After the dark ages: the evolution of luminous sources at $z < 5$

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Abstract

I review recent observational and theoretical progress in our understanding of the cosmic evolution of luminous sources. Through a combination of deep \textit{HST} imaging, Keck spectroscopy, and \textit{COBE} background measurements, important constraints have emerged on the emission history of the galaxy population as a whole. A simple stellar evolution model, defined by a star-formation density that rises from $z = 0$ to $z \approx 1.5$, a universal Salpeter IMF, and a moderate amount of dust with $A_V = 0.23$ mag ($A_{1500} = 1.2$ mag), is able to account for most of the optical-FIR extragalactic background light, and reproduces the global ultraviolet, optical, and near-IR photometric properties of the universe. By contrast, a star-formation density that stayed roughly constant at all epochs appears to overproduce the local $K$-band luminosity density. While the bulk of the stars present today formed relatively recently, the existence of a decline in the star-formation density above $z \approx 2$ remains uncertain. If stellar sources are responsible for photoionizing the intergalactic medium at $z \approx 5$, the rate of star formation at this epoch must be comparable or greater than the one inferred from optical observations of galaxies at $z \approx 3$. A population of dusty AGNs at $z \sim < 2$ could make a significant contribution to the FIR background if the accretion efficiency is $\sim 10\%$.

1 Introduction

In the last few years, the remarkable progress in our understanding of faint galaxy data made possible by the combination of HST deep imaging \cite{58} and ground-based spectroscopy \cite{31}, \cite{11}, \cite{52} has permitted to shed some light on the evolution of the stellar birthrate in the universe, to tentatively 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 evolution scenarios \cite{35}, \cite{53}, \cite{2}, \cite{19}. The explosion in the quantity of information available on the high-redshift universe at optical wavelengths has been complemented by the detection of the far-IR/sub-mm background by DIRBE and FIRAS \cite{24}, \cite{12}, that has revealed the optically ‘hidden’ side of galaxy formation, and shown that a significant fraction of the energy released by stellar nucleosynthesis is re-emitted as thermal radiation by dust. The underlying goal of all these efforts is to understand the growth of cosmic structures and the mechanisms that shaped the Hubble sequence, and ultimately to map the transition from the cosmic ‘dark age’ \cite{15} to a ionized universe populated with luminous sources. While one of the important questions recently emerged is the
nature (starbursts or AGNs?) and redshift distribution of the ultraluminous sub-mm sources discovered by SCUBA [27], [4], [32], of perhaps equal interest is the possible 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 and bluest star-forming objects. In hierarchical clustering cosmogonies, high-z dwarfs and/or mini-quasars (i.e. an early generation of stars and accreting black holes in dark matter halos with circular velocities $v_c \sim 50$ km s$^{-1}$) may actually be one of the main source of UV photons and heavy elements at early epochs [38], [21], [22]. In this talk I will focus on some of the open issues and controversies surrounding our present understanding of the history of the conversion of cold gas into stars within galaxies, and of the evolution with cosmic time of the space density of luminous sources. An Einstein-de Sitter universe ($q_0 = 0.5$) with $H_0 = 50h_{50}$ km s$^{-1}$ Mpc$^{-1}$ will be adopted in the following.

2 Extragalactic background light

The extragalactic background light (EBL) is an indicator of the total luminosity of the universe. It provides unique information on the evolution of cosmic structures at all epochs, as the cumulative emission from galactic systems and AGNs is expected to be recorded in this background. Figure 1 shows the optical EBL from known galaxies together with the recent COBE results. The value derived by integrating the galaxy counts [14] down to very faint magnitude levels [because of the flattening at faint magnitudes of the $N(m)$ differential counts most of the contribution to the optical EBL comes from relatively bright galaxies] implies a lower limit to the EBL intensity in the 0.3–2.2 $\mu$m interval of $I_{opt} \approx 12$ nW m$^{-2}$ sr$^{-1}$. When combined with the FIRAS and DIRBE measurements ($I_{FIR} \approx 16$ nW m$^{-2}$ sr$^{-1}$ in the 125–5000
Figure 2: Left: Mean comoving density of star formation as a function of cosmic time. The data points with error bars have been inferred from the UV-continuum luminosity densities of [31] (filled dots), [7] (filled squares), [35] (filled pentagons), [56] (empty dot), and [54] (empty square). The dotted line shows the fiducial rate, ⟨\dot{\rho}_*⟩ = 0.054 M⊙ yr⁻¹ Mpc⁻³, required to generate the observed EBL. Right: dust corrected values (A_{1500} = 1.2 mag, SMC-type dust in a foreground screen). The Hα determinations of [15], [55], and [17] (filled triangles), together with the SCUBA lower limit [27] (empty pentagon) have been added for comparison.

