

Searching for the reionization sources

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ABSTRACT

Using a reionization model simultaneously accounting for a number of experimental data sets, we investigate the nature and properties of reionization sources. Such a model predicts that hydrogen reionization starts at $z \approx 15$, is initially driven by metal-free (Population III) stars, and is 90 per cent complete by $z \approx 8$. We find that a fraction $f_\gamma > 80$ per cent of the ionizing power at $z \geq 7$ comes from haloes of mass $M < 10^9 M_\odot$ predominantly harbouring Population III stars; a turnover to a Population II dominated phase occurs shortly after, with this population, residing in $M > 10^9 M_\odot$ haloes, yielding $f_\gamma \approx 60$ per cent at $z = 6$. Using Lyman-break broad-band dropout techniques, J -band detection of sources contributing to 50 per cent (90 per cent) of the ionizing power at $z \sim 7.5$ requires reaching a magnitude $J_{110,AB} = 31.2$ (31.7), where ~ 15 (30) (Population III) sources arcmin^{-2} are predicted. We conclude that $z > 7$ sources tentatively identified in broad-band surveys are relatively massive ($M \approx 10^9 M_\odot$) and rare objects which are only marginally (≈ 1 per cent) adding to the reionization photon budget.

Key words: intergalactic medium – cosmology: theory – large-scale structure of Universe.

1 INTRODUCTION

The study of reionization received a big boost due to the availability of a variety of observational data accumulated over the past few years [for reviews see Fan, Carilli & Keating (2006) and Choudhury & Ferrara (2006a)]; additional progress is soon expected from a number of different ground-based (LOFAR, MWA, PAST, SKA, ALMA) and space-borne (*JWST*, *Planck*, *GLAST*) experiments.

The available results have allowed us to build self-consistent reionization scenarios that are able to account simultaneously for a number of observables [redshift evolution of Lyman-limit absorption systems, Gunn–Peterson (GP) and electron scattering optical depths, mean temperature of the intergalactic medium (IGM), and cosmic star formation history (Choudhury & Ferrara 2005, 2006b, hereafter CF05 and CF06 respectively)]. To summarize the emerging picture, the most favourable model is one in which hydrogen reionization was an extended process starting around $z \approx 15$ and being 90 per cent complete by $z \approx 8$. This (early) reionization model was also shown not to be in conflict with the GP optical depth evolution deduced from QSO absorption-line experiments at $z \gtrsim 6$ both by using the statistics of dark gaps in the Ly α transmitted flux (Gallerani, Choudhury & Ferrara 2006) and through radiative transfer simulations of ionized regions around QSOs (Maselli et al. 2007). According to the model, reionization is initially driven by metal-free stars in low-mass ($M < 10^8 M_\odot$) haloes; the conditions for the formation of these objects are soon erased by the combined action of chemical

and radiative feedback at $z < 10$. As a consequence, the photoionizing power (and therefore integrated luminosity) of these sources is most significant around $z \approx 8$ –12.

In spite of this successful overall picture, relatively less attention has been devoted so far to the observable properties of the sources responsible for cosmic reionization. Our main aim in this work is to fill such gap by providing quantitative guidelines for observers searching for the first cosmic light sources. Specifically, we use the CF05 and CF06 model to estimate the infrared fluxes and magnitude-limited counts of the primary reionization sources.

2 BASIC FEATURES OF THE MODEL

The main features of the semi-analytical model used in this work¹ can be summarized along the following lines (for a more detailed description see CF05 and CF06). The model accounts for IGM inhomogeneities by adopting a lognormal distribution according to the method outlined in Miralda-Escudé, Haehnelt & Rees (2000); reionization is said to be complete once all the low-density regions (say, with overdensities $\Delta < \Delta_{\text{crit}} \sim 60$) are ionized. The mean free path of photons is thus determined essentially by the distribution of high-density regions. We follow the ionization and thermal histories of neutral, H II and He III regions simultaneously and self-consistently, treating the IGM as a multi-phase medium.

