The State of the Universe at $z \sim 6$

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ABSTRACT

In the context stellar reionization in the standard cold dark matter model, we analyze observations at $z \sim 6$ and are able to draw three significant conclusions with respect to star formation and the state of the intergalactic medium (IGM) at $z \sim 6$. (1) An initial stellar mass function (IMF) more efficient, by a factor of $10^{-20}$, in producing ionizing photons than the standard Salpeter IMF is required at $z \sim 6$. This may be achieved by having either (A) a metal-enriched IMF with a lower mass cutoff of $\geq 30 \, M_\odot$ or (B) $2-4\%$ of stellar mass being Population III massive metal-free stars at $z \sim 6$. While there is no compelling physical reason or observational evidence to support (A), (B) could be fulfilled plausibly by continued existence of some pockets of uncontaminated, metal-free gas for star formation. (2) The volume-weighted neutral fraction of the IGM of $\langle f_{\text{HI}} \rangle_V \sim 10^{-4}$ at $z = 5.8$ inferred from the SDSS observations of QSO absorption spectra provides enough information to ascertain that reionization is basically complete with at most $\sim 0.1-1\%$ of IGM that is un-ionized at $z = 5.8$. (3) Barring some extreme evolution of the IMF, the neutral fraction of the IGM is expected to rise quickly toward high redshift from the point of HII bubble percolation, with the mean neutral fraction of the IGM expected to reach $6-12\%$ at $z = 6.5$, $13-27\%$ at $z = 7.7$ and $22-38\%$ at $z = 8.8$.

Subject headings: cosmology: theory — intergalactic medium — reionization

1. Introduction

How the universe becomes transparent at $z \sim 5.8$ is debated (Fan et al. 2006; Becker et al. 2007). Whether reionization is complete by $z = 5-6$ has been questioned (Mesinger 2009). What kind of stars reionizes the universe at $z \sim 6$ remains less than certain. We examine in greater detail this endgame to assess how reionization process may have proceeded approaching $z \sim 5.8$, how complete reionization is at $z \sim 5.8$ and what role Population III (Pop III) stars may have played in the final reionization phase at $z \sim 6$, in the context of stellar reionization in the standard cold dark matter model (Komatsu et al. 2010). We are

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also motivated by the exciting possibility of being able to statistically measure the neutral fraction of the IGM at redshift above six in the coming years, as a variety of techniques are applied to larger samples that will become available. Those include methods based on (1) QSO Stromgren sphere measures (e.g., Wyithe & Loeb 2004; Mesinger et al. 2004), (2) measurements of damping wings of high redshift gamma-ray bursts (GRB) (e.g., Totani et al. 2006), (3) statistical analyses of high redshift Lyman alpha emitters from a variety of surveys (e.g., Malhotra & Rhoads 2004; Ouchi et al. 2007, 2008; Nilsson et al. 2007; Cuby et al. 2007; Stark et al. 2007; Willis et al. 2008; McMahon et al. 2008; Hibon et al. 2009). In addition, polarization measurements of the cosmic microwave background (CMB) fluctuations by Planck satellite and others may provide some useful constraints (e.g., Kaplinghat et al. 2003). Finally, the James Webb Space Telescope (JWST) will likely be able to detect the bulk of dwarf galaxies of halo mass \( \sim 10^9 M_\odot \) that are believed to be primarily responsible for cosmological reionization at \( z \sim 6 \) (e.g., Stiavelli et al. 2004), especially if a significant fraction of stars in them are active Pop III stars.

2. Evolution of the Intergalactic Medium Toward \( z \sim 6 \)

We use a semi-numerical method (Cen 2003) to explore the parameter space and compute the coupled thermal and reionization history with star formation of the universe. The reader is referred to \S 4 of Cen (2003) for details. For a simple understanding the essential physics pertaining to reionization may be encapsulated into a single parameter, \( \eta \), defined as

\[
\eta(z) \equiv \frac{c_s f_{\text{esc}} R_h(z) \epsilon_{\text{UV}}(z) m_p c^2}{\alpha(T) C(z) n_0 (1+z)^3 h \nu_0},
\]

