The escape fraction of ionizing photons from high-redshift galaxies from data-constrained reionization models

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ABSTRACT
The escape fraction, \( f_{\text{esc}} \), of ionizing photons from high-redshift galaxies is a key parameter to understand cosmic reionization and star formation history. Yet, in spite of many efforts, it remains largely uncertain. We propose a novel, semi-empirical approach based on a simultaneous match of the most recently determined luminosity functions of galaxies in the redshift range \( 6 \leq z \leq 10 \) with reionization models constrained by a large variety of experimental data. From this procedure, we obtain the evolution of the best-fitting values of \( f_{\text{esc}} \) along with their 2σ limits. We find that, averaged over the galaxy population, (i) the escape fraction increases from \( f_{\text{esc}} = 0.068^{+0.054}_{-0.047} \) at \( z = 6 \) to \( f_{\text{esc}} = 0.179^{+0.331}_{-0.132} \) at \( z = 8 \) and (ii) at \( z = 10 \) we can only put a lower limit of \( f_{\text{esc}} > 0.146 \). Thus, although errors are large, there is an indication of a 2.6 times increase of the average escape fraction from \( z = 6 \) to \( 8 \), which might partially release the ‘starving reionization’ problem.

Key words: intergalactic medium – cosmology: theory – dark ages, reionization, first stars – large-scale structure of Universe.

1 INTRODUCTION
One of the most crucial issues regarding the evolution of intergalactic medium (IGM) and cosmic reionization is the escape fraction, \( f_{\text{esc}} \), of ionizing photons from high-redshift galaxies. This parameter remains poorly constrained in spite of the many theoretical and observational attempts made in the past few years. The difficulties largely arise from the lack of a full understanding of the physics of star formation, radiative transfer and feedback processes, and from uncertainties on the properties of the high-z galaxy interstellar medium (ISM); as a result, derived values of \( f_{\text{esc}} \) span the large range 0.01–1 (Fernandez & Shull 2011). Observationally, \( f_{\text{esc}} \) can be reliably estimated only at redshifts \( z \lesssim 3 \) (Leitherer et al. 1995; Dove, Shull & Ferrara 2000; Heckman et al. 2001; Ciardi, Bianchi & Ferrara 2002; Galliongo et al. 2002; Fernández-Soto, Lanzetta & Chen 2003; Inoue et al. 2005; Bergvall et al. 2006; Shapley et al. 2006; Vanzella et al. 2010). On the other hand, theoretical studies (Wood & Loeb 2000; Razoumov & Sommer-Larsen 2006, 2010; Gnedin 2008; Gnedin, Kravtsov & Chen 2008; Srinovisky & Wyithe 2010; Fernandez & Shull 2011; Haardt & Madau 2011; Yajima, Choi & Nagamine 2011; Kuhlen & Faucher-Giguere 2012) have been rather inconclusive so far, as illustrated by their often conflicting results in terms of \( f_{\text{esc}} \) values and trend with redshift and galaxy mass.

One key aspect of reionization lies in its close coupling with the properties and evolution of first luminous sources (for reviews, see Barkana & Loeb 2001; Loeb & Barkana 2001; Choudhury & Ferrara 2006a; Choudhury 2009). Observations of cosmic microwave background (CMB) and highest redshift quasi-stellar objects (QSOs) put very tight constraints on the reionization history; these allow us to construct self-consistent models of structure formation (Choudhury & Ferrara 2005, 2006b; Wyithe & Loeb 2005; Gallerani, Choudhury & Ferrara 2006; Dijkstra, Wyithe & Haiman 2007; Samui, Srianand & Subramanian 2007; Iliev et al. 2008; Kulkarni & Choudhury 2011). The most favourable model, which is consistent with the Thomson scattering optical depth \( \tau_{\text{el}} = 0.088 \pm 0.015 \) from WMAP data (Larson et al. 2010) and the Gunn–Peterson optical depth evolution from QSO absorption-line experiments at \( z \gtrsim 6 \) (Fan et al. 2006), suggests that reionization is an extended process over the redshift range \( 6 \lesssim z \lesssim 15 \) (Choudhury & Ferrara 2006b; Mitra, Choudhury & Ferrara 2011, 2012). This model also indicates that reionization feeds back on star formation by suppressing it in the low-mass haloes at early times (Thoul & Weinberg 1996; Choudhury & Ferrara 2007).