¹ Throughout this Letter, we use the best-fitting cosmological parameters from the 3-yr *WMAP* data (Spergel et al. 2006), i.e. a flat universe with $\Omega_m = 0.24$, $\Omega_\Lambda = 0.76$ and $\Omega_b h^2 = 0.022$, and $h = 0.73$. The parameters defining the linear dark matter power spectrum are $\sigma_8 = 0.74$, $n_s = 0.95$ and $dn_s/d\ln k = 0$.

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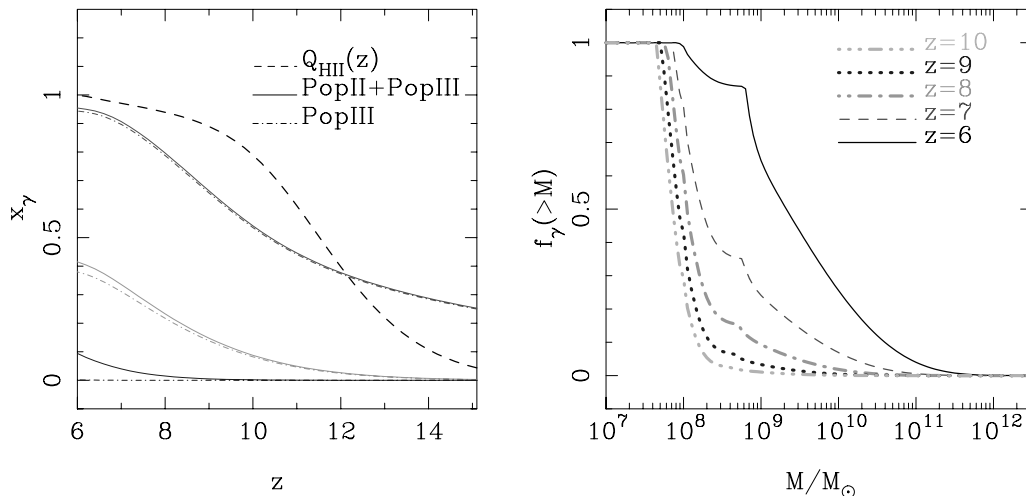


Figure 1. Left: number of ionizing photons per H atom contributed by haloes of different mass in a fraction of the Hubble time $t_H(z)$ equal to the recombination time $t_{\text{rec}}(z)$ as a function of redshift z for different halo masses and for different stellar populations. The solid and dot-dashed pairs of curves, from top to bottom, represent haloes of masses $10^7 M_\odot < M < 10^8 M_\odot$, $10^8 M_\odot < M < 10^9 M_\odot$ and $M > 10^9 M_\odot$ respectively. The dashed line represents the evolution of the volume filling factor Q_{HII} of ionized regions. Right: cumulative fraction of the ionizing power f_γ contributed by haloes of mass $>M$. The curves from right to left correspond to $z = 6, 7, 8, 9$ and 10 respectively.

Three types of reionization sources have been assumed: (i) metal-free (i.e. Population III, hereafter PopIII) stars having a Salpeter initial mass function (IMF) in the mass range $1\text{--}100 M_\odot$ – they dominate the photoionization rate at high redshifts; (ii) Population II (hereafter PopII) stars with subsolar metallicities also having a Salpeter IMF in the mass range $1\text{--}100 M_\odot$; (iii) QSOs, which are significant sources of hard photons at $z \lesssim 6$; they have negligible effects on the IGM at higher redshifts. Note that there is no compelling reason to rule out the possibility that the IMF of PopIII stars was top-heavy; however, as this is not required by current data, we limit ourselves to the most conservative model.

Reionization by ultraviolet sources is accompanied by photo-heating of the gas, which can result in a suppression of star formation in low-mass haloes. We compute such (radiative) feedback self-consistently from the evolution of the thermal properties of the IGM. Furthermore, the chemical feedback inducing the PopIII \rightarrow PopII transition is implemented according to the detailed study by Schneider et al. (2006) in which a merger-tree ‘genetic’ approach is used to determine the termination of PopIII star formation in a metal-enriched halo.

