Cosmic reionization of hydrogen and helium: contribution from both mini-quasars and stars

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\begin{abstract}
Observations on the high-redshift galaxies at $z > 6$ imply that their ionizing emissivity is unable to fully reionize the Universe at $z \approx 6$. Either a high escape fraction of ionizing photons from these galaxies or a large population of fainter galaxies below the detection limit are required. However, these requirements are somewhat in tension with present observations. In this work, we explored the combined contribution of mini-quasars and stars to the reionization of cosmic hydrogen and helium. Our model is roughly consistent with: (1) the low escape fractions of ionizing photons from the observed galaxies, (2) the optical depth of Cosmic Microwave Background (CMB) measured by the WMAP-7, and (3) the redshift of the end of hydrogen and helium reionization at $z \approx 6$ and $z \approx 3$, respectively. Neither an extremely high escape fraction nor a large population of fainter galaxies is required in this scenario. In our most optimistic model, more than $\sim 20\%$ of the cosmic helium is reionized by $z \approx 6$, and the ionized fraction of cosmic helium rapidly climbs to more than $50\%$ by $z \approx 5$. These results may imply that better measurements of helium reionization, especially at high redshifts, could be helpful in constraining the growth of intermediate-mass black holes (IMBHs) in the early Universe, which would shed some light on the puzzles concerning the formation of supermassive black holes (SMBHs).
\end{abstract}

\textbf{Key words:} dark ages, reionization, first stars – intergalactic medium – quasars: general

\section{INTRODUCTION}
One major focus in the present cosmology is the reionization of the intergalactic medium (IGM) in the Universe. Observations of the Cosmic Microwave Background (CMB) from the 7-yr Wilkinson Microwave Anisotropy Probe (WMAP-7) measure the Thomson electron scattering optical depth $\tau = 0.088 \pm 0.015$, suggesting that hydrogen reionization begins no later than $z = 10.6 \pm 1.2$ \cite{Komatsu2011}. Additional pieces of evidence come from the absorption spectra of high-redshift quasars \cite{Fan2006, Mortlock2011, Bolton2011, Schreuder2013} and the rapid evolution of the luminosity function of Ly$\alpha$ emitters at $z > 6$ \cite{Ouchi2010, Schenker2012}, implying an end to hydrogen reionization at $6 \lesssim z \lesssim 7$. All these constraints suggest that hydrogen reionization is likely to be a much more extended process in the redshift range $6 < z < 12$ \cite{Wyithe2003, Choudhury2008, Iliev2007, Haardt2012, Robertson2013}.

Among various possible ionizing sources, stars in galaxies are commonly thought to be the most likely candidates \cite{Faucher-Giguere2008, Robertson2010}. However, the ionizing emissivity of the observed galaxies at $z > 6$ seems insufficient to maintain the cosmic hydrogen in a fully ionized state at $z \sim 6$ unless the escape fraction of ionizing photons from these galaxies is larger than $\sim 30\%$, otherwise a large population of faint galaxies below the detection limit would be required \cite{Bolton2007, Bunker2010, Trenti2011, Alvarez2012, Bouwens2012, Fontanot2012, Finkelstein2012, Kuhlen2012, Robertson2013}.

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The requirement for such a high escape fraction at $z \gtrsim 6$ is somewhat in tension with current observational constraints on the escape fraction at lower redshifts (Heckman et al. 2001; Iwata et al. 2009; Vanzella et al. 2011; Nestor et al. 2011; Vanzella et al. 2012). Although there exists some evidence supporting the redshift evolution of the escape fraction (Razoumov & Sommer-Larsen 2006; Paardekooper et al. 2011; Ferrara & Loeb 2013; Mitra et al. 2013; Fontanot et al. 2014), which is still inconclusive. On the other hand, some theoretical studies suggest that the star formation activity in faint galaxies might be strongly suppressed (Krumholz & Dekel 2012; Kuhlen et al. 2012).

