PROBING THE HIGH REDSHIFT UNIVERSE WITH THE NGST

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ABSTRACT

Through a combination of deep wide-field imaging and multi-object spectroscopy, the Next Generation Space Telescope will be able to chart with unprecedented accuracy the evolution of cosmic structures after the ‘dark ages’ \( (z \lesssim 5) \), when galaxies are thought to assemble and form the bulk of their stars. In this talk I will discuss how NGST observations might determine the history of the stellar birthrate in the universe and reveal the character of cosmological ionizing sources at high redshifts.

1. INTRODUCTION

The remarkable progress in our understanding of faint galaxy data made possible by the combination of HST deep imaging (Williams et al. 1996) and ground-based spectroscopy (Lilly et al. 1996; Ellis et al. 1996; Steidel et al. 1996b), has recently permitted to shed some light on the evolution of the stellar birthrate in the universe, to identify the epoch \( 1 \lesssim z \lesssim 2 \) where most of the optical extragalactic background light was produced, and to set important contraints on galaxy formation scenarios (e.g., Madau et al. 1998c; Steidel et al. 1998). While one of the topical questions concerning our understanding of the emission history of the universe is the nature and redshift distribution of the recently discovered population of sub-mm sources (Hughes et al. 1998; Barger et al. 1998; Lilly, this volume), one could also imagine the existence of a large population of faint galaxies still undetected at high-z, as the color-selected ground-based and Hubble Deep Field (HDF) samples include only the brightest star-forming young objects. In hierarchical clustering scenarios, a population of high-z dwarfs (i.e. an early generation of stars in dark matter halos with circular velocities \( v_{\text{circ}} \approx 50 \text{ km s}^{-1} \)) is actually expected to be one of the main source of UV photons and heavy elements at early epochs (e.g. Miralda-Escudé & Rees 1998; Loeb, this volume).

While it is hard to predict in detail what the scientific focus of NGST will be ten years from now in a rapidly evolving area like physical cosmology, I believe it is a useful exercise to describe a couple of illustrative science programs which well highlight the strategic capabilities of NGST in providing a comprehensive inventory of the buildup of metals, stars, and light in the universe: (a) the determination of the rate of Type Ia and Type II supernova (SN) explosions as a function of cosmic time from intermediate to high redshifts; and (b) the study of candidate sources of photoionization at early times. Throughout this paper I will adopt an Einstein-de Sitter universe \( (q_0 = 0.5) \) with \( H_0 = 50h_{50} \text{ km s}^{-1} \text{ Mpc}^{-1} \).

2. SUPERNOVAE

The evolution of the SN rate with redshift contains unique information on the star formation history of the universe, the initial mass function (IMF) of stars, and the nature of the binary companion in Type Ia events. All are essential ingredients for understanding galaxy formation, cosmic chemical evolution, and the mechanisms which determined the efficiency of the conversion of gas into stars in galaxies at various epochs. While the frequency of “core-collapse supernovae”, SN II and possibly SN Ib/c, which have short-lived progenitors, is essentially related, for a given IMF, to the instantaneous stellar birthrate of massive stars, Type Ia SNe – which are believed to result from the thermonuclear disruption of C-O white dwarfs in binary systems – follow a slower evolutionary clock, and can then be used as a probe of the past history of star formation in galaxies (e.g., Yungelson & Livio 1998). The recent detection of Type Ia SNe at cosmological distances (Garnavich et al. 1998; Perlmutter et al. 1998) allows for the first time a detailed comparison at \( z \lesssim 1 \) between the SN rates self-consistently predicted by stellar evolution models that reproduce the optical spectrophotometric properties of field galaxies, and the observed values. Accurate measurements at all redshifts of the frequencies of Type II(+)Ib/c and Ia SNe could be used as an independent test for the star formation and heavy element enrichment history of the universe, and significantly improve our understanding of the intrinsic nature and age of the populations involved in the SN explosions (Sadat et al. 1998; Madau et al. 1998a). A determination of the amount of star formation at early epochs may be of crucial importance, as the two competing scenarios for galaxy formation, monolithic collapse – where spheroidal systems formed early and rapidly, experiencing a bright starburst phase at high-z (Eggen et al. 1962; Tinsley & Gunn 1976) – and hierarchical clustering – where ellipticals form continuously by the merger of disk/bulge systems (White & Frenk 1991; Kauffmann et al. 1993) and most galaxies never experience star formation, give rise to very different predictions.
formation rates in excess of a few solar masses per year (Baugh et al. 1998) – appear to make rather different predictions in this regard. By detecting Type II SNe at high-z, NGST should provide an important test for distinguishing between different scenarios of galaxy formation.

