection threshold, i.e. having star formation rates $< 0.5 \, M_\odot \, \text{yr}^{-1}$, with a space density well in excess of that predicted by extrapolating to faint magnitudes the $\alpha = 1.38$ best-fit Schechter function, will be discussed below. The LF of Lyman-break galaxies at $z \gtrsim 4$ is highly uncertain. An analysis of the $B$-band dropouts in the HDF – candidate star-forming objects at $3.5 < z < 4.5$ seems to imply a decrease in the comoving UV galaxy emissivity by about a factor of 2.5 in the interval $2.75 < z < 4$ [24]. In this sense star-forming galaxies with SFR in excess of $0.5 \, M_\odot \, \text{yr}^{-1}$ may have a negative evolution with lookback time similar to the one observed in bright QSOs, but the error bars are still rather large. Adopting a $L(1500)$ to $L(912)$ conversion factor of 6, we estimate a comoving ionizing emissivity of $1.7 \pm 1.1 \times 10^{25} f_{\text{esc}} \, \text{ergs s}^{-1} \, \text{Hz}^{-1} \, \text{Mpc}^{-3}$ at $z \approx 4$. One should note that,
Figure 3: The 912 Å luminosity function of galaxies at $z \approx 3$ (solid line), compared to the distribution of QSO luminosities at the same redshift (dashed line). The latter has been derived assuming a spectral slope of $\alpha_s = 0.5$. The former assumes a Salpeter IMF with constant constant star formation rate (age=1 Gyr): $M_{AB}(912 \text{ Å}) = -19$ corresponds to a rate of $13 \, M_\odot \, \text{yr}^{-1}$. The solid and dashed lines represent functional fits to the data points, and the dotted lines their extrapolation.

while a population of highly reddened galaxies at high redshifts would be missed by the dropout color technique (which isolates sources that have blue colors in the optical and a sharp drop in the rest-frame UV), it seems unlikely that very dusty objects (with $f_{\text{esc}} \ll 1$) would contribute in any significant manner to the ionizing metagalactic flux.

3 Reionization of the Universe

In inhomogeneous reionization scenarios, the history of the transition from a neutral IGM to one that is almost fully ionized can be statistically described by the evolution with redshift of the volume filling factor or porosity $Q(z)$ of H ii, He ii, and He iii regions. The radiation emitted by spatially clustered stellar-like and quasar-like sources – the number densities and luminosities of which may change rapidly as a function of redshift – coupled with absorption processes in a medium with a time-varying clumping factor, all determine the complex topology of neutral and ionized zones in the universe. When $Q << 1$ and the radiation sources are randomly distributed, the ionized regions are spatially isolated, every UV photon is absorbed somewhere in the IGM, and the ionization process cannot be described as due to a statistically homogeneous radiation field. As $Q$ grows, the crossing of ionization fronts becomes more and more common, and the neutral phase shrinks in size until the reionization process is completed at the “overlap” epoch, when every point in space is exposed to Lyman continuum radiation and $Q = 1$. 
When an isolated point source of ionizing radiation turns on, the ionized volume initially grows in size at a rate fixed by the emission of UV photons, and an ionization front separating the H II and H I regions propagates into the neutral gas. Most photons travel freely in the ionized bubble, and are absorbed in a transition layer. The evolution of an expanding H II region is governed by the equation

\[
\frac{dV_I}{dt} - 3HV_I = \frac{\dot{N}_{\text{ion}}}{n_H} - \frac{V_I}{\bar{t}_{\text{rec}}},
\]

where \(V_I\) is the proper volume of the ionized zone, \(\dot{N}_{\text{ion}}\) is the number of ionizing photons emitted by the central source per unit time, \(H\) is the Hubble constant, \(\bar{n}_H\) is the mean hydrogen density of the expanding IGM, \(\bar{n}_H(0) = 1.7 \times 10^{-7} \left(\Omega_B h_0^2/0.08\right)\), and

\[
\bar{t}_{\text{rec}} = [(1 + 2\chi)\bar{n}_H \alpha_B C]^{-1} = 0.3 \text{ Gyr} \left(\frac{\Omega_B h_0^2}{0.08}\right)^{-1} \left(\frac{1 + z}{4}\right)^{-3} C_{30}^{-1}
\]

