Updating reionization scenarios after recent data

T. Roy Choudhury$^1$ and A. Ferrara$^2$

$^1$Centre for Theoretical Studies, Indian Institute of Technology, Kharagpur 721302, India
$^2$SISSA/ISAS, via Beirut 2-4, 34014 Trieste, Italy

ABSTRACT
The recent release of data on (i) high redshift source counts from NICMOS HUDF, and (ii) electron scattering optical depth from 3-year WMAP, require a re-examination of reionization scenarios. Using an improved self-consistent model, based on Choudhury & Ferrara (2005), we determine the range of reionization histories which can match a wide variety of data sets simultaneously. From this improved analysis we find that hydrogen reionization starts around $z = 15$, driven by the metal-free stars (with normal Salpeter-like IMF), and is 90% complete by $z \approx 10$. The photoionizing power of PopIII stars fades for $z \lesssim 10$ because of the concomitant action of radiative and chemical feedbacks, which causes the reionization process to stretch considerably and to end only by $z \approx 6$. The combination of different data sets still favours a non-zero contribution from metal-free stars, forming with efficiencies $> 2\%$.

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

1 INTRODUCTION
The determination of the high Thomson electron scattering optical depth $\tau_{\text{el}} = 0.17 \pm 0.04$ in the WMAP 1st year data (Kogut et al. 2003; Spergel et al. 2003) had been a subject of extensive theoretical study over the last few years. For sudden reionization models, the high value of $\tau_{\text{el}}$ implied that reionization occurred at very high redshifts $z \approx 15$. This scenario seemed to be at tension with the measured Gunn-Peterson (GP) optical depth $\tau_{\text{GP}}(z = 6) \gtrsim 6$ from the absorption line experiments of $z \gtrsim 6$ Sloan Digital Sky Survey (SDSS) QSOs (Fan et al. 2001; Fan et al. 2003; Fan et al. 2005). Such high values of $\tau_{\text{GP}}$ seem to indicate that reionization was complete only at $z \approx 6$.

Using a self-consistent formalism confronted with a wide range of observational data sets (redshift evolution of Lyman-limit absorption systems, GP and electron scattering optical depths, temperature of the mean intergalactic gas, and cosmic star formation history), Choudhury & Ferrara (2005; hereafter CF05) showed that the most favourable model is the one in which hydrogen reionization was complete at $z \approx 12$. By using the statistics of dark gaps in the Ly$\alpha$ transmitted flux, this early reionization model was also shown not to be in conflict with QSO absorption line experiments at $z \gtrsim 6$ (Gallerani, Choudhury, & Ferrara 2005). However, a nearly equally good fit to the data could be achieved for late reionization scenarios too (i.e., scenarios in which reionization is complete only at $z \approx 6$), particularly if one relaxes the constraints on $\tau_{\text{el}}$. Given this, the need was to find an additional way to distinguish between the early and late reionization models, either through new theoretical methods (Gallerani, Choudhury, & Ferrara 2005) or from additional observational constraints.

Fortunately, two new sets of data have been made available recently which could help in constraining the reionization history. First is the observations of high redshift sources in the NICMOS HUDF (Bouwens et al. 2005), where the analysis indicate that the number of sources at $z \approx 10$ should be three or fewer. This inevitably rules out the occurrence of very massive ($\gtrsim 300 M_\odot$) stars (Salvaterra & Ferrara 2005). The second set of observations is the release of 3-year WMAP data (Hinshaw et al. 2006; Page et al. 2006; Spergel et al. 2006), which gives a lower value of $\tau_{\text{el}} = 0.09 \pm 0.03$, thus questioning very early reionization scenarios.

Given these new data sets, it is important to find out the updated constraints on reionization using self-consistent models. More importantly, one has to address the issue as to which reionization histories are still viable and which sources are responsible for it. In this work, we extend the model of CF05 incorporating some additional physics (like chemical feedback) thus reducing the number of free parameters. We then confront the model with a wide variety of available data sets (including the two most recent ones above) with the aim of identifying a set of parameter values which can fit all the data sets simultaneously.