μm range), this gives an observed EBL intensity in excess of 28 nW m⁻² sr⁻¹. The correction factor needed to account for the residual emission in the 2.2 to 125 μm region is probably ≲ 2. We shall see below how a population of dusty AGNs could make a significant contribution to the FIR background. In this talk I shall adopt a conservative reference value for the total EBL intensity associated with star formation activity over the entire history of the universe of I_{EBL} = 40 I_{40} nW m⁻² sr⁻¹.

3 Star formation history

It has become familiar to interpret recent observations of high-redshift sources via the comoving volume-averaged history of star formation. This is the mean over cosmic time of the stochastic, possibly short-lived star formation episodes of individual galaxies, and follows a relatively simple dependence on redshift. Its latest version, uncorrected for dust extinction, is plotted in Figure 2 (left panel). The measurements are based upon the rest-frame UV luminosity function (at 1500 and 2800 Å), assumed to be from young stellar populations [33]. The prescription for a ‘correct’ de-reddening of these values has been the subject of an ongoing debate. Dust may play a role in obscuring the UV continuum of Canada-France Reshift Survey (CFRS, 0.3 < z < 1) and Lyman-break (z ≈ 3) galaxies, as their colors are too red to be fit with an evolving stellar population and a Salpeter initial mass function (IMF) [35]. The fiducial model of [35] had an upward correction factor of 1.4 at 2800 Å, and 2.1 at 1500 Å. Much larger corrections have been argued for by [16] (×10 at z = 1), [37] (×15 at z = 3), and [17] (×16 at z > 2). As noted already by [33] and [35], a consequence of such large extinction values is the possible overproduction of metals and red light at low redshifts. Most recently, the evidence for more moderate extinction corrections has included measurements of star-formation rates (SFR) from Balmer lines by [37] (×2 at z = 0.2), [17] (×3.1 ± 0.4 at z = 1), and [12] (×2−6 at z = 3). ISO follow-up of CFRS fields [13] has shown that the star-formation density derived by FIR fluxes
(×2.3 ± 0.7 at 0 ≤ z ≤ 1) is about 3.5 times lower than in \[49\]. Figure 2 (right panel) depicts an extinction-corrected (with $A_{1500} = 1.2$ mag, 0.4 mag higher than in \[35\]) version of the same plot. The best-fit cosmic star formation history (shown by the dashed-line) produces a total EBL of 37 nW m$^{-2}$ sr$^{-1}$. About 60% of this is radiated in the UV+optical+near-IR between 0.1 and 5 μm; the total amount of starlight that is absorbed by dust and reprocessed in the far-IR is 13 nW m$^{-2}$ sr$^{-1}$. Because of the uncertainties associated with the incompleteness of the data sets, photometric redshift technique, dust reddening, and UV-to-SFR conversion, these numbers are only meant to be indicative. On the other hand, the model is not in obvious disagreement with any of the observations, and is able, in particular, to provide a reasonable estimate of the near-IR luminosity density in the range 0 ≲ z ≲ 1 (Fig. 3).