In parallel, direct observations of galaxies at epochs close to the end of reionization have made astonishing progresses over the past few years (Bouwens & Illingworth 2006; Iye et al. 2006; Bouwens et al. 2007, 2008, 2009, 2010a,b; Ota et al. 2008; Henry et al. 2009;...
McLure et al. 2010; Oesch et al. 2010; Bradley et al. 2012; Oesch et al. 2012), allowing us to derive the galaxy UV luminosity function (LF) up to $z \approx 10$ (Bouwens & Illingworth 2006; Bouwens et al. 2010c; Oesch et al. 2012) and to better constrain light production by reionization sources.

Here we aim at combining data-constrained reionization histories and the evolution of the LF of early galaxies to account for an empirical determination of the escape fraction. The study also provides relatively tight constraints on the evolution of the star-forming efficiency $\epsilon_*$ (Faucher-Giguère et al. 2008; Kuhlen & Faucher-Giguère 2012). Throughout the Letter, we assume a flat Universe with cosmological parameters given by the WMAP7 best-fitting values: $\Omega_m = 0.27$, $\Omega_k = 1 - \Omega_m$, $\Omega_b h^2 = 0.023$ and $h = 0.71$. The parameters defining the linear dark matter power spectrum are $\sigma_8 = 0.81$, $n_s = 0.97$ and $\ln(10^{10} A_s) = 3.04$. Unless mentioned, quoted errors are 2$\sigma$.

2 DATA-CONstrained REIONIZATION

We start by summarizing the main features of the semi-analytical model used in this work, which is based on Choudhury & Ferrara (2005, 2006b).

The model follows the ionization and thermal histories of neutral H$\text{I}$ and He$\text{II}$ regions simultaneously also accounting for IGM inhomogeneities described by a lognormal distribution as in Miralda-Escudé, Haehnelt & Rees (2000). Sources of ionizing radiation are stars and quasars. The stellar sources, all characterized by a Salpeter initial mass function (IMF) in the mass range $M_* = 1$–100 $M_\odot$, can be divided into two classes, namely (i) metal-free (i.e. Pop III) stars and (ii) Pop II stars with subsolar metallicities. The transition is based on a local critical metallicity criterion. Radiative feedback, suppressing star formation in low-mass haloes, is included through a Jeans mass prescription based on the evolution of the thermal properties of the IGM.

Given the collapsed fraction $f_{\text{coll}}$ of dark matter haloes, the production rate of ionizing photons in the IGM is

$$n_{\text{ph}}(z) = n_b N_{\text{ion}} f_{\text{coll}} \frac{dN_{\text{ph}}}{dz},$$

where $n_b$ is the IGM number density and $N_{\text{ion}}$ is the number of photons entering the IGM per baryon included into stars. The parameter $N_{\text{ion}}$ can actually be written as a combination of three parameters: the star-forming efficiency $\epsilon_*$ (fraction of baryons within collapsed haloes going into stars), $f_{\text{esc}}$ and the specific number of photons emitted per baryon in stars, $N_{\gamma}$, which depends on the stellar IMF and the corresponding stellar spectrum:

$$N_{\text{ion}} = \epsilon_* f_{\text{esc}} m_p \int_{10^4}^{\infty} \frac{dN_{\gamma}}{dM_*} \frac{dM_*}{dm_p} = \epsilon_* f_{\text{esc}} N_{\gamma}. \quad (2)$$

In our previous work (Mitra et al. 2011, 2012), we assumed $N_{\text{ion}}$ to be an unknown function of $z$ and decompose it into its principal components. The principal component analysis (PCA) filters out components of the model that are most sensitive to the data and thus the model is most accurately constrained. In the following, we assume a single stellar population (Pop II) when computing the ionizing radiation properties; any change in the characteristics of these stars over time would be accounted for indirectly by the evolution of $N_{\text{ion}}$. We also include the contribution of quasars at $z < 6$ assuming that they have negligible effects on IGM at higher redshifts; however, they are significant sources of ionizing photons at $z \lesssim 4$.