where \( z \) is redshift, \( c_s \) the star formation efficiency (i.e., the ratio of the total amount of stars formed over the product of the halo mass and the cosmic baryon to total mass ratio), \( f_{\text{esc}} \) the ionizing photon escape fraction, \( R_h(z) \) the total baryonic mass accretion rate of halos above the filter mass (i.e., those that are able to accrete gas) over the total baryonic mass in the universe, \( \epsilon_{\text{UV}}(z) \) the ionizing photon production efficiency, defined to be the total emitted energy above hydrogen Lyman limit over the total rest mass energy of forming stars, \( m_p \) proton mass, \( c \) speed of light, \( \alpha(T) \) the case-B recombination coefficient, \( C(z) \) the clumping factor of the recombining IGM, \( n_0 \) the mean hydrogen number density at \( z = 0 \) and \( h \nu_0 \) hydrogen ionization potential. The numerator on the right hand side of Equation 1 is the rate of ionizing photons per baryon pumped into the IGM from stars, whereas the denominator is the destruction rate of Lyman limit photons per baryon due to case-B recombination. If \( \eta < 1 \), the universe is opaque. When \( \eta > 1 \) is sustained, the universe becomes fully reionized and a UV radiation background is built up with time with its amplitude determined by the balance between UV emissivity, recombination and universal expansion. If \( \eta \) goes above unity at an earlier epoch and subsequently drops below unity, a double reionization would
occur\cite{Cen2003}. Present calculations are done with the following updates of input physics.

- We adopt the standard WMAP7-normalized \cite{Komatsu2010} parameters for the cosmological constant dominated, flat cold dark matter model: $\Omega_M = 0.28$, $\Omega_b = 0.046$, $\Omega_{\Lambda} = 0.72$, $\sigma_8 = 0.81$, $H_0 = 100h\text{km}s^{-1}\text{Mpc}^{-1} = 70\text{km}s^{-1}\text{Mpc}^{-1}$ and $n = 0.96$.

- We replace the standard Press-Schechter formalism of spherical collapse model with the more accurate ellipsoidal collapse model \cite{ShethTormen2002} to compute the halo formation rate $R_h$.

- Latest ultra-high resolution (0.1pc) radiation hydrodynamic simulations indicate that $c_s f_{\text{esc}} \sim 0.02 - 0.03$ for atomic cooling halos and drops about two order of magnitude for minihalos, with $f_{\text{esc}} \sim 40 - 80\%$ \cite{WiseCen2009}. Note that $c_s f_{\text{esc}}$ and $\epsilon_{\text{UV}}(z)$ are degenerate. Therefore, we adopt, conservatively, $c_s f_{\text{esc}} = 0.03$ for the calculations presented here, which enables a firm conclusion with respect to a required high value for $\epsilon_{\text{UV}}(z)$, as will be clear later.

- We allow for an evolving IMF with redshift, parameterized by an evolving ionizing photon production efficiency, $\epsilon_{\text{UV}}(z) = \epsilon_{\text{UV},6}(1+z)^{\gamma}$, where $\epsilon_{\text{UV},6}$ is $\epsilon_{\text{UV}}(z)$ at $z = 6$.

- The clumping factor, $C(z)$, of the recombining IGM at $z \sim 6$ may be lower than previous estimates. We adopt the suggested range $C_6 = 3 - 6$ for the clumping factor at $z = 6$ based on recent calculations \cite{Pawlik2009}.

In our semi-numerical method, the evolution of the clumping factor of the IGM is determined by one parameter, $C_h$, that takes into account the contribution of collapsed gas to the overall clumping factor: $C(z) = \phi_h(z)C_h + [1 - \phi_h(z)]$, where $\phi_h(z)$ is the fraction of mass in halos above the filter mass \cite{Gnedin2000} that is followed self-consistently; we adjust $C_h$ along with the other free parameter, $\epsilon_{\text{UV}}(z)$, until we obtain simultaneously a desired clumping factor at $z = 6$, $C_6$, and that the universe completes reionization at exactly $z = 5.8$. We also examine a case where reionization ends at $z = 6.8$.