The predictions of the model are compared with a wide range of observational data sets, namely (i) redshift evolution of Lyman-limit absorption systems (Storrie-Lombardi et al. 1994), (ii) IGM Ly α and Ly β optical depths (Songaila 2004), (iii) electron scattering optical depth (Spergel et al. 2006), (iv) temperature of the mean intergalactic gas (Schaye et al. 1999), (v) cosmic star formation history (Nagamine et al. 2004), and (vi) source number counts at $z \approx 10$ from the NICMOS HUDF (Bouwens et al. 2005).

The best-fitting reionization model is characterized by a PopII (PopIII) star-forming efficiency $\epsilon_{*,\text{II}} = 0.1$ ($\epsilon_{*,\text{III}} = 0.03$) and escape fraction $f_{\text{esc,II}} = 0.01$ ($f_{\text{esc,III}} = 0.68$) (keeping in mind that $f_{\text{esc,II}}$ and $f_{\text{esc,III}}$ are not independent).² The resultant value of the electron scattering optical depth is $\tau_{\text{el}} = 0.1$.

² The values are slightly different from those quoted in CF06 because of an improved likelihood analysis. The qualitative results and main conclusions are unaffected by this modification.

The data constrain the reionization scenario quite tightly. We find that hydrogen reionization starts at $z \approx 15$ driven by metal-free (PopIII) stars, and it is 90 per cent complete by $z \approx 8$. This can be seen from the dashed curve in Fig. 1 which represents the evolution of the volume filling factor $Q_{\text{HII}}(z)$ of ionized regions. After a rapid initial phase, the growth of the volume filled by ionized regions slows down at $z \lesssim 10$ because of the combined action of chemical and radiative feedback, making reionization a considerably extended process completing only at $z \approx 6$.

3 PROPERTIES OF THE REIONIZATION SOURCES

Having identified the most probable reionization scenario, we can now confidently determine the properties of the reionization sources governing it. Let us start by defining the quantity

$$x_\gamma(z) \equiv \frac{n_\gamma(z) t_{\text{rec}}(z)}{n_{\text{H}} t_{\text{H}}(z)} \quad (1)$$

as the number of ionizing photons per H-atom contributed by haloes in the mass range $[M_{\text{min}}, M_{\text{max}}]$ in a fraction of the Hubble time $t_H(z)$ equal to the recombination time $t_{\text{rec}}(z)$. By construction, the IGM is reionized when $x_\gamma \gtrsim 1$. The quantity n_{H} is the comoving number density of hydrogen atoms while n_γ is the time-integrated comoving photon density, calculated using the relation

$$n_\gamma(z) = \int_0^{t(z)} dt \dot{n}_\gamma(M_{\text{min}} : M_{\text{max}}, t), \quad (2)$$

where $\dot{n}_\gamma(M_{\text{min}} : M_{\text{max}}, t)$ is the ionizing photon comoving emissivity from haloes within $[M_{\text{min}}, M_{\text{max}}]$.

The plot of $x_\gamma(z)$ for different mass ranges is shown in Fig. 1. The lower mass $10^7\text{--}10^8 M_\odot$ haloes dominate the photon production rate at early redshifts, providing about 0.25 photon per H atom on the fractional recombination time-scale. These objects produce the first ionized regions, are preferentially metal-free, and therefore mostly harbour PopIII stars of high specific ionizing power. At $z < 8$, the contribution from PopIII haloes decreases because their formation is hampered by the heating associated with radiative feedback. As

a result, the progress of ionization fronts relies on photons emitted by more massive haloes with $M > 10^9 M_\odot$. It can be seen from Fig. 1 that such high-mass haloes do not host PopIII stars as they form from the merging of already polluted progenitors, a result of the ‘genetic’ transmission of chemical feedback (Schneider et al. 2006). This combination of radiative and chemical feedback makes the reionization process quite extended and its completion has to wait until $z \approx 6$ when the PopII stars (and QSOs, not shown in the figure; see CF06 for details) dominate the photoionization rate.