2.1. Cosmic Star Formation History

The emission history of field galaxies at ultraviolet, optical, and near-infrared wavelengths can be modeled by tracing the evolution with cosmic time of their luminosity density,

$$\rho_\nu(z) = \int_0^\infty L_\nu y(L_\nu, z) dL_\nu = \Gamma(2 + \alpha) y_\star L_\star,$$  \hspace{1cm} (1)

where $y(L_\nu, z)$ is the best-fit Schechter luminosity function in each redshift bin. The integrated light radiated per unit volume from the entire galaxy population is an average over cosmic time of the stochastic, possibly short-lived star formation episodes of individual galaxies, and follows a relatively simple dependence on redshift. A stellar evolution model, defined by a time-dependent star formation rate per unit volume, $\psi(t)$, a universal IMF, $\phi(m)$, and some amount of dust reddening, can actually reproduce the optical data reasonably well (Madau et al. 1998c). In such a system, the luminosity density at time $t$ is given by the convolution integral

$$\rho_\nu(t) = p_{\text{esc}} \int_0^t l_\nu(t') \psi(t - t') dt',$$  \hspace{1cm} (2)

where $l_\nu(t')$ is the specific luminosity radiated per unit initial mass by a generation of stars with age $t'$, and $p_{\text{esc}}$ is a time-independent term equal to the fraction of emitted photons which are not absorbed by dust. The function $\psi(t)$ is derived from the observed UV luminosity density, and is then used as input to the population synthesis code of Bruzual & Charlot (1998). Figure 1a shows the model predictions for the evolution of $\rho_\nu$ for a Salpeter function, $A_{1500} = 0.8$ mag with SMC-type dust, and a star formation history which traces the rise, peak, and sharp drop of the UV emissivity. For simplicity, the metallicity was fixed to solar values and the IMF truncated at 0.1 and 125 $M_\odot$. The data points show the observed luminosity density in six broad passbands centered around 0.15, 0.20, 0.28, 0.44, 1.0, and 2.2 $\mu$m. The model is able to account for the entire background light recorded in the galaxy counts down to the very faint magnitude levels probed by the HDF, and produces visible mass-to-light ratios at the present epoch which are consistent with the values observed in nearby galaxies of various morphological types. The bulk ($\geq 60\%$ by mass) of the stars present today formed relatively recently ($z \lesssim 1.5$), consistently with the expectations from a broad class of hierarchical clustering cosmologies (Baugh et al. 1998), and in good agreement with the low level of metal enrichment observed at high redshifts in the damped Ly$\alpha$ systems (Pettini et al. 1997).