Perhaps the most uncertain of the input physics on the list is $\epsilon_{\text{UV}}(z)$, which we now elaborate on. For a fiducial, non-evolving IMF case $\epsilon_{\text{UV}}(z) = \epsilon_{\text{UV},6}$. For an evolving IMF, we take cue from recent development in the field of star formation at high redshift, in particular, on CMB-regulated star formation physical process \cite[e.g.,][]{Larson2005,Tumlinson2007,Smith2009,Bailin2010,Schneider2010}. Following Tumlinson \cite{2007}, the CMB-regulated Bonner-Ebert mass of a collapsing cloud evolves as $M_{\text{BE}} = 3.2[(1 + z)/7]^{1.7} M_\odot$. Specifying lower mass cutoff ($M_c$) of a Salpeter IMF at $z = 6$ and assuming that evolves as $M_c[(1 + z)/7]^{1.7}$, and using the Padova 0.02Z$_\odot$ track \cite{Leitherer1999} to obtain $\epsilon_{\text{UV,6}}$ and $\epsilon_{\text{UV}}(z = 9)$, we compute $\gamma$ as a function of $M_c$, shown in Figure \ref{fig:gamma}. Depending on the exact value of $M_c$, $\gamma$ ranges from 0.6 to 1.25 for $M_c = 1 - 20 M_\odot$. 
Fig. 1.— The mean slope of the expected evolution $\epsilon_{UV}(z) = \epsilon_{UV,6}\left(\frac{1+z}{7}\right)^{\alpha}$ from $z = 9$ to $z = 6$ for an evolving IMF with a Salpeter slope and a varying lower mass cutoff at $z = 6$ shown at the x-axis.

While it is uncertain, we identify $M_{BE} = 3.2 M_\odot$ at $z = 6$ with $M_c$, giving rise to $\gamma = 0.84$. In our subsequent analyses, we treat $\gamma = 0$ and $\gamma = 0.84$ as two limiting cases for the evolution of IMF.

With $c_s f_{esc} = 0.03$, $\gamma$, $C_6$ and the completion redshift of reionization $z_{ri}$ being fixed, we can find a unique pair of values for $C_h$ and $\epsilon_{UV,6}$. Figure 2 shows the evolutionary histories of the fraction of the un-ionized IGM, $x$, for six models. A feature common in all six models is that $x$ rapidly rises toward higher redshift from $z_{ri}$. Analysis of the SDSS observations of QSO absorption spectra suggests a transition to a (volume-weighted) neutral fraction $\langle f_{HI} \rangle_V \geq 10^{-3}$ at $z \sim 6.2$ from $\langle f_{HI} \rangle_V \sim 10^{-4}$ at $z = 5.8$ (Fan et al. 2006). As we will show below, the observed $\langle f_{HI} \rangle_V \sim 10^{-4}$ at $z = 5.8$ indicates that the reionization is largely complete by $z = 5.8$. Thus, our models suggest that $x$ is expected to reach $6 - 12\%$ at $z = 6.5$, $13 - 27\%$ at $z = 7.7$ and $22 - 38\%$ at $z = 8.8$.

It is useful to have some simple physical understanding of the results. Star formation and reionization is somewhat self-regulated in that a higher star formation rate ionizes and heats up a larger fraction of the IGM that would tend to suppress gas accretion for further star formation, whereas cooling processes induce more star formation (Cen 2003). As the response time scale for this self-regulation is on the order of the halo dynamic time that is roughly 10% of the Hubble time, so if there is a protracted period during reionization, this argument suggests that it may only take place at a neutral fraction level of $x \geq 10\%$ so as to allow star formation rate to be able to dynamically respond to reionization induced heating within a halo dynamical time. Once $x$ has dropped significantly below 10%, the final stage of reionization should be prompt, which is greatly conspired by the rapid increase of $\eta(z)$.
Fig. 2.— The evolution of un-ionized fraction of the IGM, $x$, in six different reionization models with specified $\epsilon_{\text{UV}}(z)$, $C_6$ and $z_{\text{ri}}$.

toward the end of reionization (Equation 1). It can be shown that $R_{h} \propto \exp(-\delta_c^2/2\sigma_M^2)(1+z)$, leading to $\eta \propto \exp(-\delta_c^2/2\sigma_M^2)(1+z)^{\gamma-2}C^{-1}(z)$, where $\sigma_M$ is the density variance on the mass scale of $M \sim 10^9 M_\odot$ that can accrete photoheated gas and form stars (Gnedin 2000). By the end of reionization, about 1% of total mass turns out to have collapsed in these halos; in other words, the (star-forming) halo collapse rate is on the exponential rise when the universe becomes fully ionized. Since the evolution of $C$ is much weaker than exponential (Pawlik et al. 2009), $\eta(z)$ likely surpasses unity at $z_{\text{ri}}$ in an “exponential” fashion from below. As a result, it takes significantly less than $x$ times Hubble time to reionize the last small $x$ fraction of neutral IGM. These considerations are consistent with the rapid final reionization phase seen in Figure 2.