is the volume-averaged gas recombination timescale. Here \(\alpha_B\) is the recombination coefficient to the excited states of hydrogen, \(\chi\) the helium to hydrogen cosmic abundance ratio, \(C \equiv \langle n_H^2 \rangle/\bar{n}_H^2\) is the ionized hydrogen clumping factor, and a gas temperature of \(10^4\) K has been assumed. Clumps which are dense and thick enough to be self-shielded from UV radiation will stay neutral and will not contribute to the recombination rate. An empirical determination of the clumpiness of the IGM at high redshifts is hampered by our poor knowledge of the ionizing background intensity and the typical size and geometry of the absorbers. Numerical N-body/hydrodynamics simulations of structure formation in the IGM within the framework of CDM dominated cosmologies have recently provided a definite picture for the origin of intervening absorption systems, one of an interconnected network of sheets and filaments, with virialized systems located at their points of intersection. In the simulations of [9], for example, the clumping factor rises above unity when the collapsed fraction of baryons becomes non negligible, i.e. \(z \lesssim 20\), and grows to \(C \gtrsim 10\) (40) at \(z \approx 8\) (5) (because of finite resolution effects, numerical simulations will actually underestimate clumping): the recombination timescale is much shorter than that for a uniform IGM, and always shorter than the expansion time.

When \(\bar{t}_{\text{rec}} \ll t\), the growth of the H II region is slowed down by recombinations in the highly inhomogeneous IGM, and its evolution can be decoupled from the expansion of the universe. Just like in the static case, the ionized bubble will fill its time-varying Strömgren sphere after a few recombination timescales,

\[
V_I = \frac{\dot{N}_{\text{ion}} \bar{t}_{\text{rec}}}{\bar{n}_H} \left(1 - e^{-t/\bar{t}_{\text{rec}}}\right).
\]

One should point out that the use of a volume-averaged clumping factor in the recombination timescale is only justified when the size of the H II region is large compared to the scale of the clumping, so that the effect of many clumps (filaments) within the ionized volume can be averaged over. This will be a good approximation either at late epochs, when the IGM is less dense and H II zones have had time to grow, or at earlier epochs if the ionized bubbles are produced by very luminous sources like quasars or the stars within halos collapsing from very high-\(\sigma\) peaks. The mean free path between absorbers having neutral columns \(N_{\text{HI}}\) is \(0.8\) Mpc \(h_0^{-1} \left[(1 + z)/6\right]^{-4.5} \left(N_{\text{HI}}/10^{15} \text{ cm}^{-2}\right)^{0.5}\); it is only on scales greater than this value that the clumping can be averaged over. On smaller scales underdense regions are ionized first, and only afterwards the UV photons start to gradually penetrate into the higher density gas.

\[\text{1}\] This may be somewhat lower than the total gas clumping factor if higher density regions are less ionized.
With these caveats in mind, equation (2) approximately holds for every isolated source of ionizing photons in the IGM. The filling factor of H II regions in the universe, $Q_{\text{HI}}$, is then equal at any given instant $t$ to the integral over cosmic time of the rate of ionizing photons emitted per hydrogen atom and unit cosmological volume by all radiation sources present at earlier epochs, $\int_0^t \dot{n}_{\text{ion}}(t')dt'/\bar{n}_H(t')$, minus the rate of radiative recombinations, $\int_0^t Q_{\text{HI}}(t')dt'/\bar{t}_{\text{rec}}(t')$. Differentiating one gets

$$\frac{dQ_{\text{HI}}}{dt} = \frac{\dot{n}_{\text{ion}}}{\bar{n}_H} - \frac{Q_{\text{HI}}}{\bar{t}_{\text{rec}}}. \quad (5)$$

