Did Globular Clusters Reionize the Universe?

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ABSTRACT

A problem still unsolved in cosmology is the identification of the sources of radiation able to reionize H\text{I} in the intergalactic medium (IGM) by $z \sim 6$. Theoretical works and observations seem to indicate that the fraction, $\langle f_{\text{esc}} \rangle$, of H\text{I} ionizing radiation emitted from galaxies that escapes into the IGM is small in the local universe ($\langle f_{\text{esc}} \rangle \lesssim 10\%$). At high redshift galaxies are more compact and probably gas rich implying smaller values of $\langle f_{\text{esc}} \rangle$ from their disks or spheroids. But if the sites of star formation are displaced from the disk or spheroid and the star formation efficiency of the protoclusters is high, then $\langle f_{\text{esc}} \rangle$ should be about one. This star formation scenario is consistent with several models for globular clusters formation. Using simple arguments based on the observed number of globular cluster systems in the local universe and assuming that the oldest globular clusters formed before reionization and had $\langle f_{\text{esc}} \rangle \sim 1$, I show that they produced enough ionizing photons to reionize the IGM at $z \approx 6$.

Key words: Globular clusters: general – Galaxies: formation – Cosmology: theory

1 INTRODUCTION AND RATIONALE

Observation of Ly\text{a} absorption systems toward newly found high-redshift quasars [Becker et al. 2001; Djorgovski et al. 2002] indicate that the redshift of reionization of the intergalactic medium (IGM) should be close to $z = 6$ (Gnedin et al. 2002; Songaila & Cowie 2002). Perhaps the recent identification of a lensed galaxy at $z = 6.56$ points to a somewhat earlier redshift of reionization [Hu et al. 2002]. Although quasars play a dominant role in photoionizing the IGM at $z \approx 3$ (Meiksin & Madau 1993), their dwindling numbers at $z > 4$ suggest the need for another ionization source. Unless a hidden population of quasars is found, radiation emitted by high-redshift massive stars seems necessary to reionize the universe. A key ingredient in determining the effectiveness by which galaxies photoionize the surrounding IGM is the parameter $\langle f_{\text{esc}} \rangle$, defined here as the mean fraction of Ly\text{a} photons escaping from galaxy halos into the IGM. To be an important source of ionizing photons and rival with quasars, a substantial fraction ($\sim 10\%$) of them must escape the gas layers of the galaxies (Madau & Shull 1996).

Cosmological simulations and semi-analytical models of IGM reionization by stellar sources find that the ionizing background rises steeply at the redshift of reionization. Unfortunately a direct comparison between models is difficult because of different recipes used for star formation, clumping of the IGM or the definition of $\langle f_{\text{esc}} \rangle$. But a result common to all the models is that, in order to reionize the IGM by $z = 6 - 7$, the escape fraction must be relatively large: $\langle f_{\text{esc}} \rangle \gtrsim 10\%$ assuming a Salpeter initial mass function (IMF) and the standard ΛCDM cosmological model. Benson et al. (2002) finds that $\langle f_{\text{esc}} \rangle$ should be about 15\% for reionization at $z = 6$, but a smaller value $\langle f_{\text{esc}} \rangle \lesssim 10\%$ is consistent with the observed ionizing background at $z \sim 3$. Gnedin (2002) finds that assuming a primordial power spectrum index $n = 0.93$, the preferred value from CMB and LSS data, reionization at $z \gtrsim 6$ requires a large $\langle f_{\text{esc}} \rangle$; but this assumption produces an ionizing background at $z \lesssim 4$, that is too large. The common assumption of a universal star formation efficiency (SFE) (e.g., the coefficient in front of the Schmidt-Law in some models or in others the fraction $f_\star$ of baryons converted into stars) is consistent with the observed values of the star formation rate (SFR) at $0 < z < 5$ and total star fraction $\Omega_\star$ at $z = 0$. However, the assumption of a constant $\langle f_{\text{esc}} \rangle$ does not seem to be consistent with observations. An escape fraction $\langle f_{\text{esc}} \rangle \sim 1$ is required for reionization at $z \sim 6$ but the ionizing background at $z \sim 3$ is consistent with $\langle f_{\text{esc}} \rangle \lesssim 10\%$ (Bianchi et al. 2001). Small values of $\langle f_{\text{esc}} \rangle$ at $z \lesssim 3$ are also supported by direct observations of the Ly\text{c} emission from Lyman-break and starburst galaxies. Giallongo et al. (2002) find an upper limit $\langle f_{\text{esc}} \rangle < 16\%$ at $z \sim 3$ (but see Steidel et al. 2001) and observations of low-redshift starbursts are consistent with $\langle f_{\text{esc}} \rangle$ upper limits ranging from a few percent up to 10\% (Hurwitz et al. 1997; Deharveng et al. 2001).