2 MODEL DESCRIPTION
In this Section, we first summarize the main features of the model introduced in CF05; following that we discuss the modifications and improvements made for the purpose of this work.
2.1 Summary of the model

The main features of the semi-analytical model used in CF05 could be summarized along the following points (for detailed explanations see CF05). 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. Hence, the distribution of high density regions determines the mean free path of photons

\[
\lambda_{\text{mfp}}(z) = \frac{\lambda_0}{[1 - F_V(z)]^{2/3}}
\]

(1)

where \( F_V \) is the volume fraction of ionized regions and \( \lambda_0 \) is a normalization constant fixed by comparing with low redshift observations. We follow the ionization and thermal histories of neutral, \( \text{HII} \) and \( \text{HeIII} \) regions simultaneously and self-consistently, treating the IGM as a multi-phase medium. As reionization by UV sources is accompanied by heating of the medium, which can suppress star formation in low-mass halos, we compute the corresponding radiative feedback self-consistently from the evolution of the thermal properties of the IGM. To calculate the ionizing flux, three sources have been assumed: (i) metal-free (i.e., PopIII) stars, which dominate the flux at high redshifts. In CF05, they were assumed to be massive (\( M \geq 100 M_\odot \)); (ii) PopII stars with sub-solar metallicities having a Salpeter IMF in the mass range \( 1 < M < 100 M_\odot \). The transition redshift, \( z_{\text{trans}} \) from PopIII to PopII stars was a free parameter, usually fixed to be \( z_{\text{trans}} \geq 10 \); (iii) QSOs, which are significant source for hard photons at \( z \lesssim 6 \); however they have no effect on the IGM at higher redshifts.

2.2 New features

We now discuss the additional physics we have incorporated in this work in order to further improve the predictive power of the model.

- **Radiative feedback**: We have assumed that no haloes with virial temperatures lower than \( 10^4 \text{ K} \) are able to form stars; this completely neglects the contribution of minihaloes, which is now strongly supported by the 3-year WMAP data (Haiman & Bryan 2006).

- **Chemical feedback**: The main limitation of CF05 model was the idealized PopIII \( \rightarrow \) PopII transition which was assumed to start at \( z_{\text{trans}} \) and last for a dynamical time of the halo. According to the standard chemical feedback interpretation (Schneider et al. 2002; Schneider et al. 2003), the transition is driven by the enrichment of the medium which forces a drastic change in the fragmentation properties of star-forming clouds when metallicity exceeds the critical value of \( Z_{\text{crit}} = 10^{-5.5} Z_\odot \) (Schneider et al. 2002; Schneider et al. 2003). Such feedback-regulated transition has been studied in detail by Schneider et al. (2005), using a merger-tree approach to determine the termination of PopIII star formation in a given halo. We incorporate the same prescription in our model (using Fig 3 of Schneider et al. 2005), which allows us to compute the transition in a self-consistent manner. The main difference with respect to CF05 is that the transition occurs over a prolonged epoch, i.e., no precise transition redshift can be identified.

- **IMF of PopIII stars**: In CF05, a top-heavy IMF for PopIII stars was used, which was found to be disfavoured by a combination of constraints from source counts at \( z \approx 10 \) and the first year WMAP data (Schneider et al. 2005). In this work we use a very “conservative” assumption that the metal-free PopIII stars have a simple Salpeter IMF, just like the PopII stars, which is similar to the hypothesis made in Ciardi, Ferrara, & White (2003). One should keep in mind that the recent 3-year WMAP data need not necessarily rule out the possibility that PopIII stars have a top-heavy IMF; however, we limit ourselves to the most conservative model and check whether it can match all available observations.

- **Escape fraction**: In CF05, the escape fractions for PopII and PopIII stars, \( f_{\text{esc,II}} \) and \( f_{\text{esc,III}} \), were considered as free parameters, independent of the halo mass, \( M \), and redshift \( z \). In reality, the situation is quite complex and the escape fractions do depend on both \( M \) and \( z \). Unfortunately, there is still no good understanding of the process so as to model it theoretically.