It is this simple differential equation – and its equivalent for expanding helium zones – that statistically describes the transition from a neutral universe to a fully ionized one, independently, for a given emissivity, of the complex and possibly short-lived emission histories of individual radiation sources, e.g., on whether their comoving space density is constant or actually varies with cosmic time. In the case of a time-independent clumping factor, equation (5) has formal solution

$$Q_{\text{HI}}(t) = \int_0^t dt' \frac{\dot{n}_{\text{ion}}}{\bar{n}_H} \exp \left( - \frac{t'}{\bar{t}_{\text{rec}}} + \frac{t^2}{2 \bar{t}_{\text{rec}}^2} \right), \quad (6)$$

with $\bar{t}_{\text{rec}} \propto t^2$. At high redshifts, and for an IGM with $C \gg 1$, one can expand around $t$ to find

$$Q_{\text{HI}}(t) \approx \frac{\dot{n}_{\text{ion}}}{\bar{n}_H} \bar{t}_{\text{rec}}. \quad (7)$$

The porosity of ionized bubbles is then approximately given by the number of ionizing photons emitted per hydrogen atom in one recombination time. In other words, because of hydrogen recombinations, only a fraction $\bar{t}_{\text{rec}}/t$ ($\sim$ a few per cent at $z = 5$) of the photons emitted above 1 ryd is actually used to ionize new IGM material. The universe is completely reionized when $Q = 1$, i.e. when

$$\dot{n}_{\text{ion}} \bar{t}_{\text{rec}} = \bar{n}_H. \quad (8)$$

While this last expression has been derived assuming a constant comoving ionizing emissivity and a time-independent clumping factor, it is also valid in the case $\dot{n}_{\text{ion}}$ and $C$ do not vary rapidly over a timescale $\bar{t}_{\text{rec}}$.

### 4 Dwarfs at High Redshift?

As $\bar{t}_{\text{rec}} \ll t$ at high redshifts, it is possible to compute at any given epoch a critical value for the photon emission rate per unit cosmological comoving volume, $\dot{N}_{\text{ion}}$, independently of the (unknown) previous emission history of the universe: only rates above this value will provide enough UV photons to ionize the IGM by that epoch. One can then compare our determinations of $\dot{N}_{\text{ion}}$ to the estimated contribution from QSOs and star-forming galaxies. Equation (8) can then be rewritten as

$$\dot{N}_{\text{ion}}(z) = \frac{\bar{n}_H(0)}{\bar{t}_{\text{rec}}(z)} = (10^{51.2} \text{ s}^{-1} \text{ Mpc}^{-3}) C_{50} \left( \frac{1 + z}{6} \right)^3 \left( \Omega_b h^2_{50} \right)^2. \quad (9)$$

The uncertainty on this critical rate is difficult to estimate, as it depends on the clumping factor of the IGM (scaled in the expression above to the value inferred at $z = 5$ from numerical simulations [10]) and the nucleosynthesis constrained baryon density. A quick exploration of the available parameter space indicates that the uncertainty on $\dot{N}_{\text{ion}}$ could easily be of order $\pm 0.2$ in the log. The evolution of the critical rate as a function of redshift is plotted in Figure 2. While $\dot{N}_{\text{ion}}$ is comparable to the quasar contribution at $z \gtrsim 3$, there is some indication of a significant
deficit of Lyman continuum photons at \( z = 5 \). For bright, massive galaxies to produce enough UV radiation at \( z = 5 \), their space density would have to be comparable to the one observed at \( z \approx 3 \), with most ionizing photons being able to escape freely from the regions of star formation into the IGM. This scenario may be in conflict with direct observations of local starbursts below the Lyman limit showing that at most a few percent of the stellar ionizing radiation produced by these luminous sources actually escapes into the IGM \cite{20, 3}. If, on the other hand, faint QSOs with (say) \( M_{AB} = -19 \) at rest-frame ultraviolet frequencies were to provide all the required ionizing flux, their comoving space density would be such (0.0015 Mpc\(^{-3}\)) that about 50 of them would be expected in the HDF down to \( I_{AB} = 27.2 \). At \( z \gtrsim 5 \), they would appear very red in \( V - I \) as the Lyα forest is shifted into the visible. This simple model can be ruled out, however, as there is only a handful (7) of sources in the HDF with \((V - I)_{AB} > 1.5\) mag down to this magnitude limit.

