Did globular clusters reionize the Universe?

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Accepted 2002 August 16. Received 2002 August 2; in original form 2002 April 24

ABSTRACT

A problem still unsolved in cosmology is the identification of the sources of radiation able to reionize HI in the intergalactic medium (IGM) by \( z \approx 6 \). Theoretical work and observations seem to indicate that the fraction, \( \langle f_{\text{esc}} \rangle \), of HI ionizing radiation emitted from galaxies that escapes into the IGM is small in the local Universe (\( \langle f_{\text{esc}} \rangle \ll 10 \) per cent). At high redshift, galaxies are more compact and probably gas-rich, implying smaller values of \( \langle f_{\text{esc}} \rangle \) from their discs or spheroids. However, if the sites of star formation are displaced from the disc or spheroid and the star formation efficiency of the proto-clusters is high, then \( \langle f_{\text{esc}} \rangle \) should be about 1. This star formation scenario is consistent with several models for globular cluster 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\( \alpha \) absorption systems toward newly found high-redshift quasars (Becker et al. 2001; Djorgovski et al. 2001) indicates that the redshift of reionization of the intergalactic medium (IGM) should be close to \( z \approx 6 \) (Gnedin 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 & Madaj 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 with which galaxies photoionize the surrounding IGM is the parameter \( \langle f_{\text{esc}} \rangle \), defined here as the mean fraction of Lyman continuum photons escaping from galaxy haloes into the IGM. To be an important source of ionizing photons and rival with quasars, a substantial fraction (\( \sim 10 \) per cent) 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 \( \langle f_{\text{esc}} \rangle \). However, 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: \( \langle f_{\text{esc}} \rangle \gtrsim 10 \) per cent assuming a Salpeter initial mass function (IMF) and the standard ACDM cosmological model. Benson et al. (2002) find that \( \langle f_{\text{esc}} \rangle \) should be about 15 per cent for reionization at \( z = 6 \), but a smaller value \( \langle f_{\text{esc}} \rangle \lesssim 10 \) per cent is consistent with the observed ionizing background at \( z \approx 3 \). Gnedin (2002) finds that assuming a primordial power spectrum index \( n = 0.93 \), the preferred value from cosmic microwave background and large-scale structure 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 \( f_s \) 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 \( \Omega_* \) 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 \( z \approx 6 \), but the ionizing background at \( z \sim 3 \) is consistent with \( \langle f_{\text{esc}} \rangle \lesssim 10 \) per cent (Bianchi, Cristiani & Kim 2001). Small values of \( \langle f_{\text{esc}} \rangle \) at \( z \lesssim 3 \) are also supported by direct observations of the Lyman continuum emission from Lyman-break and starburst galaxies. Giallongo et al. (2002) find an upper limit \( \langle f_{\text{esc}} \rangle \lesssim 16 \) per cent at \( z \approx 3 \) (but see Steidel, Pettini & Adelberger 2001), and observations of low-redshift starbursts are consistent with \( \langle f_{\text{esc}} \rangle \) upper limits ranging from a few per cent up to 10 per cent (Hurwitz, Jelinsky & Dixon 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 and feedback processes. Moreover, the mean \( \langle f_{\text{esc}} \rangle \) results from the contribution of a variety of galaxies with ISM properties that are largely unknown at high redshift. Theoretical models (Dove, Shull & Ferrara 2000; Ciardi,
Bianchi & Ferrara 2002) for the radiative transfer of ionizing radiation through the disc layer of spiral galaxies similar to the Milky Way find \(<f_{esc}> \sim 6\text{–}10\text{ per cent. At high redshift the mean value of } f_{esc}\text{ is expected to decrease almost exponentially with increasing redshift (Ricotti & Shull 2000; Wood & Loeb 2000); at } z > 6, \langle f_{esc} \rangle \lesssim 0.1\text{–}1\text{ per cent even assuming star formation rates typical of starburst galaxies (e.g., SFR } \sim 10\text{ times that of the Milky Way).}