In this work, we retain the assumption that the escape fraction is independent of \( M \) and \( z \); however, we use a physical argument to relate the escape fraction of PopII and PopIII stars. This is based on the fact that the escape fraction should scale according to the number of ionizing photons produced by a given source. Let \( N_{\text{abs}} \) denote that number of photons that can be potentially absorbed by the star-forming halo (which can be quite different from the number of photons actually absorbed). It is usually proportional to the quantity \( f_{\text{esc}}(T) n_H n_e \), where \( C \) is the clumping factor of the halo gas density inhomogeneities. There are further uncertainties related to the distribution of stars within the halo, and we assume that such uncertainties can be absorbed within the proportionality factor. Let \( N_{\gamma,\text{II}}(N_{\gamma,\text{III}}) \) denote the number of photons produced by PopII (PopIII) stars per unit mass of star formed and \( \epsilon_{\gamma,\text{II}}(\epsilon_{\gamma,\text{III}}) \) denote the star-forming efficiency of the population. We can then define the parameter

\[
\eta_{\text{esc}} \equiv \frac{N_{\text{abs}}}{\epsilon_{\gamma,\text{II}} N_{\gamma,\text{II}}}
\]

(2)

which measures the fraction of photons absorbed in the halo. Then one can write the relation

\[
f_{\text{esc,II}} = 1 - \text{Min}\left[1, \frac{N_{\text{abs}}}{\epsilon_{\gamma,\text{II}} N_{\gamma,\text{II}}} \right] = 1 - \text{Min}[1, \eta_{\text{esc}}]
\]

(3)

which takes into account the fact that \( f_{\text{esc,II}} = 0 \) if \( \eta_{\text{esc}} > 1 \) (which essentially means that the halo is capable of absorbing more photons than what is produced by the stars and thus all the photons produced are absorbed within the halo). Note that a higher value of \( \epsilon_{\gamma,\text{II}} \) would give a higher \( f_{\text{esc,II}} \) suggesting that a higher fraction of photons will escape if the number of photons produced is larger.

We now make the simplifying assumption that \( N_{\text{abs}} \) depends only on the properties of the halo and is independent of the nature of the stellar source. Then the escape fraction for PopIII stars would be given by

\[
f_{\text{esc,III}} = 1 - \text{Min}\left[1, \frac{N_{\text{abs}}}{\epsilon_{\gamma,\text{III}} N_{\gamma,\text{III}}} \right] = 1 - \text{Min}\left[1, \frac{\epsilon_{\gamma,\text{III}} N_{\gamma,\text{III}}}{\epsilon_{\gamma,\text{II}} N_{\gamma,\text{II}} \eta_{\text{esc}}} \right]
\]

(4)

which relates the escape fractions of the two stellar populations. Note that no assumptions about the gas density structure has been made; we simply used the fact that a higher fraction of photons will escape if the number of photons produced is larger. The above prescription can be extended to helium too. It thus helps us in reducing the number of free parameters in our model with the escape fraction being given by a single free parameter \( \eta_{\text{esc}} \).

- **Self-consistent calculation of the temperature-density relation**: For calculations of the transmitted flux of the IGM (as would be observed in QSO absorption line experiments), it is usually assumed that the temperature-density relation follows a power-law
form, $T \propto \Delta \gamma^{-1}$. In this work, we solve the temperature evolution equation for fluid elements of different densities and thus obtain the value of $\gamma$ at each redshift in a self-consistent manner (Hui & Gnedin 1997).

- **Additional observational constraints:** In addition to the observations described in CF05, we use a few additional constraints to determine our free parameters. The most notable of these is the experiments related to the source counts at high redshifts (Bouwens et al. 2005). Three possible high redshift candidates have been identified by applying the J-dropout technique to the NICMOS HUDF; however the precise nature of these three sources could not be confirmed. Hence, Bouwens et al. (2005) concluded that the actual number of $z \approx 10$ sources in the NICMOS parallel fields must be three or fewer.