The SDSS observations strongly suggest $z_{\text{ri}} = 5.8$ (Fan et al. 2006), after which the ionization state of the IGM is primarily determined, on the ionizing photon sink side, by LLS. We show here, from a somewhat different angle, but in agreement with the conclusion of Fan et al. (2006), that reionization is largely complete by $z = 5.8$ (c.f., Mesinger 2009). The comoving mean free path (mfp) of Lyman limit photons, $\lambda$, may be written as

$$\lambda^{-1} = \lambda_{\text{LL}}^{-1} + \lambda_{\text{Lya}}^{-1} + \lambda_{\text{neu}}^{-1} + \lambda_{\text{other}}^{-1},$$

(2)

where $\lambda_{\text{LL}}$, $\lambda_{\text{Lya}}$ and $\lambda_{\text{neu}}$ are comoving mfp due to LLS, Ly$\alpha$ forest and un-ionized neutral IGM, respectively; $\lambda_{\text{other}}$ is due to possible other sinks. Physically, LLS are in less ionized, overdense regions within the reionized portion of the universe that are individually opaque to Lyman limit photons; Ly$\alpha$ forest is dominated by low density regions within the reionized
portion of the IGM that individually are only partially opaque to Lyman limit photons; the un-ionized neutral IGM is the portion of the IGM that has not been engulfed by the reionization front. We conservatively assume \( \lambda_{\text{other}} = \infty \). Current large-scale cosmological reionization simulations do not provide sufficiently accurate results to constrain \( \lambda_{\text{LL}} \) due to lack of adequate resolution. An extrapolation (Gnedin & Fan 2006) of observations at lower redshift \( z = 0.4 - 4.7 \) (Storrie-Lombardi et al. 1994) gives \( \lambda_{\text{LL}} \sim 22 - 48 \) comoving Mpc/h at \( z \sim 5.8 \). We use \( \lambda_{\text{LL}} = 35 \) comoving Mpc/h in our calculations. The following three equations are used to compute the neutral fraction of a region, \( x_\delta \), at overdensity \( \delta \equiv \rho_b/\langle \rho_b \rangle \), when the region is substantially ionized (i.e., \( x_\delta \ll 1 \)):

\[
x_\delta J_\nu \langle \sigma T \rangle = \delta \alpha(T) n_0 (1 + z)^3,
\]

where \( J_\nu \) is the ionizing photon radiation intensity in units of \( \text{cm}^{-2} \text{sec}^{-1} \) and \( \langle \sigma T \rangle = 2.6 \times 10^{-18} \text{cm}^2 \) is the spectrum-averaged photoionization cross section for a low-Z IMF ionizing spectrum at high-z.

\[
\Psi = C \alpha(T) n_0 (1 + z)^3,
\]

where \( \Psi \) is mean ionizing photon emissivity per baryon.

\[
J_\nu = \lambda \Psi n_0 (1 + z)^2.
\]

Equations 3, 4, 5, respectively, reflect the local ionization balance (between photoionization and recombination) (3), global ionization balance (between mean emissivity and recombination) (4) and relationship between mean emissivity, ionizing photon intensity and mfp (5). Combining (3, 4, 5) we obtain

\[
x_\delta = \frac{\delta \langle \sigma H \rangle n_0 (1 + z)^3}{\lambda C \langle \sigma H \rangle n_0 (1 + z)^3}.
\]

Thus, knowing \( C \) and \( \lambda \) allows one to compute \( x_\delta \), which, when combined with the probability distribution function of \( \delta \), PDF(\( \delta \)), can be used to compute the volume-weighted neutral fraction, \( \langle f_{\text{HI}} \rangle_V \):

\[
\langle f_{\text{HI}} \rangle_V = \int_0^\infty \text{PDF}(\delta) x_\delta d\delta.
\]

We use the density distribution, PDF(\( \delta \)), from one of the radiation-hydrodynamic simulations (Trac et al. 2008) where the universe completes reionization at \( z \sim 6 \), to compute \( \langle f_{\text{HI}} \rangle_V \) at \( z = 5.8 \). A resolution of comoving 65kpc/h in the simulation is adequate for resolving the Jeans scale of photo-ionized gas. The mfp due to Ly\( \alpha \) forest can be computed as

\[
\lambda_{\text{Ly}\alpha}^{-1} = \langle f_{\text{HI}} \rangle_V \langle \sigma T \rangle n_0 (1 + z)^2/(1 + 1/e).
\]