Using Monte Carlo simulations, Ricotti & Shull (2000) have studied how \(<f_{esc}> depends on galactic parameters. Assuming a gas density profile in hydrostatic equilibrium in the dark matter (DM) potential, a stellar density proportional to the gas density and a power law for the luminosity function of the OB associations, they found that \(<f_{esc}> \propto (\epsilon f_{DM})^{1/3} \exp(-\zeta_{v}/\epsilon)\). Here \(\epsilon\) is proportional to the SFE, \(f_{DM}\) is the fraction of collapsed gas, \(\zeta_{v}\) is the virialization redshift and \(f_{DM}\) 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 \(<f_{esc}> (see their figs 8 and 9). In the aforementioned models, \(<f_{esc}> 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 \(<f_{esc}> with increasing redshift is in contrast with models for reionization that require \(<f_{esc}> \sim 1\text{ at } z = 6\). A different star formation mode, with very luminous OB associations forming in the outer parts of galaxy haloes, could explain the large \(<f_{esc}> required for reionization. Globular clusters (GCs) are possible observable relics of such a star formation mode. Their redshift of formation is compatible with redshift of ionization (Gnedin, Lahav & Rees 2002). Because of their large stellar density they survived tidal destruction and represent the most luminous tail of the luminosity distribution of primordial OB associations. In Section 2.2 I explain that several models for the formation of proto-GCs imply an \(<f_{esc}> \sim 1\). I will also show that the total amount of stars in GCs observed today is sufficient to reionize the Universe at \(z \sim 6\) without their \(<f_{esc}> \sim 1\). This conclusion is reinforced if the GCs that we observe today are only a fraction, \(f_{obs,0}\), of primordial GCs as a consequence of mass segregation and tidal stripping.

The paper is organized as follows. In Section 2 I briefly review recent progress in our understanding of GC properties and formation theories; in Section 3 I discuss the model assumptions in light of GC observations and present the results. In Section 4 I present my conclusions.

2 SHORT REVIEW ON GC SYSTEMS

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

2.1 Observations

Most galaxies have a bimodal GC distribution indicating that luminous galaxies experience at least two major episodes of GC formation. The bulk of the globulars in the main body of the Galactic halo appear to have formed during a short-lived burst \(\sim 0.5\text{–}2\text{ Gyr}\) that took place about 13 Gyr 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 colour–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 \(t_{gc} = 12.5 \pm 1.2\text{ Gyr} (Chaboyer et al. 1998)\), consistent with radioactive dating of a very metal-poor star in the halo of our Galaxy (Carretta et al. 2001). Relative ages of Galactic GCs can be determined with greater accuracy, since many systematic errors can be eliminated. In our Galaxy \(\Delta t_{gc} = 0.5\text{ Gyr},\) but differences in age between GC systems in different galaxies could be \(\Delta t_{gc} \approx 2\text{ Gyr} (Stetson, Vandenberg & Bolte 1996).\)

2.1.2 Specific frequency

The specific frequency is defined as the number, \(N\), of GCs per \(M_{V} = -15\text{ of parent galaxy light}, S_{N} = N \times 10^{0.4(M_{V} - 15)}\) (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 Sb/Sand, and \(S_{N} = 2.5\) in field ellipticals (Kundu & Whitmore 2001a,b). Converting to luminosity \((L_{V}/L_{\odot}) = 10^{0.4(M_{V} - 4.85)}\) we have \(N = (L/L_{\odot})S_{N}/8.55 \times 10^{-7}\). I can therefore calculate the efficiency of GC formation defined as

\[
\epsilon_{gc} = \frac{M_{gc}}{M} = \frac{f_{obs}N_{gc}}{M} = \frac{S_{N}f_{obs}}{(M/L_{V})} \times 0.00585, \tag{1}
\]

where \(M_{gc}\) is the total mass of the GC system, \(m_{gc} = 5 \times 10^{5}\text{ M}_{\odot}\) 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 I show that, because of dynamical evolution, \(m_{gc}\) and \(N\) are expected to be larger at the time of GC formation than today. Therefore the parameter \(f_{obs} \geq 1\) 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 \(\text{M}_{\odot}\), 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 \(Z \approx 0.03\text{ Z}_{\odot}\). One of the most remarkable properties of GCs is the uniformity of their internal metallicity: \(\Delta[\text{Fe/H}] \lesssim 0.1\). 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 \(S \approx 3 \times 10^{33}\text{ s}^{-1}\) ionizing photons in a burst lasting 4 Myr: 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 disc or bulge of the galaxy, and tidal forces, which cause mass loss as a result of tidal truncation. Numerical simulations show that about 50–90 per cent of the mass of GCs is lost because of external processes, depending on the host galaxy environment, initial concentration and IMF of the proto-GCs (Chernoff & Weinberg 1990; Gnedin & Ostriker 1997). 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 $f_{\text{fr}}$, defined in Section 2.1.2, could be as large as $f_{\text{fr}} = 100$. Overall $f_{\text{fr}}$ is not well constrained since it depends on unknown properties of the proto-GCs. According to results of $N$-body simulations $f_{\text{fr}}$ should be in the range $f_{\text{fr}} \sim 2–10$ range.