Introducing the contribution from other ionizing sources might partially solve this so-called ”photon-starved” problem. Although it is widely believed that the contribution of quasars to the ionization radiation decreases rapidly from $z \approx 3$ to $z \approx 6$ and becomes negligible at $z \gtrsim 6$ (e.g. Fan et al. 2001; Cowie et al. 2009; Willott et al. 2010), the contribution from mini-quasars at high redshifts could still play an important role. The existence of black holes (BHs) as massive as $\sim 10^{5} M_{\odot}$ at $z \approx 7$ becomes reasonable only when starting from a seed BH which increases its mass via gas accretion or/and merging with each other. This scenario implies that there should be plenty of intermediate-mass black holes (IMBHs) with masses of the order of $10^{6} – 10^{9} M_{\odot}$ shining at $z \gtrsim 7$. The recent identification of IMBHs also provides strong evidence for this scenario (Farrell et al. 2009; Lützgendorf et al. 2013). If such IMBHs accrete as mini-quasars at high redshifts, they could be important sources of the early reionization of the IGM. A number of authors (e.g. Madau et al. 2004; Dijkstra et al. 2004; Zaroubi et al. 2006) argued that mini-quasars, consistent with the constraint from the soft X-ray background (SXRB), could still provide a relevant contribution to the reionization of the IGM at $z \gtrsim 6$.

Recently, by exploring the high-redshift $M_{\text{bb}} - \sigma_{*}$ relation in light of the numerical simulation of the merger tree of dark matter halos and using the Press-Schechter (PS) formalism, Wang et al. (2010) calculated the central IMBH mass density as a function of redshift. And furthermore, by combining it with a parametrized UV photon emission efficiency, they found that the contribution of mini-quasars to hydrogen reionization lies in the range $\sim 25\% - 50\%$ at $z \approx 6$. However, they did not consider the impact of the helium ionizing radiation of these mini-quasars on the IGM reionization and ignored the contribution from stars. In this paper, we adopt the same BH mass density to estimate the number of ionizing photons from mini-quasars, assuming a power-law spectrum for the BH emission. In combination with the fitting star formation rate density from (Li 2008), we assess the combined contribution of mini-quasars and stars to the reionization of cosmic hydrogen and helium.

The structure of this paper is as follows. In Sect. 2, we present the formalism for computing the reionization histories of hydrogen and helium and the number of ionizing photons from different types of sources. The implications of our results are discussed in Sect. 3, and our conclusions are summarized in Sect. 4. The cosmological parameters used in this paper are from the WMAP-7 results (Komatsu et al. 2011): $\Omega_{m} = 0.266$, $\Omega_{\Lambda} = 0.734$, $\Omega_{b} = 0.0449$, $h = 0.71$, $\sigma_{8} = 0.801$. We use $n = 1$ for a scale-invariant primordial power spectrum.

## 2 THE REIONIZATION HISTORY OF HYDROGEN AND HELIUM

The X-ray or UV emission from (mini-)quasars and stars can ionize the neutral hydrogen (H I), helium (He I) or singly ionized helium (He II) in the IGM. In order to estimate the evolution of the regions of the ionized hydrogen and helium during the epoch of reionization, we follow the straightforward considerations of (Barkana & Loeb 2001). Given the number $\xi_{i}$ of ionizing photons from stars and (mini-)quasars in a homogeneous but clumpy Universe, the evolution of the volume filling factor $Q_{i}$ (for species $i = \text{HI}, \text{HeII}, \text{HeIII}$) of the ionized regions can be described by

$$\frac{dQ_{i}}{dt} = \frac{1}{n_{i}^{0}(1+z)^{3}} \frac{dN_{i}}{dt} - \alpha_{i} C n_{e}(1+z)^{3} Q_{i},$$