Calculations of $\langle f_{\text{esc}} \rangle$ from first principles are difficult. The main complications arise in simulating a realistic interstellar medium (ISM) that includes small-scale physics

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and feedback processes. Moreover the mean \( \langle f_{\text{esc}} \rangle \) results from the contribution of a variety of galaxies whose ISM properties are largely unknown at high redshift. Theoretical models (Dove et al. 2000; Ciardi et al. 2002) for the radiative transfer of ionizing radiation through the disk layer of spiral galaxies similar to the Milky Way find \( \langle f_{\text{esc}} \rangle \sim 6 - 10\% \). At high redshift the mean value of \( f_{\text{esc}} \) is expected to decrease almost exponentially with increasing redshift (Ricotti & Shull 2000; Wood & Loeb 2000); at \( z > 6 \), \( \langle f_{\text{esc}} \rangle \lesssim 0.1 - 1\% \) even assuming star formation rates typical of starburst galaxies (e.g., SFR\sim 10 times that of the Milky Way). Using Monte-Carlo simulations, Ricotti & Shull (2000) have studied how \( f_{\text{esc}} \) depends on galactic parameters. Assuming gas density profile in hydrostatic equilibrium in the dark matter (DM) potential, star density proportional to the gas density and a power law for the luminosity function of the OB associations, they found that \( \langle f_{\text{esc}} \rangle \propto (\epsilon f_{\text{DM}})^{-1/3} \exp[-(z_{\text{vir}} + 1)\epsilon^{-1/3}] \). Here \( \epsilon \) is proportional to the SFE, \( f_{\text{DM}} \) is the fraction of collapsed gas, \( z_{\text{vir}} \) is the virialization redshift and \( M_{\text{DM}} \) is the DM halo mass. The majority of photons that escape the halo come from the most luminous OB associations located in the outermost parts of the galaxy. Indeed Ricotti & Shull (2000) have shown that changing the luminosity function of the OB association and the density distribution of the stars has major effects on \( \langle f_{\text{esc}} \rangle \) (see their Figs. 8 and 9). In the aforementioned models, \( \langle f_{\text{esc}} \rangle \) should be regarded as an upper limit since dust extinction and absorption of ionizing radiation from the molecular cloud in which OB associations are born are neglected.

The theoretical suggestion of a decreasing \( \langle f_{\text{esc}} \rangle \) with increasing redshift is in contrast with models for reionization. The theoretical suggestion of a decreasing \( \langle f_{\text{esc}} \rangle \) with increasing redshift is in contrast with models for reionization. To account for dynamical disruption of GCs

### 2 SHORT REVIEW ON GC SYSTEMS

In this section I review some observational and theoretical results on GCs useful to the aim of this paper. I also try to justify my assumption \( \langle f_{\text{esc}} \rangle \sim 1 \) for GCs on the base of theoretical models of proto-GC formation.