One of the biggest uncertainties in our understanding of the evolution of luminous matter in the universe is represented by the poorly constrained amount of starlight that was absorbed by dust and reradiated in the far-IR at early epochs. Figure 1b shows the model predictions for a monolithic collapse scenario, where half of the present-day stars were formed at $z > 2.5$ and were enshrouded by an increasing amount of dust, $A_{1500} = 0.09(1 + z)^{2.2}$ mag. This results in a correction to the rate of star formation by a factor of $\approx 5$ at $z = 3$ and $\approx 15$ at $z = 4$. The two models in Figure 1 produce a significant fraction ($\sim 50\%$) of the IR background detected by COBE (Dwek et al. 1998; Fixsen et al. 1998).
2.2. Type Ia and II(+Ib/c) Supernova Rates

Single stars with mass $> 8 M_\odot$ evolve rapidly ($\lesssim 50$ Myr) through all phases of central nuclear burning, ending their life as Type II SNe with different characteristics depending on the progenitor mass. For a Salpeter IMF the core-collapse supernova rate can be related to the stellar birthrate according to

$$ SNR_{II}(t) = \psi(t) \int_{125}^{\infty} dm \phi(m) \int_{0.1}^{125} dmm \phi(m). \quad (3) $$

The specific evolutionary history leading to a Type Ia event remains instead an unsettled question. SN Ia are believed to result from the explosion of C-O white dwarfs (WDs) triggered by the accretion of material from a companion, the nature of which is still unknown (see Ruiz-Lapuente et al. 1997 for a recent review). In a double degenerate (DD) system, for example, such elusive companion is another WD: the exploding WD reaches the Chandrasekhar limit and carbon ignition occurs at its center. In the single degenerate (SD) model instead, the companion is a nondegenerate, evolved star that fills its Roche lobe and pours hydrogen or helium onto the WD (Iben & Tutukov 1984). While in the latter the clock for the explosion is set by the lifetime of the primary star, and, e.g., by how long it takes to the companion to evolve and fill its Roche lobe, in the former it is controlled by the lifetime of the primary star and by the time it takes to shorten the separation of the two WDs as a result of gravitational wave radiation. The evolution of the rate depends then, among other things, on the unknown mass distribution of the secondary binary components in the SD model, or on the distribution of the initial separations of the two WDs in the DD model.

To shed light into the identification issue and, in particular, on the clock-mechanism for the explosion of Type Ia’s, it is useful to parametrize the rate of Type Ia’s in terms of a characteristic explosion timescale, $\tau$ – which defines an explosion probability per WD assumed to be independent of time – and an explosion efficiency, $\eta$. The former accounts for the time it takes in the various models to go from a newly born (primary) WD to the SN explosion itself: a spread of “delay” times results from the combination of a variety of initial conditions, such as the mass ratio of the binary system, the distribution of initial separations, the influence of metallicity on the mass transfer rate and accretion efficiency, etc. The latter simply accounts for the fraction of stars in binary systems that, because of unfavorable initial conditions, will never undergo a SN Ia explosion. Possible progenitors are all systems in which the primary star has an initial mass higher than $m_{\text{min}} = 3 M_\odot$ (final mass $\geq 0.72 M_\odot$, Weidemann 1987) and lower than $m_{\text{max}} = 8 M_\odot$: stars less massive than $3 M_\odot$ will not produce a catastrophic event even if the companion has comparable mass, while stars more massive than $8 M_\odot$ will undergo core collapse, generating a Type II explosion. With these assumptions the rate of Type Ia events at any one time will be given by the sum of the explosions of all the binary WDs produced in the past that have not had the time to explode yet, i.e.

$$ SNR_{Ia}(t) = \frac{\eta \int_0^t \psi(t') dt' \int_{m_c}^{m_{\text{max}}} \exp(-T) \phi(m) dm}{\tau \int \phi(m) dm}, \quad (4) $$