From the above model, we obtain the redshift evolution of $N_{\text{ion}}$ by doing a detailed likelihood analysis using three different data sets – the photoionization rates $\Gamma_{\text{ph}}$ obtained using Ly$\alpha$ forest Gunn-Peterson optical depth observations and a large set of hydrodynamical simulations (Bolton & Haehnelt 2007), the redshift distribution of Lyman limit systems $dN_{\text{Ly}}/dz$ in $0.36 < z < 6$ (Songaila & Cowie 2010) and the angular power spectra $C_l$ for TT, TE and EE modes using WMAP7 (Larson et al. 2010) and forecasted Planck data. We show the redshift evolution of $N_{\text{ion}}(z)$ obtained from our PCA using WMAP7 data in Fig. 1. The solid line corresponds to the model described by mean values of the parameters, while the shaded region corresponds to 2$\sigma$ limits.

![Figure 1. Redshift evolution of $N_{\text{ion}}$ obtained from the PCA using WMAP7 data. The solid line corresponds to the model described by mean values of the parameters, while the shaded region corresponds to 2$\sigma$ limits.](https://example.com/figure1.png)
 Escape fraction from high redshift galaxies

Once the (Salpeter) IMF of the (Pop II) stars is fixed, \( N_e \) is also fixed and equal to \( \approx 3200 \); from equation (2), we then get the value of \( f_{\text{esc}} \) as follows:

\[
f_{\text{esc}} = \frac{N_{\text{ion}}}{\epsilon_e N_e}
\]

As the uncertainties on \( [N_{\text{ion}}/N_e] \) and \( \epsilon_e \) are independent, the fractional uncertainty in \( f_{\text{esc}} \) can be obtained from the quadrature method (Taylor 1997), i.e.

\[
\frac{\Delta f_{\text{esc}}}{f_{\text{esc}}} = \sqrt{\left( \frac{\Delta [N_{\text{ion}}/N_e]}{N_{\text{ion}}/N_e} \right)^2 + \left( \frac{\Delta \epsilon_e}{\epsilon_e} \right)^2}.
\]

In this work, we are interested in the \( z \geq 6 \) evolution of the escape fraction. In principle, our approach can also be used for the lower redshift range \( 3 \leq z \leq 5 \), provided that a detailed treatment of dust extinction is added to our model. The underlying assumption in the present work is that dust effects on the escape fraction can be safely neglected at early times.

4 RESULTS

The observationally determined LFs are taken from Bouwens & Illingworth (2006) for \( z = 6 \), Bouwens et al. (2010c) for \( z = 7 \) and \( z = 8 \), and Oesch et al. (2012) for \( z = 10 \). Fig. 2 shows the globally averaged LFs calculated using our model for \( z = 6, 7, 8 \) and 10 compared to the observational data points. The \( z = 10 \) data are obtained from the detection of a single galaxy candidate by Oesch et al. (2012); hence, we only show results for the maximum value of \( \epsilon_e \) for which the LF curve does not exceed the experimental upper limits.

Figure 2. LF from our model for best-fitting \( \epsilon_e \) (black curve) and its \( 2\sigma \) limits (shaded region) at \( z = 6, 7, 8 \) and 10. Data points with \( 2\sigma \) errors are from Bouwens & Illingworth (2006) (\( z = 6 \)), Bouwens et al. (2010c) (\( z = 7, 8 \)) and Oesch et al. (2012) (\( z = 10 \)). For \( z = 10 \), we show the LF from our model for the maximum value of \( \epsilon_e \), for which the LF curve does not exceed the experimental upper limits.