2.2 Why is $(f_{\text{esc}}) \sim 1$ 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 $(f_{\text{esc}}) \sim 1$ comes from the observed properties of present-day GCs. The fact 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 time-scale of star formation would have enriched the gas of metals and the mechanical feedback from supernova explosions would have stopped further star formation. If $f_{\text{cs}} \approx 10$ per cent of the gas is converted into stars in a single burst (with duration $\lesssim 4$ Myr) at the centre of a spheroidal galaxy, following the simple calculations shown in Ricotti & Shull (2000) [see their equation (18)] at $z = 6$ we have

$$f_{\text{esc}} = 1 - 0.06 \frac{(1 - f_{\text{cs}})^{2}}{f_{\text{cs}}} \left(1 + \frac{z}{7}\right)^{3} \sim 50 \text{ per cent.} \quad (2)$$

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

In the ‘cosmological objects model’ ($30 < z < 7$) of Peebles & Dicke (1968), GCs form with efficiency $f_{\text{cs}} \approx 10$ per cent, implying $(f_{\text{esc}}) = 1$ [note that such a high $f_{\text{cs}}$ is not found in numerical simulations of first object formation (Ricotti, Gnedin & Shull 2002a,b)]. In ‘hierarchical formation models’ ($10 < z < 3$) (Larson 1993; Harris & Padüriz 1994; McLaughlin & Padüriz 1996; Gnedin et al. 2002), GCs form in the disc or spheroid of galaxies with gas mass $M_{\text{gas}} \sim 10^{7}–10^{9}$ $M_{\odot}$. 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 $M_{\text{gas}} \sim 10^{7} – 10^{9}$ $M_{\odot}$ implies $f_{\text{cs}} \sim 10$ per cent and therefore $(f_{\text{esc}}) \geq 50$ per cent. $(f_{\text{esc}})$ is larger than in equation (2) if proto-GCs are located off-centre (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’ model ($z_{\text{f}} < 10$) of Taniguchi, Trentham & Ikeuchi (1999) or the ‘thermal instability’ model ($z_{\text{f}} < 7$) 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 $(f_{\text{esc}})$.

### Table 1. Star census at $z = 0$.

<table>
<thead>
<tr>
<th>Type</th>
<th>$\alpha_{\text{esc}}$ (per cent)</th>
<th>$S_{\text{N}}$</th>
<th>$(M/L)_{\text{v}}$</th>
<th>$\epsilon_{\text{gc}}$ (per cent)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sph</td>
<td>$6.5^{+1.8}_{-2.5}^{+1.5}$</td>
<td>$2.4 \pm 0.4$</td>
<td>$5.4 \pm 0.3$</td>
<td>$0.26 \pm 0.06$</td>
</tr>
<tr>
<td>Disc</td>
<td>$2.0^{+0.5}_{-0.5}^{+1.5}$</td>
<td>$1 \pm 0.1$</td>
<td>$1.82 \pm 0.4$</td>
<td>$0.32 \pm 0.1$</td>
</tr>
<tr>
<td>Irr</td>
<td>$0.15^{+0.05}_{-0.05}$</td>
<td>$0.5$</td>
<td>$1.33 \pm 0.25$</td>
<td>$0.22 \pm 0.04$</td>
</tr>
<tr>
<td>Total</td>
<td>$9^{+3.5}_{-3.5}$</td>
<td>–</td>
<td>–</td>
<td>$0.3 \pm 0.07$</td>
</tr>
</tbody>
</table>

3 METHOD AND RESULTS

In this Section I estimate the number of ionizing photons emitted per baryon per Hubble time, $N_{\text{esc}}$, by GC formation. In Section 3.1 I derive $N_{\text{esc}}$ assuming that all GCs observed at $z = 0$ formed in a time period $\Delta t_{\text{esc}}$ with constant formation rate. In Section 3.2 I use the Press–Schecter formalism to model more realistically the formation rate of old GCs.