where $m_c \equiv \max\{m_{\text{min}}, m(t')\}$, $m(t') = (10 \text{Gyr}/t')^{0.4}$ is the minimum mass of a star that reaches the WD phase at time $t'$, $t_m = 10 \text{Gyr}/m^{2.5}$ is the standard lifetime of a star of mass $m$ (all stellar masses are expressed in solar units), and $T = (t - t' - t_m)/\tau$. For a fixed initial mass $m$, the frequency of Type Ia events peaks at an epoch that reflects an “effective” delay $\Delta t \approx \tau + t_m$ from stellar birth. A prompter (smaller $\tau$) explosion results in a higher SN Ia rate at early epochs.
In Figure 2 the predicted Type Ia and II(+Ib/c) rest-frame frequencies are shown as a function of redshift. Expressed in SNu (one SNu corresponding to 1 SN per 100 years per $10^{10} L_{B\odot}$), the Type II rate is basically proportional to the ratio between the UV and blue galaxy luminosity densities, and is therefore independent of cosmology. Unlike the SN frequency per unit volume, which will trace the evolution of the stellar birthrate, the frequency of Type II events per unit blue luminosity is a monotonic increasing function of redshift, and depends only weakly on the assumed star formation history. The Type Ia rates plotted in the figure assume characteristic “delay” timescales after the collapse of the primary star to a WD equal to $\tau = 0.3, 1$ and 3 Gyr, which virtually encompass all relevant possibilities. The SN Ia explosion efficiency was left as an adjustable parameter to reproduce the observed ratio of SN II to SN Ia explosion rates in the local Universe ($\text{SNR}_{Ia}/\text{SNR}_{II} \approx 3.5$), 5% $< \eta < 10\%$ for the adopted models. It appears that observational determinations of the SN Ia rate at $z \sim 1$ can unambiguously identify the appropriate delay time. In particular, we estimate that measuring the frequency of Type Ia events at both $z \sim 0.5$ and $z \sim 1$ with an error of 20% or lower would allow one to determine this timescale to within about 30%. This kind of observations are by no means prohibitive, and these goals could be achieved within a couple of years. In fact, ongoing searches for high-$z$ SNe are currently able to discover and study about a dozen new events per observing session in the redshift range 0.4–1.0, and the observations are carried out at a rate of about four sessions a year. Since determining the frequency of SN Ia with a 20% uncertainty requires statistics on more than 25 objects per redshift bin, it is clear that, barring systematic biases, those rates will soon be known with high accuracy.

Also note how, relative to the merging scenario, the monolithic collapse model predicts Type Ia rates (in SNu) that are, in the $\tau = 0.3$ Gyr case, a factor of 1.6 and 4.9 higher at $z = 2$ and 4, respectively, with even larger factors found in the case of longer delays. Therefore, once such timescale is calibrated through the observed ratio $\text{SNR}_{Ia}(z = 0)/\text{SNR}_{Ia}(z = 1)$, one should be able to constrain the star formation history of the early universe by comparing the predicted SN Ia rate at $z > 2$ with the observations.

The main results of this exercise can be summarized as follows:

- At the present epoch, the predicted Type II(+Ib/c) frequency matches remarkably well the observed local value. Note, however, that rates obtained from traditional distant (beyond 4 Mpc) sample might need to be increased by a factor of 1.5–2 because of severe selection effects against Type II’s fainter than $M_V = -16$ (Woltjer 1997).

- In the interval 0 $\leq z \leq 1$, the predicted rate of SN Ia is a sensitive function of the characteristic delay timescale between the collapse of the primary star to a WD and the SN event. Accurate measurements of SN rates in this redshift range will improve our understanding of the nature of SN Ia progenitors and the physics of the explosions. Ongoing searches and studies of distant SNe should soon provide these rates, allowing a universal calibration of the Type Ia phenomenon.