Additional insights on the source properties may be gained by considering the fractional instantaneous contribution of haloes above a certain mass,

$$f_{\gamma}(> M, z) \equiv \frac{\dot{n}_{\gamma}(> M, z)}{\dot{n}_{\gamma}(z)}, \quad (3)$$

also shown for different redshifts in the right-hand panel of Fig. 1. The results shown emphasize again that > 80 per cent of the ionizing power at $z \geq 7$ is provided by haloes with masses $< 10^9 M_\odot$ which are predominantly harbouring PopIII stars. A turnover to a PopII-dominated reionization phase occurs shortly after, with this population, residing in $M > 10^9 M_\odot$ haloes, producing ≈ 60 per cent of the ionizing photons at $z = 6$. In conclusion, PopIII stars and small galaxies initiate reionization at high redshift and remain important until they are overcome by PopII stars and QSOs below $z = 7$.

4 SOURCE COUNTS AT HIGH REDSHIFT

Having determined which haloes contribute most significantly to the ionizing power at a particular redshift, we now address the detectability of these sources in broad-band imaging surveys and the optimal strategies to do so. A halo of (dark matter) mass M at a redshift z will emit a flux given by Salvaterra & Ferrara (2006):

$$F_{\nu_0} = \frac{\epsilon_* (\Omega_b / \Omega_m) M}{4\pi d_L^2(z') \Delta \nu_0} \int d\nu' l_{\nu'}(\Delta t) e^{-\tau_{\text{eff}}(\nu_0, z=0, z')}, \quad (4)$$

where ϵ_* is the star-forming efficiency of the population under consideration, $l_{\nu'}(\Delta t)$ is a template-specific luminosity for the stellar population of age $\Delta t = t_{z'} - t_{z''}$ (the time elapsed between the two redshifts), $d_L(z')$ is the luminosity distance and $\Delta \nu_0$ is the instrumental bandwidth. The quantity $\tau_{\text{eff}}(\nu_0, z = 0, z')$ is the effective optical depth due to intervening gas at ν_0 between z' and $z = 0$. The main contribution to $\tau_{\text{eff}}(\nu_0, z = 0, z')$ comes from the combined blanketing of the Lyman series lines in the emitter rest-frame wavelength range $912 < \lambda < 1216 \text{ \AA}$ and from the continuum absorption from neutral hydrogen in the range $\lambda < 912 \text{ \AA}$. Both the contributions to the opacity can be calculated self-consistently from the (modified) lognormal density distribution (CF05) assumed in our model. For calculating the template luminosity l_{ν} , we use stellar population models (having metallicity $Z = 0.004 = 0.2 Z_\odot$) of Bruzual & Charlot (2003) for PopII stars and of Schaerer (2002) for PopIII stars. Note that the star-forming efficiency ϵ_* in the above equation is fixed by constraining the reionization history and is *not* a free parameter as far as the calculation of the source counts in this work is concerned. The flux F_{ν_0} can be transformed into a magnitude in the AB system:

$$m_{\text{AB}} = -2.5 \log_{10} \left(\frac{F_{\nu_0}}{\text{erg s}^{-1} \text{ cm}^{-2} \text{ Hz}^{-1}} \right) - 48.6. \quad (5)$$

The number of sources within a redshift interval $[z_{\text{min}}, z_{\text{max}}]$ observed in a solid angle $d\Omega$ having a flux larger than F_{ν_0} is

$$N(> F_{\nu_0}) = \int_{z_{\text{min}}}^{z_{\text{max}}} dz' \frac{dV}{dz' d\Omega} \int_{F_{\nu_0}}^{\infty} dF'_{\nu_0} \frac{dn}{dF'_{\nu_0}}(F'_{\nu_0}, z'), \quad (6)$$

where $dV/dz' d\Omega$ denotes the comoving volume element per unit redshift per unit solid angle, and

$$\frac{dn}{dF'_{\nu_0}}(F'_{\nu_0}, z') = \int_{z'}^{\infty} dz'' \frac{dM}{dF'_{\nu_0}}(F'_{\nu_0}, \Delta t) \frac{d^2 n}{dM dz''}(M, z'') \quad (7)$$

is the comoving number of objects at redshift z' with observed flux within $[F'_{\nu_0}, F'_{\nu_0} + dF'_{\nu_0}]$. The quantity $d^2 n/dM dz''$ gives the formation rate of haloes of mass M , which we obtain from our reionization model.