where $n_{i}^{0}$ is the comoving density, and $n_{i}^{0} = 1.88 \times 10^{-7}(\Omega_{b} h^{2}/0.022) \text{cm}^{-3}$ and $n_{i}^{0} = 0.19 \times 10^{-7}(\Omega_{b} h^{2}/0.022) \text{cm}^{-3}$, respectively. Here $n_{e}$ is the number density of electrons, $\alpha_{i}$ is the case B recombination coefficient and $C \equiv \langle n_{i}^{0} \rangle / n_{i}^{0}$ is the volume-averaged clumping factor of the IGM. The recombination coefficients for HI, HeII and HeIII at $T \leq 10^{4}$ K are adopted as follows (Wyithe & Loeb 2003): $\alpha_{\text{HI}} = 2.6 \times 10^{-13} \text{cm}^{3} \text{s}^{-1}$, $\alpha_{\text{HeII}} = 2.73 \times 10^{-13} \text{cm}^{3} \text{s}^{-1}$ and $\alpha_{\text{HeIII}} = 13 \times 10^{-13} \text{cm}^{3} \text{s}^{-1}$, while for the clumping factor $C$, we use the following simple form given by Haiman & Bryan (2003): $C(z) = 1 + 9(7/(1+z))^{2}$ for $z \geq 6$ and $C = 10$ for $z < 6$. The number densities of ionizing photons for HI, HI and HeIII are calculated through the integration of the corresponding spectra in the energy intervals $13.6 < E < 24.6$ eV, $24.6 < E < 54.4$ eV and $E > 54.4$ eV, respectively. Two classes of sources, mini-quasars and stars, are considered as the contributors to the ionizing photons, which will be discussed in the following sections. We also note that, following Wyithe & Loeb (2003), two constraints are considered in this model, namely, (1) $Q_{\text{HI}} \leq Q_{\text{HI}}$; and (2) $Q_{\text{HI}} \leq Q_{\text{HI}} - Q_{\text{HI}}$, showing that the helium ionization front never overtakes the hydrogen ionization front.

The optical depth of CMB photons due to the Thomson Scattering is given by

$$\tau_{e} = \int dz \frac{dt}{dz} \sigma_{T} n_{e}(z)(1+z)^{3},$$

where $\sigma_{T} = 6.65 \times 10^{-25}$ cm$^{-2}$ is the cross section of Thomson scattering and $n_{e}$ is the number density of electron.

## 2.1 Ionizing photons from mini-quasars

In this section, we derive the number of ionizing photons from the central accreting IMBHs, shining as mini-quasars.
The ionizing radiation from accreting BHs primarily depends on the following three quantities: the redshift evolution of the mass density of BHs, the emission spectrum of the accreting BH and the duty cycle of BHs.

Our calculation for the mass density of central BHs as a function of redshift closely follows the simple model of Wang et al. (2011) which is based on the PS mass function of dark matter halos. Here we only briefly describe the key features of this model, and refer the reader to that paper for more details. We assume that, at the center of each dark matter halo, there exists a BH with a mass ($M_{\text{BH}}$) that is correlated with the host halo mass. Then the mass density of BHs could be estimated simply by calculating the number density of halos as a function of redshift. Here we adopt the modified version of PS mass function proposed by Sheth & Tormen (1999) to estimate the number of dark matter halos, which is

$$n_{\text{ST}}(M, z) dM = A \sqrt{2\pi} \frac{\rho_m}{M} \left[ \frac{\sigma^2(M, z)}{a_1^2 \delta_c^2} \right] \frac{\delta_c}{\sigma(M, z)} \exp \left[ -\frac{a_1 \delta_c}{2\sigma(M, z)} \right] dM$$

where $A = 0.3222$, $a_1 = 0.707$, $p = 0.3$, $\delta_c = 1.686$ and $\rho_m$ is the current mean density of the Universe. The deviation of the linear density field $\sigma(M, z)$ is given by

$$\sigma^2(M, z) = \frac{D^2(z)}{2\pi^2} \int_0^\infty k^2 P(k) W^2(k, M) dk,$$

where $W(k, M)$ is the top-hat filter, and $D(z)$ is the growth factor of linear perturbations.