- While Type Ia rates at 1 $\leq z \leq 2$ will offer valuable information on the star formation history of the universe at earlier epoch, the full picture will only be obtained with statistics on Type Ia and II SNe at redshifts 2 $< z < 4$ or higher. At these epochs, the detection of Type II events must await NGST. A SN II has a typical peak magnitude $M_B \approx -17$; placed at $z = 3$, such an explosion would give rise to an observed flux of 15 nJy (assuming a flat cosmology with $q_0 = 0.5$ and $H_0 = 50 h_50$ km s$^{-1}$ Mpc$^{-1}$) at 1.8 $\mu$m. At this wavelength, the imaging sensitivity of an 8m NGST is 1 nJy ($10^4$ s exposure and 10$\sigma$ detection threshold), while the moderate resolution ($\lambda/\Delta \lambda = 1000$) spectroscopic limit is about 50 times higher ($10^5$ s exposure per resolution element and 10$\sigma$ detection threshold) (Stockman...
et al. 1998). The several weeks period of peak rest-frame blue luminosity would be stretched by a factor of $(1+z)^{-1}$ to few months. Figure 3 shows the cumulative number of Type II events expected per year per $4' \times 4'$ field. Depending on the history of star formation at high redshifts, NGST should detect between 7 (in the merging model) and 15 (in the monolithic collapse scenario) Type II SNe per field per year in the interval $2 < z < 4$. The possibility of detecting Type II SNe at $z \gtrsim 5$ from an early population of galaxies has been investigated by Miralda-Escudé & Rees (1997). By assuming these are responsible for the generation of all the metals observed in the Lyα forest at high redshifts, a high baryon density ($\Omega b^2 = 0.1$), and an average metallicity of $0.01 Z_\odot$, Miralda-Escudé & Rees estimate NGST should observe about 16 SN II per field per year with $z \gtrsim 5$. Note, however, that a metallicity smaller by a factor $\sim 10$ compared to the value adopted by these authors has been recently derived by Songaila (1997). For comparison, the models discussed above predict between 1 and 10 Type II SNe per field per year with $z \gtrsim 4$.

3. 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 and of hierarchical models of gravitational instability with “cold dark matter” (CDM) (Cen et al. 1994; Zhang et al. 1995; Hernquist et al. 1996). The application of the Gunn-Peterson 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 $z \approx 5$ (Schneider et al. 1991), and the helium component by $z \approx 2.5$ (Davidson et al. 1996). The plethora of discrete absorption systems which give origin to the Lyα forest in the spectra of background quasars are also inferred to be strongly photoionized: we know from QSO absorption studies, in fact, that neutral hydrogen accounts for only a small fraction, $\sim 10\%$, of the nucleosynthetic baryons at early epochs (Lanzetta et al. 1995). It thus appears that substantial sources of ultraviolet photons were present at $z > 5$, perhaps low-luminosity quasars (Haiman & Loeb 1998) or a first generation of stars in virialized dark matter halos with $T_{vir} \sim 10^5 - 10^6 K$ (Couchman & Rees 1986; Ostriker & Gnedin 1996; Haiman & Loeb 1997; Miralda-Escudé & Rees 1998): early star formation provides a possible explanation for the widespread existence of heavy elements in the IGM (Cowie et al. 1995). 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.

3.1. Quasars

A decline in the space density of bright quasars at redshifts beyond $\sim 3$ was first suggested by Osmer (1982), 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 (Hartwick & Schade 1990, HS; Warren et al. 1994, WHO; Schmidt et al. 1990, SSG; Kennefick et al. 1995, KDC). 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 (Ostriker & Heisler 1984). Radio emission, on the other hand, is unaffected by dust, and it has recently been shown (Shaver et al. 1996) that the space density of radio-loud quasars also decreases strongly for $z > 3$ (Fig. 4), demonstrating that the turnover is indeed real and that dust along the line of sight has a minimal effect on optically-selected QSOs. The QSO emission rate of hydrogen ionizing photons per unit comoving volume, $\dot{N}$, has been recently recalculated by Madau et al. (1998), and is shown in Figure 5. 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 $\phi(L) \propto L^{-1.64}$ at the faint end (Pei 1995), 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 $M_B \approx -25.4$, 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 $\tilde{N}$ obtained by including the contribution from observed quasars only would be much smaller at high redshifts than shown in Figure 5.