It is interesting to convert the derived value of \( \dot{N}_{\text{ion}} \) into a “minimum” star formation rate per unit (comoving) volume, \( \dot{\rho}_s \) (hereafter we assume \( \Omega_b h_{50}^2 = 0.08 \) and \( C = 30 \)):

\[
\dot{\rho}_s(z) = \dot{N}_{\text{ion}}(z) \times 10^{-53.1} f_{\text{esc}}^{-1} \approx 0.013 f_{\text{esc}}^{-1} \left( \frac{1 + z}{6} \right)^3 M_\odot \text{yr}^{-1} \text{Mpc}^{-3}. \tag{10}
\]

The conversion factor assumes a Salpeter IMF with solar metallicity \cite{3}. It can be understood by noting that, for each 1 \( M_\odot \) of stars formed, 8% goes into massive stars with \( M > 20 M_\odot \) that dominate the Lyman continuum luminosity of a stellar population. At the end of the C-burning phase, roughly half of the initial mass is converted into helium and carbon, with a mass fraction released as radiation of 0.007. About 25% of the energy radiated away goes into ionizing photons of mean energy 20 eV. For each 1 \( M_\odot \) of stars formed every year, we then expect

\[
\frac{0.08 \times 0.5 \times 0.007 \times 0.25 \times M_\odot c^2}{20 \text{eV}} = \frac{1}{1 \text{yr}} \sim 10^{53} \text{phot s}^{-1} \tag{11}
\]

to be emitted shortward of 1 ryd. Note that the star formation density given in equation (10) is comparable with the value directly “observed” (i.e., uncorrected for dust reddening) at \( z \approx 3 \) \cite{20, 3}.

The same massive stars that dominate the Lyman continuum flux also manufacture and return most of the metals to the ISM. In the approximation of instantaneous recycling, the rate of ejection of newly synthesized heavy elements which is required to keep the universe ionized at redshift \( z \) is, from equation (10),

\[
\dot{\rho}_Z(z) = y(1 - R) \dot{\rho}_s(z) \gtrsim 3.5 \times 10^{-4} \left( \frac{y}{2 Z_\odot} \right) \left( \frac{1 + z}{6} \right)^3 f_{\text{esc}}^{-1} M_\odot \text{yr}^{-1} \text{Mpc}^{-3}, \tag{12}
\]

where \( y \) is the net, IMF-averaged “yield” of returned metals, \( Z_\odot = 0.02 \), and \( R \approx 0.3 \) is the mass fraction of a generation of stars that is returned to the interstellar medium. At \( z = 5 \), and over a timescale of \( \Delta t = 0.5 \) Gyr corresponding to a formation redshift \( z_f = 10 \), such a rate would generate a mean metallicity per baryon in the universe of

\[
\langle Z \rangle \approx \frac{8 \pi G \dot{\rho}_Z(5) \Delta t}{3H_0^2 \Omega_b} \gtrsim 0.002 \left( \frac{y}{2 Z_\odot} \right) f_{\text{esc}}^{-1} Z_\odot, \tag{13}
\]

comparable with the level of enrichment observed in the Lyα forest at \( z \approx 3 \) \cite{10}: more than 2% of the present-day stars would need to have formed by \( z \approx 5 \). It has been recently suggested \cite{25} that a large number of low-mass galactic halos, expected to form at early times

\footnote{Note that, at \( z = 3 \), Lyman-break galaxies would radiate more ionizing photons than QSOs for \( f_{\text{esc}} \gtrsim 30\%. \)}
in hierarchical clustering models, might be responsible for photoionizing the IGM at these epochs. According to spherically-symmetric simulations \([44]\), photoionization heating by the UV background flux that builds up after the overlapping epoch completely suppresses the cooling and collapse of gas inside the shallow potential wells of halos with circular velocities \(\lesssim 35 \text{ km s}^{-1}\). Halos with circular speed \(v_{\text{circ}} = 50 \text{ km s}^{-1}\), corresponding in top-hat spherical collapse to a virial temperature \(T_{\text{vir}} = 0.5 \mu m_p v_{\text{circ}}^2 / k \approx 10^5 \text{ K}\) and halo mass \(M = 0.1 v_{\text{circ}}^3 / GH \approx 4 \times 10^9 [(1 + z)/6]^{-3/2} h_{50}^{-1} \text{ M} \odot\), appear instead largely immune to this external feedback (but see \([20]\)). In these systems rapid cooling by atomic hydrogen can then take place and a significant fraction, \(f \Omega_b\), of their total mass may be converted into stars over a timescale \(\Delta t\) comparable to the Hubble time (with \(f\) close to 1 if the efficiency of forming stars is high). If high-\(z\) dwarfs with star formation rates \(f \Omega_b M/\Delta t \sim 0.3 f_{0.5} \Delta t_{0.5}^{-1} M_\odot \text{ yr}^{-1}\) were actually responsible for keeping the universe ionized at \(z \approx 5\), their comoving space density would have to be