The mass of the central BH ($M_{\text{BH}}$) is assumed to be correlated with the the stellar velocity dispersion $\sigma_*$ through the relation

$$\log M_{\text{BH}} = \theta + \phi \log(\sigma_*/\sigma_0),$$

where $\sigma_0 = 200 \text{ km s}^{-1}$. Basing on the improved self-adaptive merger tree model of dark matter halos (Yuan et al. 2008). Wang et al. (2011) explored the $M_{\text{BH}} - \sigma_*$ relation at high redshifts with the following BH formation scenario: (i) each halo is randomly assigned a seed BH; (ii) seed BHs as remnants of Pop III stars have a slightly top-heavy initial mass function in the mass range $200 M_\odot < M_{\text{BH}} < 1000 M_\odot$; (iii) the mass growth of BHs is considered to be dependent on gas accretion during halo mergers, and the mass accretion rate is $M_{\text{BH}} = M_{\text{BH}}/t_{\text{ff}}$, where $t_{\text{ff}}$ is the Salpeter $\epsilon$-folding time; (iv) the free parameters, such as the radiative efficiency and Eddington ratio, are constrained to make sure the final BH mass agrees with the local $M_{\text{BH}} - \sigma_*$ relation. They found that the $M_{\text{BH}} - \sigma_*$ relation with parameters $\theta = 6.67$ and $\phi = 2.79$ can provide a good fit to the numerical results at $z > 6$. The stellar velocity dispersion $\sigma_*$ is related to the circular velocity of halos $V_c$ by (Ferrarese 2002; Pizzella et al. 2003)

$$\log V_c = 0.84 \log \sigma_* + 0.55.$$  

$^2$ Although recent studies imply a smaller characteristic mass of Pop III stars, it is yet inconclusive how this scenario would affect the growth of MBHs. Besides, several authors (e.g. Volonteri et al. 2003) also argued that the evolution of MBHs is not very sensitive to the initial mass of seed BHs. Thus, we prefer a traditional seed BH model in this work.

The relation between the circular velocity $V_c$ and the halo mass $M$ is given by (Barkana & Loeb 2001)

$$V_c = 23.4 \left( \frac{M}{10^9 h^{-1} M_\odot} \right)^{1/3} \left( \frac{\Omega_m}{\Omega_m + \Omega_\Lambda} \right)^{1/6} \left( \frac{1 + z}{10} \right)^{1/2} \text{ km s}^{-1},$$

with

$$\Delta_c = 18\pi^2 + 82d - 39d^2$$

and $d \equiv \Omega_\Lambda(z) - 1$.

In Fig. 1 we show the BH mass densities as a function of redshift for IMBHs and massive BHs (MBH; $M_{\text{BH}} > 10^5 M_\odot$), respectively. We henceforth refer to accreting MBHs as “quasars”. For comparison, we also plot the strong upper limit on the IMBH density at $z > 6$ of $\rho_{\text{IMBH}} < 3.8 \times 10^{-6} M_\odot \text{ Mpc}^{-3}$ derived by Salvaterra et al. (2003), which is based on the measurement of the unresolved fraction of the SXRB. As can be seen from Fig. 1, the result is well below the constraints from the SXRB.

Although the exact emission spectrum of mini-quasars remains poorly understood, its typical spectrum is expected to be harder than that of quasars. As suggested by observations of ultraluminous X-ray sources (possibly associated to IMBHs; Miller et al. 2003) in nearby galaxies, the mini-quasar spectrum has a simple power-law form. Specifically, two types of power-law spectral energy distributions (SEDs) are considered: the High Energy (HE) case with the energy range $200 \text{ eV} < E < 100 \text{ keV}$ and the Low Energy (LE) case with a low-energy cutoff of 10.4 eV. Note that, the HE case assumes that all the ionizing UV photons are absorbed in the close vicinity of the source. As a comparison, we also note that the typical spectral index of quasars is measured to be $\alpha = 1.7$ (e.g. Telfer et al. 2002; Tozzi et al. 2004).