The number of sources above a redshift $z$ observed within a solid angle $d\Omega$ in the flux range $[F_{\nu_1}, F_{\nu_2} + dF_{\nu_2}]$ is

$$N_{F_{\nu_1}}(z) = \frac{dN}{d\Omega dF_{\nu_1}}(F_{\nu_1}, z) = \int z' dz' \frac{dV}{dz'} \frac{d\Omega}{d\Omega} \frac{dF_{\nu_1}}{dF_{\nu_1}}(F_{\nu_1}, z')$$

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

$$\frac{d\Omega}{dF_{\nu_1}}(F_{\nu_1}, z') = \int z'' dz'' d\Omega(F_{\nu_1}, t_{\nu_1} - t_{\nu_2}) \frac{d^2\Omega}{dM d\Omega}(M, z'')$$

is the comoving number of objects at redshift $z'$ with observed flux within $[F_{\nu_1}, F_{\nu_2} + dF_{\nu_2}]$. The quantity $d^2\Omega/dMdz''$ gives the formation rate of haloes of mass $M$, calculated using Press-Schechter formalism. The flux is related to the mass of the halo $M$ by the relation

$$F_{\nu_1} = \frac{\epsilon_\nu(\Omega_\nu/M_{\odot}) M \int d\nu \nu' \int_{t_{\nu_1}}^{t_{\nu_2}} \int_{z''}^{z'} \int_{z''}^{z''} 4\pi d^2\lambda^2 d\nu' d\lambda'}{4\pi d^2\lambda^2 d\nu'}$$

where $\epsilon_\nu$ is the star-forming efficiency of the population under consideration, $\lambda'_{\nu}(t_{\nu_1} - t_{\nu_2})$ is template luminosity per unit solar mass for the stellar population of age $t_{\nu_1} - t_{\nu_2}$ (the time elapsed between the two redshifts), $d^2\lambda^2(d\nu')$ is the luminosity distance and $d\Omega_\nu$ is the instrumental bandwidth. The quantity $\tau_{\Omega}(v_0, z = 0, z')$ is the effective optical depth at $v_0$ between $z'$ and $z = 0$, which can be calculated self-consistently from the semi-analytical model given the density distribution. While calculating the source distribution, we apply the same selection criteria as is used in the observational analysis. For calculating the template luminosity $\lambda'$, we use stellar population models of Bruzual & Charlot (2003) for PopII stars and of Schaerer (2002) for PopIII stars.

We have also incorporated constraints from the observed transmitted flux in the Ly$\beta$ region of the QSO absorption spectra (in addition to Ly$\alpha$), setting more severe constraints on the background ionizing flux.

### 2.3 Free parameters

For the background cosmology, we use the best-fit parameters as given by the 3-year WMAP data (Spergel et al. 2006), i.e., we assume a flat universe with total matter, vacuum, and baryonic densities in units of the critical density of $\Omega_m = 0.24$, $\Omega_{\Lambda} = 0.76$, and $\Omega_b h^2 = 0.022$, respectively, and a Hubble constant of $H_0 = 100 h$ km s$^{-1}$ Mpc$^{-1}$, with $h = 0.73$. The parameters defining the linear dark matter power spectrum are $\sigma_8 = 0.74$, $n_s = 0.95$, $\Omega_{\Lambda} h^2/d\ln k = 0$. The reionization model, after improvements and modifications, contain just four free parameters. They are the star-forming efficiencies of PopII and PopIII stars ($\epsilon_{II}$ and $\epsilon_{III}$ respectively), $\eta_{esc}$ related to the escape fractions of the two stellar populations [see equations (2)-(5)] and the normalization of the mean free path $\lambda_0$ [equation (1)]. The main exercise of this paper would be to find the range of parameter values which can match all the observational data we have considered. A detailed exploration of the parameter space using a statistical approach would be reported elsewhere.

### 3 RESULTS

We now constrain the above free parameters and select the best-fit model as the one that fits simultaneously all the available experimental data.

#### 3.1 The best-fit model

The best-fit model is characterized by the parameter values $\epsilon_{II} = 0.2$, $\epsilon_{III} = 0.07$, $\epsilon_{esc,II} = 0.003$, $\epsilon_{esc,III} = 0.72$ (keeping in mind that $\epsilon_{esc,II}$ and $\epsilon_{esc,III}$ are not independent). The comparison between the best-fit model and different observations is shown in nine panels of Figure 1. Quite remarkably, the model matches a wide variety of observations by fitting only four parameters.