For definiteness, let us consider two bands corresponding to the NICMOS observations of the HUDF (Bouwens et al. 2004, 2005), namely J_{110} and H_{160} ; these broad-band filters are appropriate to detect Lyman-break dropout sources at $z \sim 7.5$ and ~ 10 , respectively. The main results of the calculation are shown in Fig. 2, where we plot the number of sources (i.e. galaxies powered by either PopII or PopIII stars) observed in a particular redshift interval and band as a function of the limiting magnitude m_{AB} . The halo masses corresponding to m_{AB} for the particular redshift under consideration [given by equations (4) and (5)] are shown by the straight lines and the relevant values can be read off from the right vertical axis.

From Fig. 2, we deduce that, at the currently achieved sensitivity limit of ~ 28 AB magnitude, our best-fitting model predicts ~ 10 (1) Lyman-break sources per arcmin² at $z \sim 7.5$ (10) observable in the J_{110} (H_{160}) band. Note that all these sources are bright PopII star-forming haloes having masses $\sim 10^{10} M_\odot$. In the previous section we found that such sources provide only a negligible (≈ 1 per cent) contribution to reionization at $z > 6$.

Some of these sources have been tentatively identified in broad-band observations. For example, observations of the HUDF using the NICMOS filter (Bouwens et al. 2004, 2005) at AB magnitude limit ~ 28 reveal ~ 1 source per arcmin² at $z \sim 7.5$ and < 1 source per arcmin² at $z \sim 10$ respectively. On the other hand, deep near-infrared photometry of two lensing clusters (A1835 and AC114) obtained with ISAAC/VLT (Richard et al. 2006) seems to indicate ~ 1 source per arcmin² at $z \sim 7-10$ at a magnitude limit equivalent to $H_{160, \text{AB}} \sim 26$, which is considerably higher than the NICMOS results. Stringent constraints are difficult to obtain from theoretical models as there remains considerable confusion regarding the actual number of reliable detections. However, although the actual source count is disputed, it is most likely that these tentatively detected sources are bright massive haloes which are not significant for reionization.

The sources responsible for the bulk of reionization are galaxies formed inside low-mass $< 10^8 M_\odot$ haloes and powered by PopIII stars. By inspecting the right-hand panel of Fig. 1 we conclude that, in order to observe sources that contribute to 50 per cent (90 per cent) of the ionizing power at $z \sim 7.5$, it is necessary to observe PopIII sources of mass $< 10^{8.1} M_\odot$ ($< 10^{7.9} M_\odot$). This in turn requires us to reach a magnitude sensitivity of $J_{110, \text{AB}} = 31.2$ (31.7) (left-hand panel of Fig. 2), currently beyond the reach of any instrument. Interestingly, one can expect to observe ~ 15 (30) PopIII sources per arcmin² once such sensitivities are reached. Similar conclusions can be drawn from the right-hand panel for sources at $z \sim 10$ observable in the H_{160} band. For detecting sources that contribute to 50 per cent (90 per cent) of the ionizing power, the magnitude sensitivity required would be $H_{160, \text{AB}} = 32.2$ (32.5), which would again correspond to halo masses of $10^{7.8} M_\odot$ ($10^{7.7} M_\odot$). Hence the detection of reionization sources would require sensitivities better than 32 AB magnitudes in this band.