Then the number of hydrogen (helium) ionizing photons from accreting IMBHs can be evaluated by

$$\frac{dN_\gamma}{dt} = \frac{f_{\text{Edd}} F(E) dE}{\int F(E) dE} \epsilon LP,$$

where $\epsilon$ is the Eddington ratio, $P$ represents the duty cycle and $L$ is the total luminosity emitted by accreting IMBHs per unit of comoving volume:

$$L = \int_{200}^{10^5} N(M(M_{\text{BH}}, z), z) L_{\text{Edd}}(M_{\text{BH}}) dM_{\text{BH}},$$

where $L_{\text{Edd}}$ is the Eddington luminosity, $L_{\text{Edd}}(M_{\text{BH}}) = 1.26 \times 10^{38} (M_{\text{BH}}/M_\odot) \text{ erg s}^{-1}$, and $P$ is the duty cycle of BHs, i.e. the probability that a BH is in the active state. A number of studies suggest that the duty cycle increases rapidly with increasing redshift (e.g. Wang et al. 2006; Shen et al. 2007; Tanaka 2014). From the measurements of clustering of quasars, Shankar et al. (2010) suggested that $P \sim 0.2, 0.5$ and 0.9 at $z = 3.1, 4.5$ and 6, respec-
tively. To match these results, we therefore adopt a parameterized form of \( P(z) = 0.03 + 0.97(z/\tau_{\text{reion}})^{\beta}[1 + (z/\tau_{\text{reion}})]^{\beta} \) with \( \beta = 2 \) and \( \tau_{\text{reion}} = 4 \). To be optimistic, we also assume that all the ionizing photons produced by accreting BHs escape the host halo, i.e. \( f_{\text{esc, BH}} = 1 \). Based on the above assumptions and descriptions, consequently, it is straightforward to calculate the number of ionizing photons emitted at a particular energy range \([E_{\text{min}}, E_{\text{max}}]\) from accreting IMBHs per unit time.

### 2.2 Ionizing photons from stars

In order to determine the number of ionizing photons produced by stars, the high-redshift star formation rate (SFR) density is estimated according to [L3 (2008), in which Hopkins & Beacom (2006)]’s compilation on the SFR density was updated with the observations by Giavalisco et al. (2004), Banker et al. (2004), Ouchi et al. (2004), Reddy et al. (2008) and Bourgens et al. (2008). Basing on these observational data, L3 (2008) obtained a piecewise-linear fitting, as in Hopkins & Beacom (2006), which is

\[
\log \dot{\rho}_* (z) = a + b \log (1 + z),
\]

where

\[
(a, b) = \begin{cases} 
(-1.70, 3.30), & z < 0.993 \\
(-0.727, 0.0549), & 0.993 < z < 3.80 \\
(2.35, -4.46), & z > 3.80 
\end{cases}
\]

and \( \dot{\rho}_* \) is the SFR in units of \( M_\odot \text{yr}^{-1} \text{Mpc}^{-3} \). Then the number of ionizing photons is calculated by

\[
\frac{dN_\gamma}{dt} = n_\gamma f_{\text{esc}} \dot{\rho}_*(z),
\]

where \( f_{\text{esc}} \) represents the escape fraction of ionizing photons from stars and \( n_\gamma \) gives the number of photons emitted per unit mass of stars. Unfortunately, the escape fraction of stellar ionizing photons from high-redshift galaxies remains poorly constrained, making this parameter one of the primary goals of many theoretical and observational studies.

A number of studies (e.g. Iwata et al. 2009, Vanzella et al. 2011, Nestor et al. 2011) have measured the escaping ionizing photons at \( z \sim 3-4 \), suggesting that the escape fraction is between 0.05 and 0.2. Although the samples are small, almost all the average escape fractions of ionizing photons from the observed massive galaxies are less than 0.2. By integrating over appropriate energy ranges, the parameter \( n_\gamma \) gives \((8.05, 2.62, 0.01) \times 10^{60} \text{M}_\odot^{-1} \text{yr}^{-1} \) for H II, He II, He III, respectively, as suggested by Choudhury & Ferrara (2005).