#### 2.1 Observations

Most galaxies have a bimodal GCs distribution indicating that luminous galaxies experience at least two major episodes of GCs formation. The bulk of the globulars in the main body of the Galactic halo appear to have formed during a short-lived burst (\( \sim 0.5 \) – 2 Gyr) that took place about 13 Gyrs ago. This was followed by a second burst associated with the formation of the galactic bulges. Clusters may have been formed in dwarf spheroidal galaxies and accreted by the Galactic halo (van den Bergh 1999). Massive cluster formation occurred in galaxies as small as the Fornax dwarf spheroidal but not in massive ones such as the small magellanic cloud (Zepf et al. 1999).

##### 2.1.1 Absolute and relative ages

The method for determining the absolute age of GCs is based on fitting the observed color-magnitude diagram with theoretical evolutionary tracks. The systematics in the evolutionary model and the determination of the cluster distance are the major sources of errors. Recent determinations of the absolute age of old GCs find \( f_{\text{gc}} = 12.5 \pm 1.2 \) Gyr (Chaboyer et al. 1998), consistent with radioactive dating of a very metal-poor star in the halo of our galaxy (Cayrel et al. 2000). Relative ages of Galactic GCs can be determined with greater accuracy, since many systematic errors can be eliminated. In our Galaxy \( \Delta t_{\text{gc}} = 0.5 \) Gyr, but differences in age between GC systems in different galaxies could be \( \Delta t_{\text{gc}} \sim 2 \) Gyr (Stetson et al. 1994).

##### 2.1.2 Specific frequency

The specific frequency is defined as the number, \( N \), of GCs per \( M_{\odot} \) of parent galaxy light, \( S_N = N \times 10^{4.4(M_V + 15)} \) (Harris & van den Bergh 1981). The most striking characteristic is that \( S_N \text{(Ellipticals)} > S_N \text{(Spirals)} \). \( S_N = 0.5 \) in Sc/Ir galaxies (Harris, 1991), \( S_N = 1 \) in spirals of types Sa/Sb, \( S_N = 2.5 \) in field ellipticals (Kundu & Whitmore 2001a). Converting to luminosity \( (L/\odot) = 10^{4.4(M_V + 15)} \) we have \( N = (L/\odot)S_N/8.55 \times 10^5 \). I can therefore calculate the efficiency of GC formation defined as,

\[
\epsilon_{\text{gc}} = \frac{M_{\text{gc}}}{M} = \frac{f_{\text{di}}N_{\text{mgc}}}{M} = \frac{SN_{\text{di}}}{(M/L)_V} \times 0.00585, \tag{1}
\]

where \( M_{\text{gc}} \) is the total mass of the GC system, \( m_{\text{gc}} = 5 \times 10^5 \) M\(_{\odot} \) is the mean mass of GCs today, \( M \) is the stellar mass and \((M/L)_V \) is the mass to light ratio of the galaxy. In the next paragraph we show that, because of dynamical evolution, \( m_{\text{gc}} \), and \( N \) are expected to be larger at the time of GC formation than today. Therefore, the parameter \( f_{\text{di}} \geq 1 \) is introduced to account for dynamical disruption of GCs during their lifetime.

##### 2.1.3 IMF, Metallicity and Dynamical Evolution

The IMF of GCs is not known. The present mass function is known only between 0.2 and 0.8 M\(_{\odot} \) since high-mass stars are lost because of two-body relaxation and stellar evolution processes. Theoretical models show that the shape is consistent with a Salpeter-like IMF. The mean metallicity of old GCs is \( Z \sim 0.03 Z_{\odot} \). One of the most remarkable
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properties of GCs is the uniformity of their internal metallicity \( \Delta [Fe/H] \lesssim 0.1 \). This implies that the bulk of the stars that constitute a GC formed in a single monolithic burst of star formation. A typical GC emits \( S \approx 3 \times 10^{53} \text{ s}^{-1} \) ionizing photons in a burst lasting 4 Myrs: about 300 times the ionizing luminosity of largest OB associations in our Galaxy.