3.1 The simplest estimate

I start by estimating the fraction, $\omega_{\text{gc}}$, of cosmic baryons converted into GC stars. By definition $\omega_{\text{gc}} = \omega_{\text{esc}} \epsilon_{\text{gc}}$, where $\omega_{\text{esc}}$ is the fraction of baryons in stars at $z = 0$ and $\epsilon_{\text{gc}}$ is the efficiency of GC formation defined in Section 2.1.2. In all the calculations I assume $\Omega_{\text{b}} = 0.04$. In Table 1, I summarize the star census at $z = 0$ according to Persic & Salucci (1992) and I derive $\epsilon_{\text{gc}}$ using equation (1), assuming $f_{\text{fr}} = 1$. Using similar arguments McLaughlin (1999) finds a universal efficiency of GC formation $\epsilon_{\text{gc}} = 0.26 \pm 0.05$ per cent, in agreement with the simpler estimate presented here. It follows that $\omega_{\text{gc}} = f_{\text{fr}}(2.7^{+2.3}_{-1.7} \times 10^{-4})$ at $z = 0$.

The total number of ionizing photons per unit time emitted by GCs is $\eta \omega_{\text{esc}} \epsilon_{\text{gc}} \Omega_{\text{b}}$, where $\eta$ is the number of ionizing photons emitted per baryon converted into stars, and $\omega_{\text{esc}} \approx 2.1 \omega_{\text{fr}}$ takes into account the mass loss due to stellar winds and supernova 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 stellar metallicity Z = 0.03 $Z_{\odot}$ (see Section 2.1.3) with the 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

$$N_{\text{esc}} = \eta \omega_{\text{esc}} \epsilon_{\text{gc}} \Omega_{\text{b}} \frac{t_{\text{H}}}{{\Delta t_{\text{esc}}}} = \left(5.1^{+1.2}_{-1.1}\right) f_{\text{fr}} \Delta t_{\text{esc}} \Omega_{\text{b}} \Omega_{\text{H}} \Omega_{\text{b}} \Omega_{\text{b}}.$$  (3)

where I have assumed $(f_{\text{esc}}) = 1$ and the Hubble time at $z = 6$ is $t_{\text{H}} = 1 \pm 0.1$ Gyr. I expect $1 \lesssim f_{\text{fr}} \lesssim 100$ and $0.5 \lesssim \Delta t_{\text{esc}} \lesssim 2$ Gyr. A conservative estimate of $f_{\text{fr}} \gtrsim 2$ and $\Delta t_{\text{esc}} \lesssim 2$ Gyr (i.e. $10 < z_{\text{f}} < 3$) implies that $f_{\text{fr}} / \Delta t_{\text{esc}} \gtrsim 1$. The IGM is reionized when $N_{\text{esc}} = C$, where $C = (n_{\text{HI}}/n_{\text{HII}})^{2}$ 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 Lyman forest (Miralda-Escudé, Haehnelt & Rees 2000; Gnedin 2000). The estimate from equation (3) is rather rough because I have implicitly assumed that the SFR is constant during the period of GC formation $\Delta t_{\text{esc}}$. 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 modelling

I assume that the formation rate of stars or GCs in galaxies is proportional to the merger rate of galaxy haloes (each galaxy
The thick solid, dashed and short-dashed lines show \( N \) haloes of mass (i), (ii) and (iii), respectively. For comparison, I show (thin solid line) (ii) \( 5 \times \langle z \rangle \) mean redshift, IGM assuming a continuous star formation mode. Emitted from Lyman break galaxies is insufficient to reionize the IGM according to stellar winds and supernova explosions adopting a continuous star formation law. I assume that GCs form in haloes with masses \( M_1 < M_{DM} < M_2 \). The choice of \( M_1 \) and \( M_2 \) determines the mean redshift, \( z_\text{f} \), and time period, \( \Delta t_{\text{esc}} \), for the formation of old GCs. In order to be consistent with observations I consider three cases: (i) haloes with virial temperature \( 2 \times 10^4 < T_{\text{vir}} < 5 \times 10^4 \) K; (ii) \( 5 \times 10^4 < T_{\text{vir}} < 10^5 \) K; and (iii) \( 10^5 < T_{\text{vir}} < 5 \times 10^6 \) K. In cases (i), (ii) and (iii) \( \Delta t_{\text{esc}} = 2, 3.7 \) and 5.2 Gyr, respectively, and the GC formation rate has a peak at \( z = 7.5, 6 \) and 4.6, respectively. Disc and spheroid stars form in haloes with \( M_{DM} > M_* \). At \( z > 10 \) I assume that the first objects form in haloes with \( M_* \) corresponding to a halo virial temperature \( T_{\text{vir}} = 5 \times 10^4 \) K. At \( z < 10 \) only objects with \( T_{\text{vir}} > 2 \times 10^4 \) K can form (see Ricotti et al. 2002b). The comoving star formation rate, given by \( \rho_* = \rho \phi_* \), where \( \rho = 5.51 \times 10^8 \) M_\odot Mpc^{-3} \) 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. 2 I show \( N_\text{ph}^\text{GC} \) for GCs (thick lines) and for galaxies (thin lines) defined as