3.2. Star-forming Galaxies

Galaxies with ongoing star-formation are another obvious source of Lyman continuum photons. A composite UV luminosity function of Lyman-break galaxies at $z \approx 3$ has been recently derived by Dickinson (1998). It is based on spectroscopically 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 $3.5 \times 10^{26}$ erg s$^{-1}$ Hz$^{-1}$ Mpc$^{-3}$. Since the rest-frame UV continuum at 1500 Å (redshifted into the visible band for a source at $z \approx 3$) 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 to the galaxy history for $t \gg 10^7$ yr.

Figure 6 shows the Lyman continuum luminosity function of galaxies at $z \approx 3$ [at all ages $\gtrsim 0.1$ Gyr one has $L(1500)/L(912) \approx 6$ for a Salpeter mass function and constant star formation rate], 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 intrinsic H I absorption: the data points plotted in Figure 6 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.

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 $2.75 \lesssim z \lesssim 4$ (Madau et al. 1996, 1998c). In this sense star-forming galaxies with SFR in excess of $0.5 M_\odot$ 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 $1.7 \pm 1.1 \times 10^{25} f_{\text{esc}}$ ergs s$^{-1}$ Hz$^{-1}$ Mpc$^{-3}$ at $z = 4$. One should note that, while highly reddened sub-mm sources at high redshifts (Lilly, this volume) 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 $f_{\text{esc}} < 1$) would contribute in any significant manner to the ionizing metagalactic flux.

3.3. 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 I, He I, and He II 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. The filling factor of H I regions in the universe, $Q_{\text{HI}}$, is 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, $\int_0^t \tilde{n}_{\text{ion}}(t')dt'/\tilde{n}_H(t')$, minus the rate of radiative recombinations, $\int_0^t Q_{\text{HI}}(t')dt'/\tilde{r}_{\text{rec}}(t')$ (Madau et
al. 1998b). Differentiating one gets

$$\frac{dQ_{\text{HI}}}{dt} = \frac{\dot{n}_{\text{ion}}}{\bar{n}_H} - \frac{Q_{\text{HI}}}{t_{\text{rec}}}.$$  \hfill (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. Here $\dot{n}_{\text{ion}}$ is the emission rate of ionizing photons per unit proper volume, $\bar{n}_H$ is the mean hydrogen density of the expanding IGM, $\bar{n}_H(0) = 1.7 \times 10^{-7} (\Omega_b h^2_{50}/0.08)$ cm$^{-3}$, 

$$t_{\text{rec}} = \left[ (1+2\chi)\bar{n}_H\alpha_B C \right]^{-1} = 0.3 \text{ Gyr} \left( \frac{1+z}{4} \right)^{-3} C^{\text{vol-1}}_{30} \text{ Mpc}^{-1}.$$  \hfill (6)

is the volume-averaged gas recombination timescale, $\alpha_B$ 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 Gnedin & Ostriker (1997), 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.

For an IGM with $C \gg 1$, and in the case $\dot{n}_{\text{ion}}$ and $C$ do not vary rapidly over a timescale $t_{\text{rec}}$, one can expand around $t$ to find

$$Q_{\text{HI}}(t) \approx \frac{\dot{n}_{\text{ion}}}{\bar{n}_H} t_{\text{rec}}.$$  \hfill (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 $t_{\text{rec}}/t$ (~ 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 $Q_{\text{HI}} = 1$, i.e. when

$$\frac{\dot{n}_{\text{ion}}}{\bar{n}_H} t_{\text{rec}} = \bar{n}_H.$$  \hfill (8)