It is clear from the evolution of the neutral hydrogen fraction $x_{HI}$ [Panel (a)] that current observations favour a model where reionization starts around $z = 15$ and is 90 per cent complete by $z \approx 10$.

The initial phase of reionization is driven by metal-free (PopIII) stars which are capable of producing a large number of ionizing photons, as can be seen from the evolution of the photoionization rate of neutral hydrogen $\Gamma^H_{II}$ [Panel (b)]. The PopIII star-formation is severely quenched at $z \approx 10$ both because of the comacton action of both radiative and chemical feedback. In fact, chemical feedback allows PopIII star formation only in small mass ($\lesssim 2 \times 10^8 M_\odot$) haloes, while radiative feedback tends to prohibit star formation in those, thus gradually terminating the PopIII stars. The total mass of PopIII stars formed is $\Omega_{x_{HI}} \approx 10^{-4}/z$. As PopIII stars can no longer be formed, the progress of ionization fronts is limited, and hence the reionization extends and is completed only by $z \approx 6$. This evolution of $x_{HI}$ is consistent both with high QP optical depths for Ly$\alpha$ [Panel (e)] and Ly$\beta$ [Panel (f)] and with the constraints from Ly$\alpha$ emitters at $z \approx 6.5$ [Panel (a)].

At lower redshifts, the ionizing background seems to be dominated by QSOs as the PopII stars have negligible escape fraction. Unlike CF05, the escape fractions of the PopII and PopIII stars in this work are determined by the same quantity $\eta_{esc}$; hence it is not possible to hike up $f_{esc,II}$ without affecting $f_{esc,III}$, in turn possibly violating some other observational constraints. At $z \approx 3 - 5$, our best-fit model is consistent with the observed evolution of the SFR [Panel (b)], Lyman-limit systems [Panel (g)] and the temperature of the mean density IGM [Panel (i)]; finally, our estimates of $\Gamma^H_{II}$ are consistent with those obtained from numerical simulations of (Bolton et al. 2005) [Panel (h)]. Note that the SFR is almost always dominated by PopII stars [Panel (b)] as metal-free stars have a low star formation efficiency (3 times smaller than that of PopII stars); however, PopIII stars can still dominate the photoionization rate at high redshifts as they produce larger number of photons per unit mass of stars formed.

The best-fit model produces negligible source counts at $z \approx 10$, which suggests that the three NICMOS HUDF candidates at $z \approx 10$ are probably spurious detections. Note that the main contribution to the source counts comes from the nebular and Ly$\alpha$ line emission of the PopIII stars. The low value of source count
is mainly determined by the required high value of $f_{\text{esc,III}}$; since most of the photons escape the host halo, the amount of nebular and Lyα line emission is small, and hence no sources are above the detection threshold of the NICMOS experiments. In this sense, one can rule out this best-fit model if at least one of the sources observed in the NICMOS HUDF turns out to be indeed at $z \approx 10$. We shall discuss this possibility later. Before addressing other issues, it might be worthwhile mentioning the ionization history of doubly-ionized helium. We find that the escape fraction for photons with energies above 54.4 eV is not very high for PopIII stars, and hence the propagation of doubly-ionized helium fronts is not very efficient at high redshifts. The complete reionization occurs only around $z \approx 3.5$ because of QSOs.

### 3.2 Variants of the best-fit model

In spite of the success of our best-fit model in fitting observations, it is instructive to study some of its variants. In particular, we ask some interesting questions and try to find what the current data imply:

(i) Is it possible to fit the data with reionization at higher redshifts? By increasing $\epsilon_{\text{III}}$, one can force an earlier start of the reionization process. For example, a model with parameter values $\epsilon_{\text{HII}} = 0.2, \epsilon_{\text{III}} = 0.2, f_{\text{esc,III}} = 0.006, f_{\text{esc,HII}} = 0.9$ gives a nearly equal good fit to the data. In this model, reionization starts much earlier and the IGM is 95 (99) per cent ionized by $z \approx 6$. However, as in the best-fit model, the contribution of the PopIII stars to the ionizing flux decreases because of feedback and hence the reionization is extended till $z \approx 6$. Interestingly, the most severe constraint on the early reionization scenarios comes from Ly/β observations at $z \approx 6$ which rule out high values of $\epsilon_{\text{III}}, f_{\text{esc,III}}$.

