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 model predicts that hydrogen reionization starts at \( z \approx 15 \), is initially driven by metal-free (PopIII) stars, and is 90% complete by \( z \approx 8 \). We find that a fraction \( f_s > 80\% \) of the ionizing power at \( z \geq 7 \) comes from haloes of mass \( M < 10^9 M_\odot \) predominantly harboring PopIII stars; a turnover to a PopII-dominated phase occurs shortly after, with this population, residing in \( M > 10^9 M_\odot \) haloes, yielding \( f_s \approx 60\% \) at \( z = 6 \). Using Lyman-break broadband dropout techniques, \( J \)-band detection of sources contributing to 50% (90%) of the ionizing power at \( z \approx 7.5 \) requires to reach a magnitude \( J_{10,AB} = 31.2(31.7) \), where \( \sim 15(30) \) (PopIII) sources/arcmin\(^2\) are predicted. We conclude that \( z > 7 \) sources tentatively identified in broadband surveys are relatively massive \( (M \approx 10^9 M_\odot) \) and rare objects which are only marginally \( (\approx 1\%) \) 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 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 progresses are soon expected from a number of different ground-based (LOFAR, MWA, PAST, SKA, ALMA) and space-born (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 absorptions of galaxies, GP and electron scattering optical depths, mean temperature of the intergalactic medium (IGM), and cosmic star formation history; Choudhury & Ferrara 2005, 2006; hereafter CF05 and CF06 respectively). To summarize the emerging picture, the most favorable model is one in which hydrogen reionization was an extended process starting around \( z \approx 15 \) and being 90% complete by \( z \approx 8 \). This (early) reionization model was also shown not to be in conflict with the Gunn-Peterson optical depth evolution deduced from QSO absorption line experiments at \( z \gtrsim 6 \) both by using the statistics of dark gaps in the Ly\( \alpha \) 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 \( (M < 10^9 M_\odot) \) 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 IR 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 work\(^1\) could be summarized along the following points (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 \( \delta < \Delta_{\text{crit}} \approx 60 \)) 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, HII and HeIII regions simultaneously and self-consistently, treating the IGM as a multi-phase medium.

Three types of reionization sources have been assumed: (i)\footnote{Throughout the paper, we use the best-fit cosmological parameters from the 3-year WMAP data (Spergel et al. 2006), i.e., a flat universe with \( \Omega_m = 0.24 \), \( \Omega_\Lambda = 0.76 \), and \( \Omega_bh^2 = 0.022 \), and \( h = 0.73 \). The parameters defining the linear dark matter power spectrum are \( \sigma_8 = 0.74 \), \( n_s = 0.95 \), \( \frac{dn_s}{d\ln k} = 0 \).}

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metal-free (i.e. PopIII) stars having a Salpeter IMF in the mass range $1 - 100 \, M_\odot$: they dominate the photoionization rate at high redshifts; (ii) PopII stars with sub-solar metallicities also having a Salpeter IMF in the mass range $1 - 100 \, M_\odot$; (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 UV 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 (radial) feedback self-consistently from the evolution of the thermal properties of the IGM. Furthermore, the chemical feedback inducing the PopIII → 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 Lyα and Lyβ 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 NICMOS HUDF (Bouwens et al. 2005).

The best-fit reionization model is characterized by a PopII (PopIII) star-forming efficiency $\epsilon_{\text{star}} = 0.1$ ($\epsilon_{\text{star}} = 0.03$) 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 $\tau_e = 0.1$.

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 $z \lesssim 10$ due to 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

$$x_\gamma(z) \equiv \frac{n_\gamma(z)}{n_H} \frac{t_{\text{rec}}(z)}{t_H(z)} \tag{1}$$

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 $n_\gamma$ is the time-integrated comoving photon density, calculated using the relation

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

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 $10^7$-$10^8 \, M_\odot$ haloes dominate the photon production rate at early redshifts providing about 0.25 photon/H-atom on the fractional recombination timescale. These objects produce the first ionized regions, are preferentially metal-free, and therefore mostly harbor 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

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\(^2\) 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.
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7 < z < 8, Jν10 Band

9.5 < z < 10.5, Hν180 Band

Figure 2. Number density of reionization sources (PopII and PopIII) as a function of the limiting magnitude, mAB, at 7 < z < 8 observed in Jν10 band (left panel) and at 9.5 < z < 10.5 observed in Hν180 band (right). Halo masses corresponding to mAB 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.