\[
N_\text{ph}^\text{GC} = \eta f_* \frac{d\phi_*}{dz} t_\text{f}(z),
\]

\[
N_\text{ph}^\text{GC} = \eta (f_* \phi_* \frac{dz}{dt}) t_\text{f}(z).
\]

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

### 4 CONCLUSIONS

Observed Lyman break galaxies at \( z \sim 3 \) 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 \( \langle f_* \rangle \) from Lyman break galaxies is \( \langle f_* \rangle < 10 \) per cent, insufficient to reionize the IGM according to numerical simulations. Recently Ferguson, Dickinson \& Papovich (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.

\[1\text{By definition, } \int_0^\infty \Omega(M_{DM}, z) d\ln(M_{DM}) = 1. I find the following values of the constants: } A = 1.3, 1.6 \text{ and } 0.6 \text{ per cent for cases (i), (ii) and (iii) respectively (see text), and } B = 12 \text{ per cent.} \]
I propose that GCs could produce enough ionizing photons to reionize the IGM. Assuming \( f_{\text{bio}} = 2 \) (i.e. during their evolution GCs have lost half of their original mass), I find \( \omega_{\text{GC}} \approx 0.1 \) per cent, small compared with the total \( \omega_\nu \approx 10 \) per cent at \( z = 0 \). However, GCs are around 12–13 Gyr old and, if they formed in the redshift interval \( 7 < z < 5 \) (in about 0.5 Gyr), the expected total \( \omega_{\text{GC}} \) formed during this time period is about \( \omega_{\text{GC}} \approx 1 \) per cent, only 10 times larger than \( \omega_{\text{GC}} \). Assuming \( f_{\text{bio}} = 20 \), expected from the results of N-body simulations, I find \( \omega_{\text{GC}} \approx 0.1 \) per cent, 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 in the bulk of old GCs in Gyr. Using simple calculations based on the Press–Schechter formalism (see Fig. 2) I find that the number of ionizing photons per baryon emitted in a Hubble time at \( z = 6 \) by GCs is \( N_{\text{phot}} = (5.1^{+1.3}_{-1.2}) f_{\text{bio}} / \Delta t_{\text{GC}} > 1 \), therefore sufficient to reionize the IGM even if we assume \( f_{\text{bio}} = 1 \). Here, \( \Delta t_{\text{GC}} \approx 0.5–2 \) is the period of formation of the bulk of old GCs in Gyr. Using simple calculations based on the Press–Schechter formalism (see Fig. 2) I find that, if normal star formation in galaxies has \( f_{\text{esc}} \lesssim 5 \) per cent, the GC contribution to reionization should be important. If GCs formed by thermal instability in the halo of \( T_{\text{vir}} \sim 10^3 \) K galaxies (case iii), the ionizing sources are located in rare peaks of the initial density field. Therefore the mean size of intergalactic \( \text{H} \) regions before overlap is large and reionization is inhomogeneous on large scales.

In this Letter I have considered the possibility that an increasing \( f_{\text{esc}} \) at \( z \approx 6 \) because of GC 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, owing to a varying IMF, would have similar effects on the IGM. Chemical evolution studies should be able to distinguish between these two scenarios.

ACKNOWLEDGMENTS

I thank Oleg and Nick Gnedin for their helpful support with the manuscript.

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