\[
\frac{0.013 f_{\text{esc}}^{-1} M_\odot \text{ yr}^{-1} \text{ Mpc}^{-3}}{0.6 f M_\odot \text{yr}^{-1}} \sim 0.1 \left( \frac{f_{\text{esc}} f}{0.25} \right)^{-1} \text{ Mpc}^{-3},
\]

(14)

two hundred times larger than the space density of present-day galaxies brighter than \(L^* (4400)\), and about five hundred times larger than that of Ly\(\alpha\)-break objects at \(z \approx 3\) with \(M < M_{AB}(1500)\), i.e. with star formation rates in excess of \(10 \text{ M}_\odot \text{ yr}^{-1}\). Only a rather steep luminosity function, with Schechter slope \(\alpha \sim 2\), would be consistent with such a large space density of faint dwarfs and, at the same time, with the paucity of brighter \(B\)- and \(V\)-band dropouts observed in the HDF. The number density on the sky would be \(\approx 0.2 \text{ arcsec}^{-2}\), corresponding to more than three thousands sources in the HDF. With a typical apparent magnitude at \(z = 5\) of \(I_{AB} \sim 29.5\) mag (assuming \(f = 0.5\)), these might be too faint to be detected by the \(HST\), but within the range of the proposed Next Generation Space Telescope \([13]\).

These estimates are in reasonable agreement (although towards the low side) with the calculations of \([23]\), who used the observed metallicity of the Ly\(\alpha\) forest as the starting point of their investigation. A higher density of sources – which would therefore have to originate from lower amplitude peaks – would be required if the typical efficiency of star formation and/or the escape fraction of ionizing photons were low, \((f, f_{\text{esc}}) \ll 1\). In this case the dwarfs could still be detectable if a small fraction of the gas turned into stars in very short bursts (there would then be an extra parameter associated with their duty cycle, in addition to \(f_{\text{esc}}\) and \(f\)). A reduction of the star formation rate in halos with low circular velocities (necessary in hierarchical cosmogonies to prevent too many baryons from turning into stars as soon as the first levels of the hierarchy collapse \([46]\)) may result from the heating and possible expulsions of the gas due to repeated supernova (SN) explosions after only a very small number of stars have formed. Recent numerical simulations \([23]\) show, however, that metal-enriched material from SN ejecta is accelerated to velocities larger than the escape speed from such systems far more easily than the ambient gas. If the same population of dwarf galaxies that may keep the universe ionized at \(z \approx 5\) were also responsible for polluting the IGM with heavy elements, it is interesting to ask whether these atoms could diffuse uniformly enough to account for the observations of weak but measurable C\(\text{iv}\) absorption lines associated with the Ly\(\alpha\) forest clouds \([21]\). \([40]\). Our fiducial estimate of 0.1 sources per comoving Mpc\(^3\) implies that, in order to pollute the entire IGM, the metal-enriched material would have to be expelled to typical distances of order 1 Mpc, which would require an ejection speed of about \(200[(1 + z)/6]^{1/2} \text{ km s}^{-1}\). In fact, the heavy elements may be restricted to filaments within only (say) 20 proper kpc (100-150 comoving kpc) of the halos, and in this case it would be enough to accelerate the outflowing metals to velocities comparable to the escape velocity, rather than to the higher speeds associated with SN ejecta. The required diffusion of heavy elements would be a more serious constraint if the relevant
galaxies were rarer and more luminous, as would happen if they originated from 3-σ peaks and star formation was postulated to occur with higher efficiency than in more typical peaks.

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