Photons emitted by more massive haloes with M > 10^9 M⊙. 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 ≈ 6 when the PopII stars (and QSOs, not shown in the Figure; see CF06 for details) dominate.

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

\[ f_s(M, z) = \frac{\dot{n}_s(M, z)}{\dot{n}_s(z)} \]

also shown for different redshifts in the right hand panel of Figure 1. The results shown emphasize again that > 80% of the ionizing power at z ≥ 7 is provided by haloes with masses < 10^9 M⊙ which are predominantly harboring PopIII stars. A turnover to a PopII-dominated reionization phase occurs shortly after, with this population, residing in M > 10^9 M⊙ haloes, producing ≈ 60% of the ionizing photons at z = 6. In conclusion, PopII 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 broadband 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)

\[ F_{\nu_0} = \frac{\epsilon_s(\Omega_h/\Omega_m) M}{4\pi d_l^2(z')^2} \int d\nu' l_{\nu'}(\Delta t) e^{-\tau_{\nu_0}(\nu_0, z = 0, z')} \]

where \( \epsilon_s \) 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 \( \Delta t_{\nu_0} \) is the instrumental bandwidth. The quantity \( \tau_{\nu_0}(\nu_0, z = 0, z') \) is the effective optical depth due to intervening gas at \( \nu_0 \) between \( z' \) and \( z = 0 \). The main contribution to \( \tau_{\nu_0}(\nu_0, z = 0, z') \) comes from the combined blanketing of the Lyman series lines in the emitter rest frame wavelength range 912 Å < \( \lambda \) < 1216 Å and from the continuum absorption from neutral hydrogen in the range \( \lambda < 912 \) Å. 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 \( l_{\nu} \), we use stellar population models (having metallicity \( Z = 0.004 = 0.22 Z_\odot \)) of Bruzual & Charlot (2003) for PopII stars and of Schaerer (2002) for PopIII stars. Note that the star-forming efficiency \( \epsilon_s \) 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 \( F_{\nu_0} \) can be transformed into a magnitude in the AB system:

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

The number of objects within a redshift interval \([z_{\min}, z_{\max}]\) observed in a solid angle \( d\Omega \) having a flux larger than \( F_{\nu_0} \) is

\[ N(> F_{\nu_0}) = \int_{z_{\min}}^{z_{\max}} \frac{dz'}{dz} dV \int_{F_{\nu_0}}^{\infty} dF_{\nu_0} \frac{dN}{dF_{\nu_0}}(F_{\nu_0}, z') \]

where \( dV/dz = \frac{dV}{dt} \) denotes the comoving volume element per unit redshift per unit solid angle, and

\[ \frac{dN}{dF_{\nu_0}}(F_{\nu_0}', z') = \int_{z'}^{\infty} dz'' \frac{dM}{dF_{\nu_0}}(F_{\nu_0}', \Delta t) \frac{d^2n}{dM dz''}(M, z'') \]

is the comoving number of objects at redshift \( z' \) with observed flux within \([F_{\nu_0}', F_{\nu_0} + dF_{\nu_0}']\). The quantity \( d^2n/dM dz'' \) 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; Bouwens et al. 2005), namely J_{110} and H_{160}; these broadband filters are appropriate to detect Lyman-break dropout sources at \( z \sim 7.5 \) and \( z \sim 10 \), 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-fit model predicts \( \sim 10(1) \) Lyman-break sources per arcmin\(^2\) 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 \( \sim 10^9 M_\odot \). In the previous Section we found that such sources provide only a negligible (\( \approx 1\% \)) contribution to reionization at \( z > 6 \).

Some of these sources have been tentatively identified in broadband observations. For example, observations of HUDF using the NICMOS filter (Bouwens et al. 2004; Bouwens et al. 2005) at AB magnitude limit \( \sim 28 \) reveal \( \sim 1 \) source per arcmin\(^2\) at \( z \sim 7.5 \) and \( < 1 \) source per arcmin\(^2\) at \( z \sim 10 \) respectively. On the other hand, deep near-IR photometry of two lensing clusters (A1835 and AC114) obtained with ISAAC/VLT (Richard et al. 2006) seem to indicate \( \sim 1 \) source per arcmin\(^2\) at \( z \sim 7 \sim 10 \) at a magnitude limit equivalent to \( H_{160,AB} \sim 26 \), 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 \( < 10^9 M_\odot \) haloes and powered by PopIII stars. By inspecting the right hand panel of Fig. 1 we conclude that in order to observe sources which contribute to 50% (90%) of the ionizing power at \( z \sim 7.5 \), it is necessary to observe PopIII sources of mass \( < 10^{8.3} M_\odot \) (\( < 10^{7.9} M_\odot \)). This in turn requires to reach a magnitude sensitivity of \( J_{110,AB} = 31.2(31.7) \) (left panel of Fig. 2), currently beyond the reach of any instrument. Interestingly, one can expect to observe \( \sim 15(30) \) PopIII sources per arcmin\(^2\) 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 which contribute to 50% (90%) of the ionizing power, the magnitude sensitivity required would be \( H_{160,AB} = 32.2(32.5) \), which would again correspond to halo masses of \( 10^{8.8} M_\odot (10^{7.7} M_\odot) \). Hence, the detection of reionization sources would require sensitivities better than 32 AB magnitudes in this band.