(ii) What if one or some of the candidates in the NICMOS HUDF do turn out to be valid $z \approx 10$ sources? Then the best-fit model above could be ruled out as it predicts negligible source counts at $z > 10$. However, there are parameters within $2\sigma$ of the best-fit value which predict high number of sources at $z \approx 10$. For example, a model with parameter values $\epsilon_{\text{HII}} = 0.2, \epsilon_{\text{III}} = 0.4, f_{\text{esc,III}} = 0.0, f_{\text{esc,HII}} = 0.36$ predicts $\approx 2.6$ sources at $z \approx 10$. The condition for producing high source counts is that the escape fraction of PopIII stars should be low, which in turn means that the ionizing flux is lower and reionization would be de-
layed. Such models tend to overpredict the Ly$_\alpha$ optical depth at $z \approx 4 - 5$ and thus the parameter space is severely constrained. In other words, if one observes sources at high redshifts, a very small parameter space would be allowed, and we would possibly be able to identify uniquely how reionization occurred.

(iii) Do we still require a prolonged epoch of metal-free star formation to explain observations? In fact, one can explain the low redshift SFR constraints and the WMAP $\tau_{\text{el}}$ without PopIII stars provided $\epsilon_{*,11} = 0.2$ and $f_{\text{esc}} > 0.07$. However, such a high value of escape fraction violates the Ly$_\alpha$ and Ly$_\beta$ optical depths at $z \approx 3 - 4$; the GP optical depth measurements require that $f_{\text{esc}} < 0.05$, which when combined with the WMAP $\tau_{\text{el}}$, gives $\epsilon_{*,11} > 0.02$. Thus a combination of low redshift SFR, $\tau_{\text{el}}$ and GP optical depth constraints imply that we still do require a non-zero contribution from metal-free PopIII stars, albeit with a small star-forming efficiency.

4 SUMMARY

We have extended the self-consistent model of CF05 incorporating key additional physical processes and compared the model predictions with a variety of data sets. Our formalism now includes the inhomogeneous IGM density distribution, three different classes of ionizing photon sources (metal-free PopIII stars, PopII stars and QSOs), chemical feedback inhibiting formation of PopIII stars in metal-enriched haloes, and radiative feedback preventing the formation of stars in galaxies below a certain circular velocity threshold. Our model is able to: (i) predict the star formation/emissivity history of sources and the number of sources above a given flux detection threshold at various redshifts, (ii) follow the evolution of H and He reionization and of the intergalactic gas temperature, and (iii) yield a number of additional predictions involving directly observable quantities.

By constraining the model free parameters with the available experimental data we have found a best-fit model and a set of allowed parameter values which matches very well all the available observations. From this analysis, an updated reionization scenario, which also takes into account the 3-year WMAP data, emerges:

- Hydrogen reionization starts around $z \approx 15$ driven by metal-free (PopIII) stars, and it is 90 per cent complete by $z \approx 10$. The contribution of PopIII stars decrease below this redshift because of the combined action of radiative and chemical feedback. As a result, reionization is extended considerably only at $z \approx 6$.
- Scenarios in which reionization is completed much earlier are ruled out by a combination of constraints from $\tau_{\text{el}}$, the NICMOS source counts at $z \approx 10$ and the Ly$_\beta$ optical depths at $z \approx 6$.
- The combination of $\tau_{\text{el}}$ and GP optical depth constraints require non-zero contribution from metal-free stars with a normal Salpeter IMF. Non-inclusion of PopIII stars would require a relatively larger ionization flux from PopII stars to match the WMAP $\tau_{\text{el}}$, which would then violate the GP optical depth constraints.

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