4 The stellar mass density today

With the help of some simple stellar population synthesis tools it is possible at this stage to make an estimate of the integrated stellar mass density today. The total bolometric luminosity of a simple stellar population (a single generation of coeval stars) having mass $M$ can be well approximated by a power-law with time for all ages $t > 100$ Myr,

$$L(t) = 1.3 L_\odot \frac{M}{M_\odot} \left( \frac{t}{1 \text{ Gyr}} \right)^{-0.8}$$  \hspace{1cm} (1)

(cf. \[3\]), where we have assumed solar metallicty and a Salpeter IMF truncated at 0.1 and 125 $M_\odot$. In a stellar system with arbitrary star-formation rate per unit cosmological volume, $\dot{\rho}_*$, the comoving bolometric emissivity at time $t$ is given by the convolution integral

$$\rho_{\text{bol}}(t) = \int_0^t L(\tau) \dot{\rho}_*(t-\tau) d\tau.$$  \hspace{1cm} (2)

The total background light observed at Earth ($t = t_H$) is

$$I_{\text{EBL}} = \frac{c}{4\pi} \int_0^{t_H} \frac{\rho_{\text{bol}}(t)}{1 + z} dt,$$  \hspace{1cm} (3)

where the factor $(1 + z)$ at the denominator is lost to cosmic expansion when converting from observed to radiated luminosity density. From the above equations it is easy to derive

$$I_{\text{EBL}} = 740 \text{ nW m}^{-2} \text{ sr}^{-1} \langle \frac{\dot{\rho}_*}{M_\odot \text{ yr}^{-1} \text{ Mpc}^{-3}} \rangle \left( \frac{t_H}{13 \text{ Gyr}} \right)^{1.87}.$$  \hspace{1cm} (4)

The observations shown in Figure 1 therefore imply a “fiducial” mean star formation density of $\langle \dot{\rho}_* \rangle = 0.054 I_{40} M_\odot \text{ yr}^{-1} \text{ Mpc}^{-3}$. In the instantaneous recycling approximation, the total stellar mass density observed today is

$$\rho_*(t_H) = (1 - R) \int_0^{t_H} \dot{\rho}_*(t) dt \approx 5 \times 10^8 I_{40} M_\odot \text{ Mpc}^{-3},$$  \hspace{1cm} (5)

(corresponding to $\Omega_\ast = 0.007 I_{40}$) where $R$ is the mass fraction of a generation of stars that is returned to the interstellar medium, $R \approx 0.3$ for a Salpeter IMF. The optical/CeBE background therefore requires that about 10% of the nucleosynthetic baryons ($\Omega_b h_{50} = 0.08$ \[4\]) are in the forms of stars and their remnants. The predicted stellar mass-to-blue light ratio is $\langle M/L_B \rangle \approx 5$. Note that these values are quite sensitive to the lower-mass cutoff of the IMF, as very-low mass stars can contribute significantly to the mass but not to the integrated light of the whole stellar population. A lower cutoff of 0.5 $M_\odot$ instead of the 0.1 $M_\odot$ adopted would decrease the mass-to-light ratio (and $\Omega_\ast$) by a factor of 1.9 for a Salpeter function.
Figure 3: Left: Evolution of the near-IR luminosity density at rest-frame wavelengths of 1.0 µm (long-dashed line) and 2.2 µm (short-dashed line). The data points are taken from [31] (filled dots) and [16] (filled square). The model assumes a constant star-formation rate of $\dot{\rho}_* = 0.054 \, M_\odot \, yr^{-1} \, Mpc^{-3}$ (Salpeter IMF). Right: Same but with the star-formation history depicted in the right panel of Fig. 2.

5 A constant star-formation density?

Based on the agreement between the $z \approx 3$ and $z \approx 4$ luminosity functions at the bright end, it has been recently argued by [37] that the decline in the luminosity density of faint HDF Lyman-break galaxies observed in the same redshift interval [33] may not be real, but simply due to sample variance in the HDF. When extinction corrections are applied, the emissivity per unit comoving volume due to star formation may then remain essentially flat for all redshift $z \gtrsim 1$ (see Fig. 2). While this has obvious implications for hierarchical models of structure formation, the epoch of first light, and the reionization of the intergalactic medium (IGM), it is also interesting to speculate on the possibility of a constant star-formation density at all epochs $0 \leq z \leq 5$, as recently advocated by [41]. Figure 3 (left panel) shows the time evolution of the near-IR rest-frame luminosity density of a stellar population characterized by a Salpeter IMF, solar metallicity, and a (constant) star-formation rate of $\dot{\rho}_* = 0.054 \, M_\odot \, yr^{-1} \, Mpc^{-3}$ (needed to produce the observed EBL). The predicted evolution appears to be a poor match to the observations: it overpredicts the local $K$-band luminosity density [16] and undepredicts the 1 µm emissivity at $z \approx 1$ from the CFRS survey [31].