3 LUMINOSITY FUNCTION EVOLUTION

The effect of reionization on the high-redshift galaxy LF was studied using the semi-analytical models by Samui et al. (2007) and Kulkarni & Choudhury (2011). In this work, we follow their method to study the evolution of LF for our model.

The LF is derived as follows. We compute the luminosity at 1500 Å of a galaxy having the halo mass \( M \) and age \( \Delta t \) using

\[
L_{1500}(M, \Delta t) = \epsilon_e \left( \frac{\Omega_0}{\Omega_m} \right) M_{1500}(\Delta t).
\]

Here the age of the galaxy formed at \( z' \) and observed at \( z \) is \( \Delta t = t_z - t_{z'} \), and \( L_{1500}(\Delta t) \) is a template specific luminosity at 1500 Å for the stellar population of age \( \Delta t \). As we restrict to a single stellar population, i.e. Pop II stars, \( \epsilon_e \) indicates the star-forming efficiency of Pop II stars throughout the Letter.

To compute \( l_{1500} \), we use stellar population models of Bruzual & Charlot (2003) for Pop II stars. The UV luminosity depends on galaxy properties including the IMF, star formation rate, stellar metallicity (Z) and age. Dayal et al. (2009) and Dayal, Ferrara & Saro (2010) have shown that the metallicity correlates with stellar mass, and the best-fitting mass–metallicity relation they find is

\[
Z/Z_\odot = (0.25 - 0.05\Delta z) \log_{10}(M_* - (2.0 - 0.3\Delta z)),
\]

where \( \Delta z = (z - 5.7) \) and \( M_* \) is the total stellar mass of the galaxy. We take all the available stellar population models in the metallicity range \( Z = 0.0001-0.05 \) for Pop II stars and interpolate them to compute \( l_{1500} \) following the mass–metallicity relation given by the above relation for our model galaxies.

The luminosity can be converted to a standard absolute AB magnitude (Oke & Gunn 1983; Samui et al. 2007; Kulkarni & Choudhury 2011) using

\[
M_{AB} = -2.5 \log_{10} \left( \frac{L_{1500}}{\text{erg s}^{-1} \text{Hz}^{-1}} \right) + 51.60.
\]

The LF \( \Phi(M_{AB}, z) \) at any redshift \( z \) is then given by

\[
\Phi(M_{AB}, z) = \frac{dn}{dM_{AB}} = \frac{dn}{dL_{1500}} \frac{dL_{1500}}{dM_{AB}},
\]

where

\[
\frac{dn}{dL_{1500}} = \int_{z}^{\infty} d\nu^* \frac{dM}{dL_{1500}}(L_{1500}, \Delta t) \frac{d^2n}{dM dz^*}(M, z^*)
\]

is the coming number of objects at redshift \( z \) with observed luminosity within \( [L_{1500}, L_{1500} + dL_{1500}] \). The quantity \( d^2n/dM dz^* \) gives the formation rate of haloes of mass \( M \), which we obtain as in Choudhury & Ferrara (2007). Note that we can vary the star-forming efficiency \( \epsilon_e \) in equation (3) as a free parameter and obtain its best-fitting value by comparing the high-redshift LFs computed using the above equations with observations.

3.1 Constraining the escape fraction

Our strategy to constrain \( f_{\text{esc}} \) exploits the combination between the previously derived (Section 2) evolution of \( N_{\text{ion}} \) and the constraints on \( \epsilon_e \) that can be derived from matching LFs at different redshifts.

technique in a regime where the variance in \( N_{\text{ion}} \) is small enough to produce a useful constraint on the reionization history without the need to truncate the PCA modes so severely and hence without introducing any bias. This technique will become more applicable as more data become available for \( z > 6 \) region.
parameters of reionization models, the escape fraction $f_{\text{esc}}$ of ionizing photons from high-redshift galaxies. The main findings of our work are that, averaged over the galaxy population, (i) the escape fraction shows a moderate increase from $f_{\text{esc}} = 0.068_{-0.047}^{+0.054}$ at $z = 6$ to $f_{\text{esc}} = 0.179_{-0.132}^{+0.331}$ at $z = 8$ and (ii) at $z = 10$ we can only put a lower limit of $f_{\text{esc}} > 0.146$. Thus, although errors are large, there is an indication of a 2.6 times increase of the average escape fraction from $z = 6$ to 8, which might partially release the ‘starving reionization’ problem. At the same time, the best-fitting value of the star formation efficiency $\epsilon_*$ nominally increases from 3.6 per cent at $z = 6$ to 5.2 per cent at $z = 8$. Such a small variation is statistically consistent with a constant value of $\epsilon_*$, i.e. no evolution.