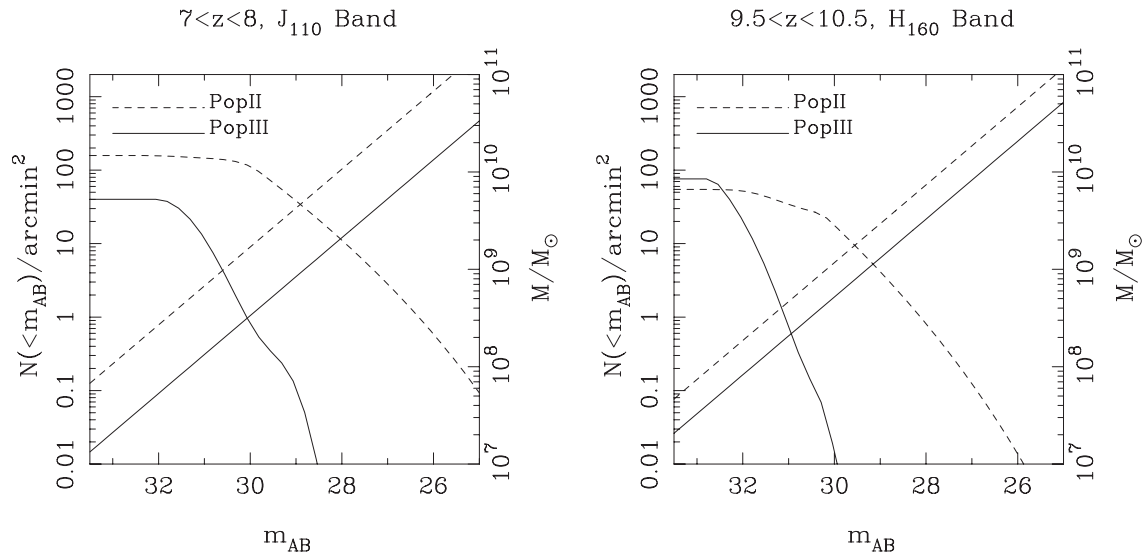


Figure 2. Number density of reionization sources (PopII and PopIII) as a function of the limiting magnitude, m_{AB} , at $7 < z < 8$ observed in the J_{110} band (left-hand panel) and at $9.5 < z < 10.5$ observed in the H_{160} band (right-hand panel). Halo masses corresponding to m_{AB} for the particular redshift under consideration [given by equations (4) and (5)] are shown by the straight lines and the relevant values can be read off from the right vertical axis.

4.1 Variants of the best-fitting model

In this subsection, we try to obtain some indication about how much the source count estimates can vary without violating any other observational constraints. We first note that the star-forming efficiency of PopII sources is quite stringently constrained by low-redshift observations, e.g. the cosmic star formation rate (SFR) and the QSO absorption lines; hence their numbers cannot vary significantly. The situation is markedly different for PopIII stars as there are very few observations constraining their properties. In order to calculate the variation in PopIII source counts, we consider two extreme limits of the parameter $\epsilon_{*,III}$ which are essentially determined by the bounds on τ_{el} :

(i) The high- $\epsilon_{*,III}$ model. This model is characterized by the parameters $\epsilon_{*,II} = 0.1$, $\epsilon_{*,III} = 0.15$, $f_{esc,II} = 0.0$ and $f_{esc,III} = 0.4$. The resultant τ_{el} is 0.12 (the 1σ upper limit given by *WMAP3*; Spergel et al. 2006). The initial stages of reionization in this case proceed much faster than in the best-fitting model and 90 per cent of the IGM is ionized by $z \approx 10.5$. However, because of the high efficiency of the PopIII stars, the radiative feedback is more severe and hence the reionization gets extended until $z \approx 6$ as in the best-fitting model.

(ii) The low- $\epsilon_{*,III}$ model. This model is characterized by the parameters $\epsilon_{*,II} = 0.1$, $\epsilon_{*,III} = 0.01$, $f_{esc,II} = 0.04$ and $f_{esc,III} = 0.06$. The resultant τ_{el} is 0.06 (the 1σ lower limit given by *WMAP3*; Spergel et al. 2006). This model corresponds to the minimum ionizing power contribution required from PopIII stars. This model has an important qualitative difference from the high- $\epsilon_{*,III}$ model: because of such low PopIII efficiency, almost all of the reionization process is driven by the PopII stars. In fact, the lack of ionizing power at high z makes reionization start much later. Also, the effects of feedback are minor in this model; as a result, the reionization occurs rapidly and shortly before $z = 6$.