During their lifetime GCs lose a large part of their initial mass or are completely destroyed by internal and external processes. Prominent internal processes are mass loss by stellar evolution (about half of the initial mass is lost) and two-body relaxation, the effects of which are mass segregation (change in the mass function) and core collapse (expansion and evaporation). External processes can be divided roughly into two classes: gravitational shocks from GC motion through the disk or bulge of the galaxy, and tidal forces, which cause mass loss due to tidal truncation. Numerical simulations show that about 50%–90% of the mass of GCs is lost due to external processes, depending on the host galaxy environment, initial concentration and IMF of the proto-GCs (Chernoff & Weinberg 1999; Gnedin & Ostriker 2001). Many of the low-metallicity halo field stars in the Milky-Way could be debris of disrupted GCs. The mass in stars in the halo is about 100 times the mass in GCs. Therefore the parameter \( f_{\text{esc}} \), defined in \( \S 2.1.2 \), could be as large as \( f_{\text{esc}} = 100 \). Overall \( f_{\text{esc}} \) is not well constrained since it depends on unknown properties of the proto-GCs. According to results of N-body simulations \( f_{\text{esc}} \) should be in the range \( f_{\text{esc}} \approx 2 \times 10^{-3} \).

2.2 Why is \( f_{\text{esc}} \approx 1 \) plausible for GCs?

I discuss separately two issues: (i) the \( f_{\text{esc}} \) from the gas cloud in which the GC forms, and (ii) the \( f_{\text{esc}} \) through any surrounding gas in the galaxy.

(i) The evidence for \( f_{\text{esc}} \approx 1 \) comes from the observed properties of present-day GCs. The facts that they are compact self-gravitating systems with low and uniform metallicity points to a high efficiency of conversion of gas into stars. A longer timescale of star formation would have enriched the gas of metals and the mechanical feedback from SN explosions would have stopped further star formation. If \( f_s \approx 10\% \) of the gas is converted into stars in a single burst (with duration \(< 4 \text{ Myr} \) at the center of a spheroidal galaxy, following the simple calculations shown in Ricotti & Shull (2000) [see their eq. (18)] at \( z = 6 \) we have,

\[
f_{\text{esc}} = 1 - 0.06 \left( \frac{1 - f_s}{f_s} \right)^2 \left( 1 + \frac{z}{7} \right)^3 \approx 50\%	ag{2}
\]

(ii) The justification for \( f_{\text{esc}} \approx 1 \) is model dependent but in general there are two main arguments: a) the high efficiency of star formation \( f_s \), and b) the sites of proto-GC formation in the outermost parts of the galaxy halo.

In the “cosmological objects model” \((30 < z_f < 7)\) of Peebles & Dicke (1968) GCs form with efficiency \( f_s \approx 100\% \), implying \( f_{\text{esc}} = 1 \) (note that such a high \( f_s \) is not found in numerical simulations of first object formation [Ricotti et al. 2002]). In “hierarchical formation models” \((10 < z_f < 3)\) Larson 1993; Harris & Podrutz 1994; McLaughlin & Podrutz 1993; Gnedin et al. 2002) GCs form in the disk or spheroid of galaxies with gas mass \( M_g \approx 10^{9} - 10^{10} M_\odot \). Compact GCs survive the accretion by larger galaxies while the rest of the galaxy is tidally stripped. Assuming that \( 1 - 10 \) GCs form in a galaxy with \( M_g \approx 10^{7} - 10^{8} M_\odot \) implies \( f_s \approx 10\% \), and therefore \( f_{\text{esc}} \) is larger than in eq. (2) if proto-GCs are located off-center (e.g., if they form from cloud-cloud collisions during the galaxy assembly) or if part of the gas in the halo is collisionally ionized as a consequence of the virialization process.

In models such as the “supershell fragmentation” \((z_f < 10)\) of Taniguchi et al. (1990) or the “thermal instability” \((z_f < 7)\) of Fall & Rees (1985), \( f_{\text{esc}} \approx 1 \) since proto-GCs form in the outermost part of an already collisionally ionized halo.

In summary, since \( f_{\text{esc}} \) depends strongly on the luminosity of the OB associations and on their location, proto-GCs, being several hundred times more luminous than Galactic OB associations, should have a comparably larger \( f_{\text{esc}} \).