### 4.1 Variants of the best-fit model

In this subsection, we try to obtain some indication about how much can the source count estimates vary without violating any other observational constraints. We first note that the star-forming efficiency of PopII sources are quite stringently constrained by low-redshift observations, e.g., the cosmic 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 \( \tau_{el} \):

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

2. **The low-\( \epsilon_{*,III} \) model:** This model is characterized by the parameters \( \epsilon_{*,III} = 0.1 \), \( f_{esc,III} = 0.01 \), \( f_{esc,II} = 0.04 \), \( f_{esc,III} = 0.06 \). The resultant \( \tau_{el} = 0.06 \) (the 1-\( \sigma \) lower limit given by WMAP3; Spergel et al. 2006). This model corresponds to the minimum 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 \( H_{160,AB} \sim 30.5 \), a limit almost certainly 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-fit and low-\( \epsilon_{*,III} \)) models. This is because the efficient star formation at high-\( z \) makes the radiative feedback more effec-

![Figure 3. Number density of PopIII sources as a function of the limiting magnitude, \( m_{AB} \), at 9.5 < \( z < 10.5 \) observed in \( H_{160} \) 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.](image-url)
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tive, 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-$\epsilon_{111}$ 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 $\epsilon_{111} \approx 0.01$, 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% 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 $z \sim 7 - 10$. According to our analysis:

- The best-fit model predicts $\gtrsim 1$ sources at $z \sim 7 - 10$ per arcmin$^{2}$ at a sensitivity limit of $\sim 28$ AB magnitude, roughly consistent with present observations. However, these sources are bright massive ($\gtrsim 10^{10} M_{\odot}$) haloes forming PopIII stars which have negligible contribution to reionization of the IGM.

- Reionization at $z > 6$ is actually driven by PopIII stars in low mass ($< 10^{7} M_{\odot}$) haloes. The required sensitivity to detect these sources would be 31-32 AB magnitude.

- In case the star-forming efficiency of PopIII stars is higher than what is assumed in our best-fit 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-fit model because of negligible star formation in low-mass haloes due to radiative feedback.

- For low star-forming efficiencies of PopIII stars ($\sim 0.01$), 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 the ones which take advantage of gravitational lensing magnification. For example, the NIR Wide Field Camera 3 (WFC3), scheduled to be installed on HST in near future, promises to achieve a sensitivity limit of $m_{AB} \sim 31$ in the J110 and H160 filters for a field of view of $\sim 5$ arcmin$^{2}$ in about a few hundred hours of observation time (Stark, Loeb, & Ellis 2007). 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 hours 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 up to 50% 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$\alpha$ emitters. A rough estimate of the Ly$\alpha$ luminosity from a halo of mass $M$ forming PopIII stars is given by

$$L_{\alpha} = \epsilon_{111}(1 - f_{esc,111}) \frac{\Omega_{b}}{\Omega_{m}} M c_{Ly\alpha} q(H)$$

where $c_{Ly\alpha} = 1.04 \times 10^{13}$ 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 $10^{6} M_{\odot}$ halo would produce a luminosity of $\sim 10^{41}$ erg s$^{-1}$ in our best-fit model. Such luminosities seem to be well within the reach of lensed Ly$\alpha$ surveys. For example, Stark et al. (2007) have detected $\sim 2$ sources having luminosities $\sim 10^{41.5}$ erg s$^{-1}$ at $z \sim 10$ within a area of 0.3 arcmin$^{2}$ using a Keck survey of gravitationally-lensed sources. There is a possibility that these sources could be PopIII stars forming in haloes of masses $\gtrsim 10^{6} M_{\odot}$ which do have $\lesssim 30\%$ contribution to the ionizing power at $z \approx 10$. Future narrowband Ly$\alpha$ surveys like DAZLE$^{3}$ 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/