We now proceed to discuss how these models differ in their predictions for PopIII source counts (Fig. 3). Since the effects of PopIII stars are most noticeable at $z \gtrsim 10$, we focus on the H_{160} band. The first important point is that the number of bright sources increases with $\epsilon_{*,III}$, a direct consequence of the higher specific SFR within dark matter haloes. This would imply that one can observe most of the reionization sources at a magnitude limit of $H_{160,AB} \sim 30.5$,

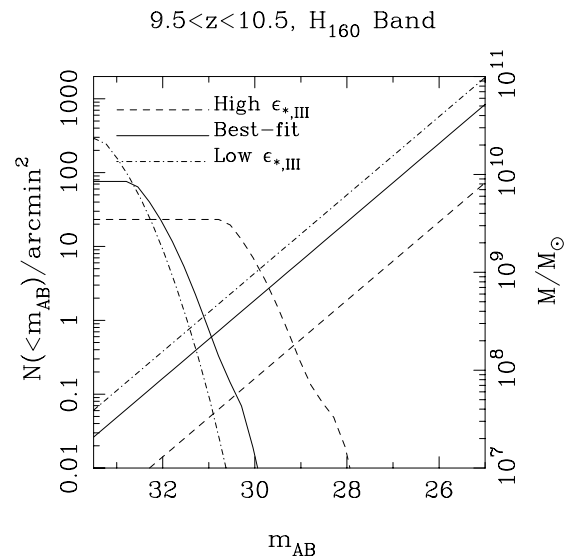


Figure 3. Number density of PopIII sources as a function of the limiting magnitude, m_{AB} , at $9.5 < z < 10.5$ observed in the H_{160} band. The plots are for three models of PopIII star formation as discussed in the text. Halo masses corresponding to m_{AB} for the particular redshift under consideration [given by equations (4) and (5)] are shown by the straight lines and the relevant values can be read off from the right vertical axis.

a limit that will almost certainly be attained by near-future experiments. However, the number of sources detected at fainter magnitudes is smaller for the high- $\epsilon_{*,III}$ model than for the other two (best-fitting and high- $\epsilon_{*,III}$) models. This is because the efficient star formation at high z makes the radiative feedback more effective, hence effectively quenching star formation in low-mass haloes and suppressing the number of faint sources. Of course, one finds a rise in the number of faint sources for the low- $\epsilon_{*,III}$ model when the feedback has the least effect; one should be able to observe, in principle, $\gtrsim 100$ sources at $H_{160,AB} \sim 33$. However, one should keep in mind that for low values of $\epsilon_{*,III} \approx 0.01$, PopIII stars are *not* the main driving force for reionization anyway, and the main focus

should be the source counts for PopII sources. In fact, we find that sources contributing to 90 per cent of the ionizing power at $z \approx 7.5$ would be the PopII stars with haloes of mass $< 10^8 M_{\odot}$; they can be observed with a sensitivity limit of $J_{110,AB} \sim 33$, which is quite difficult with near-future experiments.

It is thus clear from the above discussion that the luminosity function of PopIII sources at $z \approx 10$ could be important for constraining the star-forming efficiency of PopIII stars and also for some indirect understanding of feedback effects.

5 DISCUSSION

We have used the self-consistent model of CF06, which is consistent with a variety of observations, to estimate the number of sources (galaxies) at $z \sim 7-10$. From our analysis we can state the following.

(i) The best-fitting model predicts $\gtrsim 1$ sources at $z \sim 7-10$ per arcmin² at a sensitivity limit of ~ 28 AB magnitude, roughly consistent with present observations. However, these sources are bright massive ($\gtrsim 10^{10} M_{\odot}$) haloes forming PopII stars which have a negligible contribution to reionization of the IGM.