6 A population of hidden AGNs?

Recent dynamical evidence indicates that supermassive black holes reside at the center of most nearby galaxies. The available data (about 30 objects) show a strong correlation (but with a large scatter) between bulge and black hole mass [38], with $M_{bh} = 0.006 \, M_{\text{bulge}}$ as a best-fit. The total mass density in spheroids today is $\Omega_{\text{bulge}} = 0.0036^{+0.0024}_{-0.0017}$ [14], implying a mean mass

1The near-IR light is dominated by near-solar mass evolved stars, the progenitors of which make up the bulk of a galaxy’s stellar mass, and is sensitive to the past star-formation history.
density of dead quasars
\[ \rho_{bh} = 1.34^{+0.9}_{-0.6} \times 10^6 \text{ M}_\odot \text{ Mpc}^{-3}. \] (6)

Noting that the observed energy density from all quasars is equal to the emitted energy divided by the average quasar redshift \[ [53] \], the total contribution to the EBL from accretion onto black holes is
\[ I_{bh} = \frac{c^3}{4\pi} \frac{\eta \rho_{bh}}{\langle 1 + z \rangle} \approx 18 \text{ nW m}^{-2} \text{ sr}^{-1} \eta_{0.1} \langle 1 + z \rangle^{-1}, \] (7)

where \( \eta_{0.1} \) is the efficiency for transforming accreted rest-mass energy into radiation (in units of 10\%). A population of AGNs at (say) \( z \sim 1 \) could then make a significant contribution to the FIR background if dust-obscured accretion onto supermassive black holes is an efficient process \[ [20] \].

7 Reionization of the IGM

The history of the transition from a neutral universe to one that is almost fully ionized can reveal the character of cosmological ionizing sources and constrain the star formation activity at high redshifts. 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 \[ [8] \] and of hierarchical models of gravitational instability with “cold dark matter” (CDM) \[ [1] [26] \]. 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 \( z \approx 5 \) \[ [49] \], and the helium component by \( z \approx 2.5 \) \[ [4] \]. 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 \[ [29] \]. It thus appears that substantial sources of ultraviolet photons were present at \( z \gtrsim 5 \), perhaps low-luminosity quasars \[ [22] \] or a first generation of stars in virialized dark matter halos with \( T_{\text{vir}} \sim 10^4 - 10^5 \text{ K} \) \[ [10] [21] [38] \]. The existence of a decline in the space density of bright quasars at redshifts beyond \( z \sim 3 \) was first suggested by \[ [39] \], 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 \[ [23] [57] [48] [28] \]. 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. Radio emission, on the other hand, is unaffected by dust, and it has recently been shown \[ [50] \] that the space density of radio-loud quasars also decreases strongly for \( z > 3 \). This argues that the turnover is indeed real and that dust along the line of sight has a minimal effect on optically-selected QSOs (Figure 4, left panel). The QSO emission rate of hydrogen ionizing photons per unit comoving volume is shown in Figure 4 (right panel) \[ [14] \]. 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 \[ [13] \], 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 \( M_\lambda \approx -25.4 \), 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 quasar emissivity is therefore produced by sources that have not been actually observed, and are assumed to be present based on an extrapolation from lower redshifts.

Galaxies with ongoing star-formation are another obvious source of Lyman continuum photons. Since the rest-frame UV continuum at 1500 Å (redshifted into the visible band for a
Figure 4: *Left:* comoving space density of bright QSOs as a function of redshift. The data points with error bars are taken from [23] (filled dots), [57] (filled squares), [48] (crosses), and [28] (filled pentagon). The empty triangles show the space density of the Parkes flat-spectrum radio-loud quasars with $P > 7.2 \times 10^{26}$ W Hz$^{-1}$ sr$^{-1}$ [25]. *Right:* 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 gas clumping factor $C = 30$) Einstein–de Sitter universe with $\Omega_b h^2_0 = 0.08$. Models based on photoionization by quasar sources appear to fall short at $z = 5$. The data point shows the estimated contribution of star-forming galaxies at $z \approx 3$, assuming that the fraction of Lyman continuum photons which escapes the galaxy H i layers into the intergalactic medium is $f_{\text{esc}} = 0.5$ (see [34] for details).
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 of the galaxy history for $t > 10^7$ yr. Figure 4 shows the estimated Lyman-continuum luminosity density of galaxies at $z \approx 3$. The data point assumes 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. A substantial population of dwarf galaxies below the detection threshold, and has been recently proposed by [38] and [34] as a possible candidate for photoionizing the IGM at these epochs. One should note that, while 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.