3 METHOD AND RESULTS

In this section I estimate the number of ionizing photons emitted per baryon per Hubble time, \( N_{ph} \), by GC formation. In §3.1 I derive \( N_{ph} \) assuming that all GCs observed at \( z = 0 \) formed in a time period \( \Delta t_{gc} \) with constant formation rate. In §3.2 I use the Press-Schechter formalism to model more realistically the formation rate of old GCs.

3.1 The simplest estimate

I start by estimating the fraction, \( \omega_{gc} \), of cosmic baryons converted into GC stars. By definition \( \omega_{gc} = \omega_{ph, gc} \), where \( \omega_{ph} \) is the fraction of baryons in stars at \( z = 0 \) and \( \epsilon_{gc} \) is the efficiency of GC formation defined in §2.1.2. In all the calculations I assume \( \Omega_b = 0.04 \). In Table 1 I summarize the star census at \( z = 0 \) according to Fukugita et al. (1998) and I derive \( \epsilon_{gc} \) using eq. (4), assuming \( f_{di} = 1 \). Using similar arguments McLaughlin (1999) finds a universal efficiency of globular cluster formation \( \epsilon_{gc} = (0.26 \pm 0.05\%) \), in agreement with the simpler estimate presented here. It follows that \( \omega_{gc} = f_{di}(2.7 \pm 1.7) \times 10^{-4} \) at \( z = 0 \).

The total number of ionizing photons per unit time emitted by GCs is \( n \omega_{ph, gc} / \Delta t_{gc} \), where \( n \) is the number of ionizing photons emitted per baryon converted into stars, and \( \omega_{ph, gc} \approx 2.1 \omega_{ph} \) takes into account the mass loss due to stellar winds and SN explosions adopting an instantaneous-burst star formation law. GCs did not recycle this lost mass since they formed in a single burst of star formation. \( \eta \) depends on the IMF and on the metallicity of the star. I calculate \( \eta \) using a Salpeter IMF and star metallicity \( Z = 0.03 Z_\odot \) (see §2.1.3) with Starburst99 code (Leitherer et al. 1999), and find \( \eta = 8967 \). The number of ionizing photons per baryon emitted in a Hubble time at \( z = 6 \) is,

\[
N_{ph} = n \omega_{ph, gc} / \Delta t_{gc} = (5.1 \pm 3.3) f_{di} / (Gyr),
\tag{3}
\]
where I have assumed ⟨f_{esc}⟩ = 1 and Hubble time at z = 6

\[ t_H = 1 \pm 0.1 \text{ Gyr}. \]

I expect \( 1 \leq f_{\text{d}} \lesssim 100 \) and \( 0.5 \lesssim \Delta_{\text{gc}} \lesssim 2 \) Gyr. A conservative estimate of \( f_{\text{d}} \gtrsim 2 \) and \( \Delta_{\text{gc}} \gtrsim 2 \) Gyr (i.e., \( 10 < z < 3 \)) implies \( f_{\text{d}}/\Delta_{\text{gc}} \gtrsim 1 \). The IGM is reionized when \( N_{\text{ph}} = C \), where \( C = (n_{\text{HI}})/\langle n_{\text{HII}} \rangle^2 \) is the ionized IGM clumping factor. According to the adopted definition of \( f_{\text{esc}} \), \( C = 1 \) for a homogeneous IGM, or \( 1 \lesssim C \lesssim 10 \) taking into account IGM density fluctuations producing the Lyα forest (Miralda-Escudé et al. 2000; Gnedin 2000). The estimate from eq. \( \text{(3)} \) is rather rough because I have implicitly assumed that the SFR is constant during the period of GC formation \( \Delta_{\text{gc}} \). A more realistic SFR as a function of redshift requires assuming a specific model for the formation of GCs. I try to address this question in the next section.