(ii) Reionization at $z > 6$ is actually driven by PopIII stars in low-mass ($< 10^8 M_{\odot}$) haloes. The required sensitivity to detect these sources would be 31–32 AB magnitude.

(iii) In case the star-forming efficiency of PopIII stars is higher than what is assumed in our best-fitting model, the reionization sources can be detected with sensitivities of 30 AB magnitude; however, the number of sources detected could be smaller than the best-fitting model because of negligible star formation in low-mass haloes due to radiative feedback.

(iv) For low star-forming efficiencies of PopIII stars (~ 0.01), the reionization is actually driven by PopII stars and occurs rapidly and shortly before $z = 6$. In this case, the sensitivity required to observe the reionization sources (PopII stars within haloes of masses $< 10^8 M_{\odot}$) at $z \gtrsim 6$ would be 33 AB magnitude.

The sensitivities required to observe the reionization sources are expected to be achieved in future deep imaging surveys, particularly those that take advantage of gravitational lensing magnification. For example, the near-infrared Wide Field Camera 3 (WFC3), scheduled to be installed on the *HST* in the near future, promises to achieve a sensitivity limit of $m_{AB} \sim 31$ in the J_{110} and H_{160} filters for a field of view of ~ 5 arcmin² in about a few hundred hours of observation time (Stark, Loeb & Ellis 2007b). According to our estimates, such lensed surveys should be able to detect quite a few PopIII reionization sources (via Lyman-break dropout techniques) in the field of view. A much better prospect of detecting these sources would be through the Ultra-Deep Imaging Survey using the *JWST* which too plans to achieve a sensitivity limit of $m_{AB} \gtrsim 31$ over 100–200 h of observation time per filter (Gardner et al. 2006). Direct detection of these sources would put stringent constraints on reionization history, and in addition can be used for understanding physical processes like feedback.

Provided that the contamination problems due to bright atmospheric emission lines, which could restrict visibility by up to 50 per cent of the redshift range in the J band, could be maintained under control, a complementary approach for detecting the reionization sources would be through narrow-band surveys for Ly α emitters. A rough estimate of the Ly α luminosity from a halo of mass M forming PopIII stars is given by

$$L_{\alpha} = \epsilon_{*,III} (1 - f_{esc,III}) \frac{\Omega_b}{\Omega_m} M c_{Ly\alpha} q(H), \quad (8)$$

where $c_{Ly\alpha} = 1.04 \times 10^{11}$ erg and $q(H)$ is the rate of hydrogen-ionizing photons per unit mass of stars formed (Schaerer 2002). The above relation does not take into account the attenuation arising from neutral hydrogen around the source, hence the luminosities could possibly be overestimated. Under the above assumptions, a $10^8 M_{\odot}$ halo would produce a luminosity of $\sim 10^{41}$ erg s⁻¹ in our best-fitting model. Such luminosities seem to be well within the reach of lensed Ly α surveys. For example, Stark et al. (2007a) have detected ~ 2 sources having luminosities $\sim 10^{41.5}$ erg s⁻¹ at $z \sim 10$ within a area of 0.3 arcmin² using a Keck survey of gravitationally lensed sources. There is a possibility that these sources could be PopIII stars forming in haloes of masses $\gtrsim 10^8 M_{\odot}$ which do have $\lesssim 30$ per cent contribution to the ionizing power at $z \approx 10$. Future narrow-band Ly α surveys like DAzLE³ thus would be extremely important for direct detection of primary reionization sources at high redshift.

Finally, it is worth mentioning that our models do not include (i) star formation in minihaloes where molecular cooling is efficient, or (ii) the possibility of a top-heavy IMF for PopIII stars. The predictions regarding the source counts could vary considerably depending on the details of the above two processes, and hence future surveys present an excellent opportunity to probe such effects.

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³ <http://www.ast.cam.ac.uk/~optics/dazle/>