We use the same simulation to also compute \( \lambda_{\text{neu}} \), simply by computing the average distance that a random ray can travel before it hits an un-ionized cell. We identify regions that have not been reionized and photon-heated with cells in the simulation box that have
Fig. 3.— Top panel shows the total comoving mean free path (mfp) $\lambda$ for two cases with $C = 3$ (solid squares) and $C = 6$ (stars) as well as $\lambda_{\text{LL}}$ (open diamonds), $\lambda_{\text{LyA}}$ (open triangles) and $\lambda_{\text{neu}}$ (open circles) for the case with $C = 3$, as a function of $x$ at $z = 5.8$. Bottom panel shows the volume-weighted neutral fractions of the IGM, $\langle f_{\text{HI}} \rangle_V$, as a function of $x$ for the two cases with $C = 3$ (solid squares) and $C = 6$ (stars). Also shown as the shaded region is the total range of $\langle f_{\text{HI}} \rangle_V$ at $z = 5.8$ based on the SDSS QSO sample (Fan et al. 2006).
\( \lambda_{\text{neu}} \) at \( x \geq 0.01 \) and \( \lambda_{\text{LL}} \) at \( x \leq 0.005 \), and Ly\( \alpha \) forest has secondary importance at all \( x \). A comparison between the computed results and observations indicates that the un-ionized fraction \( x \) does not exceed \( 0.1 - 1\% \) at \( z = 5.8 \) and reionization is complete or largely complete by \( z = 5.8 \). In combination with our previous finding of rapid reionization near \( z_{\text{ri}} \), it suggests that \( z_{\text{ri}} = 5.8 \) or very near it.

Fig. 4.— show the required ionizing photon production efficiency at \( z = 6, \epsilon_{\text{UV},6} \), as a function of IGM clumping factor at \( z = 6, C_6 \), for several models. Also shown as stars are the expected \( \epsilon_{\text{UV}} \) for Salpeter IMF (with 0.02\( Z_{\odot} \) metallicity) (Leitherer et al. 1999) with the lower mass cutoff \( M_c \) indicated by the top x-axis. The diamonds are \( \epsilon_{\text{UV}} \) for Pop III metal-free stars, again, with the lower mass cutoff \( M_c \) indicated by the top x-axis (Schaerer 2002).

Finally, in Figure 4 we show the required ionizing photon production efficiency at \( z = 6, \epsilon_{\text{UV},6} \), as a function of \( C_6 \), for several models. Several expected trends are noted. First, a higher \( C_6 \) requires a higher \( \epsilon_6 \). Second, an earlier reionization requires a higher \( \epsilon_6 \). Third, a rising \( \epsilon_{\text{UV}} \) with redshift lessens the required \( \epsilon_6 \) fractionally. What is most striking is that stars with the standard metal-enriched IMF and \( M_c = 1\, M_{\odot} \) fall short of providing the required ionizing photons, by a factor of 10 – 20 at \( z \sim 6 \). Having \( M_c \sim 5\, M_{\odot} \) would help reduce the deficit to a factor of 3 – 6. Only with \( M_c \sim 30\, M_{\odot} \) and \( C_6 = 3 \), one is barely able to meet the requirement to reionize the universe at \( z \sim 6 \) by Population II stars. But such an extreme scenario with \( M_c \geq 30\, M_{\odot} \) may be disfavored by the existence of old stars in
observed high-z galaxies (e.g., Mobasher et al. 2005) that need be less massive than \( \sim 10 \, \text{M}_\odot \) to be long-lived.