### 3.2 A bit of modeling

I assume that the formation rate of stars or GCs in galaxies is proportional to the merger rate of galaxy halos (each galaxy undergoes a major star burst episode when it virializes). Using the Press-Schechter formalism I calculate,

\[
d\omega_{\text{gc}}(z) = A \int_{M_1}^{M_*} \frac{dM}{d\ln M} \frac{d\ln M_{DM}}{dt} d\ln M_{DM},
\]

\[
d\omega_{\text{c}}(z) = B \int_{M_m}^{\infty} \frac{dM}{d\ln M} \frac{d\ln M_{DM}}{dt} d\ln M_{DM},
\]

where \( \Omega(M_{DM}, z) d\ln(M_{DM}) \) is the mass fraction in virialized DM halos of mass \( M_{DM} \) at redshift \( z \). I determine the constants \( A \) and \( B \) by integrating eqs. \( \text{(4)-(5)} \) with respect to time, and assuming \( \omega_{\text{gc}}^0 = 0.1% \) (i.e., \( f_{\text{d}} \gtrsim 2 \)) and \( \omega_c^0 = 1.4 \omega_{\text{gc}}^0 = 13% \) at \( z = 0 \) (the factor \( 1.4 \) takes into account the mass loss due to stellar winds and SN explosions adopting a continuous star formation law). I assume that GCs form in halos with masses \( M_1 < M_{DM} < M_2 \). The choice of \( M_1 \) and \( M_2 \) determine the mean redshift, \( z_f \), and time period, \( \Delta_{\text{gc}} \), for the formation of old GCs. In order to be consistent with observations I consider three cases: case (i) halos with virial temperature \( 2 \times 10^6 < T_{\text{vir}} < 5 \times 10^5 \) K; case (ii) \( 5 \times 10^5 < T_{\text{vir}} < 10^5 \) K; and case (iii) \( 10^5 < T_{\text{vir}} < 5 \times 10^5 \) K. In case (i),(ii) and (iii) \( \Delta_{\text{gc}} = 2.2, 3.7 \) and 5.2 Gyr, respectively, and the GC formation rate has a peak at \( z = 7.5, 6 \) and 4.6, respectively. Disk and spheroid stars form in halos with \( M_{DM} > M_m \). At \( z > 10 \) I assume that the first objects form in halos with \( M_{\text{d}} \) corresponding to a halo virial temperature \( T_{\text{vir}} = 5 \times 10^5 \) K. At \( z < 10 \) only objects with \( T_{\text{vir}} > 2 \times 10^5 \) K can form (see Ricotti et al. 2002b). The comoving star formation rate, given by \( \dot{\rho}_{\star} = \rho_{\star, c} \dot{\rho}_{\star, c} \), where \( \dot{\rho}_{\star, c} = 5.51 \times 10^3 \text{ M}_\odot \text{ Mpc}^{-3} \text{ yr}^{-1} \), is the mean baryon density at \( z = 0 \) is shown in Fig. 1. The points show the observed SFR from Lanzetta et al. (2002). In Fig. 1 I show \( N_{\text{ph}} \) for GCs (thin lines) and for galaxies (thick lines) defined as,

\[
N_{\text{ph}}^{gc} = \eta f_{\text{d}} \frac{d\omega_{\text{gc}}}{dt} t_{\text{H}}(z),
\]

\[
N_{\text{ph}} = \eta (f_{\text{esc}}) \frac{d\omega_{\text{c}}}{dt} t_{\text{H}}(z).
\]

The thick solid, dashed and short-dashed lines show \( N_{\text{ph}}^{gc} \) for case (i), (ii) and (iii), respectively. For comparison, I show (thin solid line) \( N_{\text{ph}}^{gc} (f_{\text{esc}}) = 0.1 \times \exp[-z/2] \), chosen to fit the observed values (squares) of \( N_{\text{ph}}^{gc} \) at \( z = 2, 3, 4 \) (Miralda-Escudé et al. 2000). The thin dashed line shows \( N_{\text{ph}} \) assuming constant \( f_{\text{esc}} = 5% \).