For comparison, we show how the ratio \( N_{\gamma, \text{HII}} / N_{\gamma, \text{HII}} \) evolves as a function of redshift for three different \( f_{\text{esc}} \) in Fig. 4. Here we consider only the LE case for the IMBH spectrum, as for the HE case, the hydrogen ionizing photons from mini-quasars are simply zero. It is also worth stressing that all the ionizing photons from mini-quasars are assumed to be available for ionizing the IGM. As shown in Fig. 4, the ratio peaks at \( z \sim 13 \) for all three models, decreases rapidly at lower redshifts and becomes negligible at \( z \lesssim 5 \). Only for the model with \( f_{\text{esc}} < 0.2 \), mini-quasars have a higher ionizing flux contribution than that of stars at \( z \gtrsim 6 \).

### 3 RESULTS

We first consider the contribution of mini-quasars, i.e., accreting IMBHs alone to the reionization of cosmic hydrogen and helium. Fig. 3 shows the evolution of the filling factor of the ionized regions \( Q_{\text{HII}} \) (solid line) and \( Q_{\text{HeIII}} \) (dashed line) due to the accreting IMBHs alone. Note that only the LE case for the IMBH emission is shown here, since accreting IMBHs only provide a negligible contribution to hydrogen reionization for the HE case as mentioned above. As can be seen, the accreting IMBHs can only contribute \( \sim 20\% \) of hydrogen ionizing photons at \( z \sim 6 \). The difference between the evolution of \( Q_{\text{HII}} \) and that of \( Q_{\text{HeIII}} \) is very subtle, because of the assumption that the He III ionization front never overtakes the hydrogen ionization front, i.e. \( Q_{\text{HII}} > Q_{\text{HeIII}} \). This result implies that, in an optimistic case (LE case), the contribution of mini-quasars to hydrogen reionization is not negligible at \( z \sim 6 \), but still insufficient to provide the required number of ionizing photons, consistent with previous studies (Madau et al. 2004, Dijkstra et al. 2004, Wang et al. 2010, McQuinn 2012).

As a reference, the contribution from accreting MBHs (“quasars”) is also considered. Note that we set the emission spectrum of quasars with a spectral index of \( \alpha = 1.7 \) and ionizing UV and X-ray photons (i.e. energy range of 10.4 eV < \( E < 100 \text{keV} \)). As shown in Fig. 3, only at relatively low redshifts (\( z \lesssim 6 \)) does the contribution from MBHs play a relevant role in reionizing the IGM. When considering the contributions from both IMBHs and MBHs, we find that helium reionization ends at \( z \approx 3 \), consistent with recent observations of helium reionization (e.g. Zheng et al. 2004, McQuinn 2009, Furlanetto & Duxer 2010, Shull et al. 2010, Becker et al. 2011, Worseck et al. 2011, Meiksin & Tittley 2012). Moreover, in this scenario, the middle of helium reionization occurs at \( z \sim 5 \) and hydrogen reionization ends at \( z \approx 4 \). It is worth stressing that, for simplicity, we have assumed the same \( M_{\text{BH}} - \sigma \) relation at all redshifts. This almost certainly constitutes an underestimate for the contribution of accreting BHs at low redshifts and delays the completion of helium reionization.

We then consider the combined contribution from accreting BHs and stars to the reionization of hydrogen and helium. Here, for the ionizing emission from accreting BHs, both IMBHs and MBHs are included. Given the uncertainty in the escape fraction of ionizing photons from stars, we present the results of modeling the reionization histories of hydrogen and helium for three different choices of the escape fraction of ionizing photons from stars (\( f_{\text{esc}} = 0.05; 0.2; 0.5 \)). Fig. 4 shows the evolution of both \( Q_{\text{HII}} \) and \( Q_{\text{HeIII}} \). The upper panel refers to the HE case for the IMBH emission, while the lower panel is for the LE case. It is clear that the Universe is reionized earlier for the LE case. As seen in both panels, the escape fraction \( f_{\text{esc}} \) of ionizing photons from stars does not have strong influence on the evolution of \( Q_{\text{HII}} \), because stars provide a negligible contribution to the helium ionizing photons.