However, we note that Pop III metal-free stars (diamonds in Figure 4), thought to be more massive than \( 30 \, \text{M}_\odot \) (e.g., Abel et al. 2002; Bromm et al. 2002; McKee & Tan 2008), could provide ample ionizing photons. Unfortunately, normally, Pop III stars would not be expected to form at \( z \sim 6 \), had some earlier supernovae uniformly enriched the intergalactic medium. With gaseous low-temperature coolants, it is believed that the critical metallicity for transition from Pop III to Pop II IMF is \( Z_{\text{crit}} \sim 10^{-3.5} \, \text{Z}_\odot \) (e.g., Bromm et al. 2001; Bromm & Loeb 2003). If dust is formed in the Pop III.1 supernova ejecta, Schneider et al. (2006) argue that dust cooling may significantly lower the critical transition metallicity to as low as \( Z_{\text{crit}} \sim 10^{-6} \) (e.g., Cherchneff & Dwek 2010). If a fraction \( 10^{-4} \) of baryons forms into Pop III stars and their supernovae uniformly enrich the IGM, the expected metallicity of the IGM will likely exceed \( Z \sim 10^{-3.5} \, \text{Z}_\odot \) (e.g., Fang & Cen 2004). Since a fraction of \( \geq 10^{-4} \) of baryons needs to form into Pop III stars to reionize the universe, therefore, in the case of uniform IGM enrichment, the contribution of Pop III stars to ionizing photon budget at \( z \sim 6 \) is expected to have become negligible. In addition, a very small amount of metals \( (Z \leq 10^{-3} \, \text{Z}_\odot) \) would change the internal dynamics of massive stars (core temperature, size, effective surface temperature, etc) and render them much less efficient UV producers and notably different from Pop III massive stars (e.g., Hirschi et al. 2008), as already hinted in Figure 4 between stars \( (Z = 0.02 \, \text{Z}_\odot) \) and diamonds (Pop III) at \( M_c \sim 30 \, \text{M}_\odot \).

We suggest that, if the metal enrichment process of gas, including IGM and gas in collapsed minihalos and other galaxies, is highly inhomogeneous, then it is possible that a small fraction of star-forming gas may have remained primordial to allow for Pop III star formation at \( z \sim 6 \). A significant amount of gas in the central regions of non-star-forming galaxies (e.g., Wyithe & Cen 2007; Cen & Riquelme 2008) as well as a fraction of IGM that has not been swept by galactic winds emanating from star-forming galaxies could remain uncontaminated. Cosmological simulations at lower redshift \( (z = 0 - 6) \) suggest that metal enrichment process of the IGM is indeed extremely inhomogeneous, leaving significant pockets of metal-free gas even at \( z = 0 \) (e.g., Cen & Ostriker 1999; Aguirre et al. 2001; Oppenheimer & Davé 2006; Cen & Chisari 2010). The common assumption is that earlier generations of stars not resolved in these simulations would have put in a metallicity-floor in all regions. But this needs not be the case. Observationally, while the majority of local star formation has metallicity close to solar, relatively low-metallicity \( (1/30 \, \text{of solar}) \) star formation does occur occasionally (e.g., Izotov & Thuan 1999) and some of the observed local supernovae may be pair-instability supernovae (e.g., Smith et al. 2007; Gal-Yam et al. 2009) that may be due to metal-free progenitors (c.f., Smith et al. 2007; Langer et al. 2007; Woosley et al. 2007). At redshift \( z = 2 - 3 \) the low density Ly\( \alpha \) forest, regions of density around and less than the global mean, appears to have not been enriched to a detectable level \( (\leq 10^{-3.5} \, \text{Z}_\odot) \) (e.g., Lu et al. 1998). Therefore, it seems plausible that an increasing fraction
of star-forming gas toward high redshift may be pristine, due to a combination of inefficient and non-uniform mixing and a decreasingly amount of metals having been injected.

From Figure 4, we see that what is minimally required in order to have enough ionizing photons at \( z \sim 6 \) is that about 2-4% of stars forming at \( z \sim 6 \) are Pop III stars and the remainder normal Pop II metal-enriched stars with a Salpeter-like IMF or other forms; the lower mass cutoff for the latter is unconstrained but \( M_c \sim 3 \, M_\odot \) or so is perhaps physically motivated and fully in line with other evidence that hints on an evolving IMF from redshift zero (e.g., van Dokkum 2008; Davé 2008). With 2-4% being Pop III stars, Pop III stars’ contribution to ionizing photons and FUV are dominant over the remaining normal stars, which would give rise to an “apparent”, very low metallicity, top-heavy IMF for these high redshift galaxies. Interestingly, galaxies with such required properties - a dust-free, very low metallicity, top-heavy IMF with a very high ionizing photon escape fraction of 40 – 80% - may have already been detected in the Hubble Ultra Deep Field (UDF) at \( z \sim 7 – 8 \) (e.g., Bouwens et al. 2010).