### 4 CONCLUSIONS

Observed Lyman break galaxies at \( z \approx 3 \) are probably the most luminous starburst galaxies of a population that produced the bulk of the stars in our universe. Their formation epoch corresponds to the assembly of the bulges of spirals and ellipticals. Nevertheless the observed upper limit on \( f_{\text{esc}} \) from Lyman break galaxies is \( f_{\text{esc}} < 10\% \), insufficient to reionize the IGM according to numerical simulations. Recently Ferguson et al. (2002), using different arguments, have claimed that the radiation emitted from Lyman break galaxies is insufficient to reionize the IGM assuming a continuous star formation mode.

I propose that GCs could produce enough ionizing photons to reionize the IGM. Assuming \( f_{\text{d}} = 2 \) (i.e., during their evolution, GCs have lost half of their original mass), I find \( \omega_{\text{gc}}^0 \approx 0.1\% \), small compared to the total \( \omega_{\text{c}}^0 \sim 10\% \) at \( z = 0 \). But GCs are around 12-13 Gyr old and, if they formed between \( 7 < z < 5 \) (in about 0.5 Gyr), the expected total \( \omega_{\text{c}}^0 \) formed during this time period is about \( \omega_{\text{c}}^0 \sim 1\% \), only times larger than \( \omega_{\text{gc}}^0 \). Assuming \( f_{\text{d}} = 0 \), expected from the results of N-body simulations, I find \( \omega_{\text{gc}}^0 \approx 1\% \), suggesting that GC formation is an important mode of star formation at high-redshift. The special star formation mode required to explain the formation of GCs suggests an \( f_{\text{esc}} \sim 1 \)
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Figure 2. Emissivity (photons per baryon per Hubble time) as a function of redshift. The thick solid, dashed and short-dashed lines show the contribution of GCs for cases (i), (ii) and (iii), respectively (assuming $f_{\text{dot}} = 2$). The thin lines show the contribution of galaxies assuming a realistic $\langle f_{\text{esc}} \rangle = 0.1 \times \exp[-z/2]$ (solid) and a constant $\langle f_{\text{esc}} \rangle = 5\%$ (dashed).

from these objects. This is because $\langle f_{\text{esc}} \rangle$ is dominated by the most luminous OB associations and GCs are extremely luminous, emitting $S \sim 3 \times 10^{53}$ s$^{-1}$ ionizing photons in bursts lasting 4 Myrs. Moreover, according to many models, GCs form in the hot, collisionally-ionized galaxy halo, from which all the ionizing radiation emitted can escape into the IGM. Therefore it is not too surprising, if GCs started forming before $z = 6$, that their contribution to reionization is large. I find that the number of ionizing photons per baryon emitted in a Hubble time at $z = 6$ by GCs is $N_{\text{ph}}^{gc} = (5.1 + 0.7) f_{\text{dot}} / \Delta t_{\text{esc}} > 1$, therefore sufficient to reionize the IGM even if we assume $f_{\text{dot}} = 1$. Here, $\Delta t_{\text{esc}} \sim 0.5 - 2$ is the period of formation of the bulk of old GCs in Gyr. Using simple calculations based on Press-Schechter formalism (see Fig. 2) I find that, if normal star formation in galaxies have $\langle f_{\text{esc}} \rangle \lesssim 5\%$, GC contribution to reionization should be important. If GCs formed by thermal instability in the halo of $T_{\text{vir}} \sim 10^9$ K galaxies (case (iii)), the ionizing sources are located in rare peaks of the initial density field. Therefore, the mean size of intergalactic H II regions before overlap is large and reionization is homogeneous on large scales.

In this letter I have considered the possibility that an increasing $\langle f_{\text{esc}} \rangle$ at $z \sim 6$ due to GCs formation could explain IGM reionization and still be consistent with the observed values of the ionizing background at $z < 3$. Alternatively an increasing production of ionizing photons per baryon converted into stars, due to a varying IMF, would have similar effects on the IGM. Chemical evolution studies should be able to distinguish between these two scenarios.