In the HE case, helium reionization ends at \( z \approx 2.7 \), consistent with observations, while in the LE case the end redshift of helium reionization \( z \approx 3.5 \) is much earlier. Models with \( f_{\text{esc}} = 0.2 \) and \( f_{\text{esc}} = 0.5 \) satisfy the observational constraints of the Gunn-Peterson trough (i.e. hydrogen reionization at \( 6 \lesssim z_{\text{reion}} \lesssim 7 \)). However, when considering
the constraints on the CMB optical depth, only the model with \( f_{\text{esc}} = 0.5 \) is consistent with the WMAP-7 result of \( \tau_c = 0.088 \pm 0.015 \), as shown in Fig. 5.

In the LE case, only the model with \( f_{\text{esc}} = 0.2 \) is consistent with observations of the Gunn-Peterson trough, whereas hydrogen reionization in the other two models is completed either too early (\( z \gtrsim 7 \)) or too late (\( z \lesssim 5.5 \)). However, although the model with \( f_{\text{esc}} = 0.2 \) is able to reionize the Universe at \( z \sim 6 \), it is not able to satisfy the constraints on the CMB optical depth simultaneously. This result imply that, to simultaneously satisfy the joint constraints from the Gunn-Peterson test and the CMB optical depth, an escape fraction \( f_{\text{esc}} \) within the range from 0.2 to 0.5 is needed in this case.

So far, we have analyzed the evolution of the reionization histories for different escape fractions, assuming a power-law spectral index of \( \alpha = 1 \) for the ionizing emission of accreting IMBHs. For comparison, we also explore the possibility of a quasar-like spectral index of \( \alpha = 1.7 \) for the emission spectrum of IMBHs. The results are shown in Fig. 6 and Fig. 7. As seen in Fig. 6, helium reionization ends much earlier at \( z \gtrsim 3.5 \) for both HE and LE cases. For the HE case, the results turn out to be similar to those found in the \( \alpha = 1 \) scenario, except that helium reionization ends much earlier at \( z \gtrsim 3.5 \). On the other hand, for the LE case, all three models with different \( f_{\text{esc}} \) can produce enough ionizing photons to obtain the CMB optical depth, as shown in Fig. 7. In this extreme case, only an escape fraction of \( f_{\text{esc}} \lesssim 0.05 \) is large enough. These results show that, if high-redshift star-forming galaxies have an escape fraction larger than 0.05, then accreting IMBHs with a quasar-like spectrum would produce too many ionizing photons to be more or less in tension with observations.

In the most optimistic model, mini-quasars are able to reionize more than \( \sim 20\% \) of the cosmic helium by redshift \( z \sim 6 \), and the ionized fraction of cosmic helium rapidly climbs to more than 50\% by redshift \( z \sim 5 \) when considering both IMBHs and MBHs. These results may imply that, in addition to the constraint from the SXRB, better measurements of the evolution history of helium reionization, especially at high redshifts, would also be helpful in placing limits on the growth of IMBHs in the early Universe. If successful, this would not only represent a breakthrough in our understanding of the epoch of reionization, but it would also shed some light on the puzzles concerning the formation of SMBHs at \( z \sim 7 \).

4 DISCUSSION AND CONCLUSIONS

In this paper, basing on recent observational results, we have studied the reionization history of cosmic hydrogen and helium by both mini-quasars and stars. The contribution from quasars is also included. In order to take into account the contribution from (mini-)quasars, the \( M_{\text{bh}} - \sigma_\star \) relation at \( z > 6 \), which is from the simulation on the merger tree of dark matter halos, is applied. Several types of power-law spectra for the mini-quasar emission are considered. Three different escape fractions \( f_{\text{esc}} \) of ionizing photons from stars are tested. By simultaneously considering the constraints from the CMB optical depth and observations of the Gunn-Peterson trough in the spectra of high-redshift quasars, we find the following results for models with a power-law IMBH spectrum (spectral index \( \alpha = 1 \)).