Parallel to our more phenomenological approach, in the past few years many numerical and analytical studies have attempted to constrain $f_{\text{esc}}$ reaching often contradictory conclusions, likely due to uncertainties on star formation history, feedback, radiation transfer and the geometry of the ISM distribution (Fernandez & Shull 2011). Increasing (Razoumov & Sommer-Larsen 2006, 2010; Haardt & Madau 2011), decreasing (Wood & Loeb 2000) or un-evolving (Gnedin 2008; Yajima et al. 2011) trends have been suggested as a function of redshift.

A strong redshift evolution of the escape fraction was recently found by Kuhlen & Faucher-Giguere (2012). They show that models in which star formation is strongly suppressed in low-mass haloes can simultaneously satisfy reionization and lower redshift Ly$\alpha$ forest constraints only if the escape fraction of ionizing radiation increases from $\sim$4 per cent at $z = 4$ to $\sim$1 at higher redshifts. Although broadly in agreement with their conclusions, our results show instead that reionization and LF data can be satisfied simultaneously if $f_{\text{esc}}$ grows from $\sim$7 per cent at $z = 6$ to $\sim$18 per cent at $z = 8$, but without requiring an escape fraction of the order of unity at these redshifts. We believe that this discrepancy can be understood as due to the fact that unlike Kuhlen & Faucher-Giguere (2012), we are fitting the full CMB spectrum rather than the single value of $\tau_{\alpha}$; the latter choice can be thought as a simplification of CMB polarization observations. In addition, we have used a PCA to optimize model parameters to reionization data, yielding a more robust statistical analysis.

Although here we have only considered the evolution of $z \geq 6$ LFs, our approach can also be applied to model the LFs at $3 \leq z \leq 5$. As hydrogen reionization mostly occurs at $z \gtrsim 6$, the LFs in this lower redshift range are very unlikely to be sensitive to the details of reionization history. Also, dust extinction at $z < 6$ can decrease $f_{\text{esc}}$ by absorbing the ionizing photons at these epochs (Yajima et al. 2011). As a caveat, we mention that the present results can be responsive to changes in some cosmological parameters, mainly $\sigma_8$ and $n_s$ (Pandolfi et al. 2011). A larger $\sigma_8$ or $n_s$ may lead to an increase in the number of collapsed haloes at all redshifts. In principle, then, one should include these two quantities in the analysis as additional free parameters. Also, it could be interesting to evaluate the effects of Pop III stars and other feedback processes.

**Table 1.** Best-fitting values and 2σ limits of $\epsilon_*$ and the derived parameter $f_{\text{esc}}$ for the reionization model obtained from the LF calculation at different redshifts. At $z = 10$, we get only an upper limit of $\epsilon_*$ and a corresponding lower limit of $f_{\text{esc}}$.

| Redshift ($z$) | Best-fitting $\epsilon_*$ | 2σ limits | Best-fitting $f_{\text{esc}}$ | 2σ limits |
|----------------|--------------------------|-----------|---------------------------|-----------|
| 6              | 0.0365                   | [0.0253, 0.0481] | 0.0684 | [0.0210, 0.1221] |
| 7              | 0.0385                   | [0.0193, 0.0576] | 0.1607 | [0.0319, 0.4451] |
| 8              | 0.0523                   | [0.0129, 0.0822] | 0.1794 | [0.0466, 0.5098] |
| 10             | <0.0841                  |            | >0.1456                   |           |
in our LF calculation. We hope to revisit some of these topics in more detail in future work.

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