4. A POPULATION OF EARLY DWARFS

As $t_{\text{rec}} \ll t$ 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, $\dot{N}_c$, 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 $\dot{N}_c$ to the estimated contribution from QSOs and star-forming galaxies. Equation (8) can then be rewritten as

$$\dot{N}_c = \frac{\bar{n}_H(0)}{t_{\text{rec}}(z)} = \left( 10^{51.2} \text{ s}^{-1} \text{ Mpc}^{-3} \right) C_{30} \left( \frac{1+z}{6} \right)^3.$$  \hfill (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) and the nucleosynthesis constrained baryon density. A quick exploration of the available parameter space indicates that the uncertainty on $\dot{N}_c$ 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 5. While $\dot{N}_c$ 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 (Leitherer et al. 1995). 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 expected in the HDF down to $I_{AB} = 27.2$. At $z > 5$, they would appear very red in $V-I$ as the Ly$\alpha$ 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 $\dot{N}_c$ into a “minimum” star formation rate per unit (comoving) volume, $\dot{\rho}_s$:

$$\dot{\rho}_s(z) = \dot{N}_c(z) \times 10^{-5.1} f_{\text{esc}}^{-1}$$

$$\approx 0.013 f_{\text{esc}}^{-1} (\frac{1+z}{6})^3 M_\odot \text{yr}^{-1} \text{Mpc}^{-3}$$

(Salpeter IMF with solar metallicity), comparable with the value directly “observed” (i.e., uncorrected for dust reddening) at $z \approx 3$ (Dickinson 1998). The same massive stars that dominate the Lyman continuum flux also manufacture and return most of the metals, $Z$, 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 (11),

$$\rho_2(z) = y(1-R) \dot{\rho}_s(z) \gtrsim 3.5 \times 10^{-4}$$

$$\times \left(\frac{y}{2Z_\odot}\right) (\frac{1+z}{6})^3 f_{\text{esc}}^{-1} M_\odot \text{yr}^{-1} \text{Mpc}^{-3}$$

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

$$\langle Z \rangle \approx \frac{8\pi G \rho_2(5) \Delta t}{3H_0^2\Omega_b} \gtrsim 0.002 \left(\frac{y}{2Z_\odot}\right) f_{\text{esc}}^{-1} Z_\odot$$

comparable with the level of enrichment observed in the Ly$\alpha$ forest at $z \approx 3$ (Songaila 1997): more than 2% of the present-day stars would need to have formed by $z \approx 5$. It has been recently suggested (Miralda-Escudé & Rees 1998) that a large number of low-mass galactic halos, expected to form at early times in hierarchical clustering models, might be responsible for photoionizing the IGM at these epochs. According to spherically-symmetric simulations (Thoul et al. 1996), 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 $\lesssim 35$ km s$^{-1}$. Halos with circular speed $v_{\text{circ}} = 50$ km s$^{-1}$, corresponding in top-hat spherical collapse to a virial temperature $T_{\text{vir}} = 0.5 \mu m_p c^2 / k \approx 10^8$ K and halo mass $M = 0.1 v_{\text{circ}}^3 / G H \approx 4 \times 10^9 [(1+z)/6]^{-3/2} h^{-1} M_\odot$, appear instead largely immune to this external feedback (but see Navarro & Steinmetz 1997). In these systems rapid cooling by atomic hydrogen can then take place and a significant fraction, $f_{\text{esc}}$, 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 $f_{\text{esc}} M/\Delta t \sim 0.3 f_0 \Delta t_{\text{esc}} M_\odot \text{yr}^{-1}$ were actually responsible for keeping the universe ionized at $z \sim 5$, their comoving space density would have to be

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

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 Lyman-break objects at $z \approx 3$ with $M < M_{AB} (1500)$, i.e., with star formation rates in excess of $10 M_\odot \text{yr}^{-1}$. Only a rather steep luminosity function, with Schechter slope $\alpha \approx 2$, 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 dropout sources observed in the HDF. The number density on the sky would be $\approx 0.2$ 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 are too faint to be detected by the HST, but within the range of the proposed NGST. 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, $(f_{\text{esc}}) < 1$. In this case the dwarfs could still be detectable if a small fraction of the gas turned into stars in very short bursts.

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