As the hydrogen mean recombination timescale, $\bar{t}_{\text{rec}}$, at high redshifts is much smaller than the then Hubble time [34], it is possible to compute at any given epoch a critical value for the photon emission rate per unit cosmological comoving volume,

$$\dot{N}_{\text{ion}}(z) = \frac{\bar{n}_H(0)}{\bar{t}_{\text{rec}}(z)} = (10^{51.2} \text{ s}^{-1} \text{ Mpc}^{-3}) C_{30} \left(\frac{1 + z}{6}\right)^3 \left(\frac{\Omega_b h^2_{50}}{0.08}\right)^2,$$

(8)

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. Here $\bar{n}_H(0)$ is the mean hydrogen density of the expanding IGM at the present epoch, and $C$ is the ionized hydrogen clumping factor. One can then compare our determinations of $\dot{N}_{\text{ion}}$ to the estimated contribution from QSOs and star-forming galaxies. The uncertainty on this critical rate is difficult to estimate, as it depends on the clumpiness of the IGM (scaled in the expression above to the value inferred at $z = 5$ from numerical simulations [18]) and the nucleosynthesis constrained baryon density. The evolution of the critical rate as a function of redshift is plotted in Figure 4. While $\dot{N}_{\text{ion}}$ is comparable to the quasar contribution at $z \gtrsim 3$, there is some indication of a 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 [30].

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 $z \gtrsim 5$, 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 $\dot{N}_{\text{ion}}$ into a “minimum” SFR per unit (comoving) volume, $\dot{\rho}_* (hereafter we assume $\Omega_b h^2_{50} = 0.08$ and $C = 30$):

$$\dot{\rho}_*(z) = \dot{N}_{\text{ion}}(z) \times 10^{-53.1} f_{\text{esc}}^{-1} \approx 0.013 f_{\text{esc}}^{-1} \left(\frac{1 + z}{6}\right)^3 \text{ M}_\odot \text{ yr}^{-1} \text{ Mpc}^{-3},$$

(9)

$^2$At all ages $\gtrsim 0.1$ Gyr one has $L(1500)/L(912) \approx 6$ for a Salpeter mass function and constant SFR [8]. This number neglects any correction for intrinsic H I absorption.

$^3$Note that, at $z = 3$, Lyman-break galaxies would radiate more ionizing photons than QSOs for $f_{\text{esc}} \gtrsim 30\%$. The hydrogen mean recombination timescale, $\bar{t}_{\text{rec}}$, at high redshifts is much smaller than the then Hubble time [34], it is possible to compute at any given epoch a critical value for the photon emission rate per unit cosmological comoving volume,

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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. Here $\bar{n}_H(0)$ is the mean hydrogen density of the expanding IGM at the present epoch, and $C$ is the ionized hydrogen clumping factor. One can then compare our determinations of $\dot{N}_{\text{ion}}$ to the estimated contribution from QSOs and star-forming galaxies. The uncertainty on this critical rate is difficult to estimate, as it depends on the clumpiness of the IGM (scaled in the expression above to the value inferred at $z = 5$ from numerical simulations [18]) and the nucleosynthesis constrained baryon density. The evolution of the critical rate as a function of redshift is plotted in Figure 4. While $\dot{N}_{\text{ion}}$ is comparable to the quasar contribution at $z \gtrsim 3$, there is some indication of a 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 [30]. 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 $z \gtrsim 5$, 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.

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(The conversion factor assumes a Salpeter IMF with solar metallicity). The star-formation density given in equation (3) is comparable with the value directly “observed” (i.e., uncorrected for dust reddening) at $z \approx 3$.

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