3. Conclusions and Discussion

We study the evolution of the IGM at \( z \sim 5.8 \) when universe finally turns transparent in the context of stellar reionization in the standard cold dark matter model. Under the conservative assumption, \( c_s f_{\text{esc}} = 0.03 \), that is based on recent calculations of ionizing photon escape fraction \( f_{\text{esc}} \) and star formation efficiency \( c_s \), we find that metal-enriched Pop II stars with a normal IMF fail, by a factor of 10 – 20, to provide enough ionizing photons to reionize the universe at \( z \sim 6 \). Only under the scenario that the vast majority of Pop II stars are more massive than \( \sim 30 \, M_\odot \) one may be able to reionize the universe, if the clumping factor of the recombining IGM is \( \leq 3 \) at \( z = 6 \). Perhaps the observed existence of high-z galaxies at \( z \sim 6 \) already rules out this scenario.

Alternatively, we suggest that, if a mass fraction of 2 – 4% of stars forming at \( z \sim 6 \) is massive Pop III metal-free stars, enough ionizing photons can be produced. Physically, this scenario can be plausibly accommodated by existence of a fraction of uncontaminated, metal-free gas at \( z \sim 6 \), due to non-uniform mixing of metals in the universe. The dominant contribution of UV light from these Pop III stars, likely being dust-free and expected very high ionizing photon escape fraction (40 – 80%) would combine to make these galaxies look very blue, which would be consistent with recent observations of \( z = 7 – 8 \) galaxies in the UDF. This hints exciting possibilities for JWST in detecting signatures of Pop III stars.

Based on extant observations that the volume-weighted neutral fraction of the IGM is \( \sim 10^{-4} \) at \( z \sim 5.8 \), we conclude that the reionization is basically complete by \( z = 5.8 \) with no more than 0.1-1% of the IGM remaining neutral. In other words, \( z_{\text{re}} = 5.8 \) or very near
it, in agreement with earlier, independent analyses (Fan et al. 2006).

With the complete percolation of HII bubbles occurring at \( z = 5.8 \), the mean neutral fraction of the IGM is expected to reach \( 6 - 12\% \) at \( z = 6.5 \), \( 13 - 27\% \) at \( z = 7.7 \) and \( 22 - 38\% \) at \( z = 8.8 \). Future measurements shall test this stellar reionization paradigm in the standard model.

Finally, we mention the possibility of probing other physics with reionization. Significant alteration of the properties of dark matter particles from “vanilla cold” may have substantial impact on the reionization process. Weakly interacting massive particle (WIMP) annihilation heating may affect the balance of cooling and heating processes and hence change the primordial star formation process, if dark matter particles are sufficiently cold to allow for very concentrated profiles at stellar scales (e.g., Spolyar et al. 2008; Natarajan et al. 2009). Turning particles from “cold” to somewhat “warm” may also have profound effects on reionization. Current astronomical observational constraints place a lower limit on dark matter particle mass \( m_x \) in the neighborhood of \( 0.5 - 1 \) keV (Narayanan et al. 2000; Barkana et al. 2001; Viel et al. 2005; Abazajian 2006). The smoothing scale, defined as the comoving half-wavelength of the mode for which the linear perturbation amplitude is suppressed by 2, is

\[
R_S = 0.34 \left( \frac{\Omega_m}{0.3} \right)^{0.15} \left( \frac{h}{0.7} \right)^{1.3} \left( \frac{m_X}{\text{keV}} \right)^{-1.15} h^{-1} \, \text{Mpc} \quad \text{[Bode et al. 2001]}
\]

For \( m_X = (1, 10) \) keV, the mass smoothing scale is \( (1.2 \times 10^{10}, 4.3 \times 10^{10}) \) M\(_\odot\), respectively. Naturally, the formation epoch of Pop III star formation in a warm dark matter model of gravitino particle mass \( m_x = 15 \) keV is found to be delayed relative to the case with cold dark matter by \( 10^8 \) yr or from \( z \sim 16 \) to \( z \sim 13 \) (O’Shea & Norman 2006). Given that even \( m_x = 15 \) keV has a significant impact on Pop III star formation, it seems very promising that observations of high-z galaxies will place constraints on the nature of dark matter particles. With a dark matter particle mass of \( \sim 1 \) keV, minihalo formation would be largely suppressed and give rise to a very different, “favorable” scenario in which larger galaxies form stars out of primordial gas that may otherwise have been contaminated by star formation in minihalos. Thus, observations of reionization may provide a powerful probe of the physics of dark matter.

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