(i) For mini-quasars with no UV ionizing photons (200 eV < \( E < 100 \) keV), the hydrogen ionizing photons emitted by mini-quasars are negligible. Helium reionization occurs at \( z \approx 2.7 \), consistent with observational results. Only the model with \( f_{\text{esc}} \approx 0.5 \) is simultaneously consistent with the constraints from the Gunn-Peterson test and the CMB optical depth.

(ii) When considering mini-quasars with UV ionizing photons (10.4 eV < \( E < 100 \) keV), both hydrogen and helium reionization are completed earlier. In this case, an escape fraction in the range 0.2 < \( f_{\text{esc}} < 0.5 \) is able to satisfy the joint constraints. Note that, in this optimistic case, mini-quasars are able to contribute \( \sim 20\% \) of hydrogen ionizing photons, consistent with previous studies (Madau et al. 2004; Wang et al. 2010).

We also consider the possibility that the mini-quasar has a quasar-like spectral index of \( \alpha = 1.7 \). In this scenario, mini-quasars significantly over-produce the helium ionizing photons, leading to an early completion of helium reionization at \( z \gtrsim 4 \), which is inconsistent with observations.

There are some caveats which could significantly affect our expectations about the contribution to cosmic reionization from mini-quasars. First, we have assumed that all the ionizing photons from mini-quasars are available for ionizing the IGM. This is because the high production rate of ionizing photons from mini-quasars would allow the surrounding gas to be ionized very quickly (e.g. Whalen et al. 2004). However, Benson et al. (2013) argued that the escape fraction of ionizing photons from the early quasars could be only \( f_{\text{esc,BH}} \sim 0.3 \). If this is the case, the contribution from mini-quasars would be significantly reduced. Another important consideration is the assumption on the duty cycle of mini-quasars at high redshifts, i.e. \( P(z > 6) \sim 0.9 \) – 1. If the duty cycle of mini-quasars at high redshifts is similar to that of present quasars (\( P(z \sim 0) \sim 0.1 \)), the contribution of mini-quasars to cosmic reionization would become negligible. Besides, on the assumption of the spectrum of mini-quasars, instead of a simple power-law, one can also adopt a multicomponent spectrum (e.g. Tanaka et al. 2012). Also note that we have ignored the secondary ionizations from the mini-quasar emission in our model for simplicity. We caution that, until most of these properties of mini-quasars have been better understood, a stringent constraint on the contribution of mini-quasars can not be obtained. In turn, it is also reasonable to expect that, improved measurements of helium reionization, especially at high redshifts, coupled with the constraint from the SXRB, could be used to better constrain these properties of mini-quasars, which would make a relevant contribution to the solution of the puzzles related to the formation of SMBHs at high redshifts.

Moreover, it is commonly believed that the feedback from the accretion onto central BHs could play an important role. For example, the radiation from accreting BHs can limit the gas supply by radiation pressures and photon-heating, leading to the self-regulation of the BH growth (e.g. Jeon et al. 2012; Park & Ricotti 2012). Additionally, Tanaka et al. (2012) suggest that the IGM heating by mini-quasars can also suppress the formation and growth of central BHs in low-mass halos. On the other hand, the star for-
mation in low-mass galaxies may be affected by both local and global heating from mini-quasars (e.g., Ripamonti et al. 2008, Jeon et al. 2012). This would thus influence the relative contributions of mini-quasars and stars to cosmic reionization. However, this additional complication is beyond the scope of this paper, and will be addressed in our future work.

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Figure 1. Evolution of the mass density of central BHs as a function of redshift. The solid line and short-dashed line represent the mass density of IMBHs and MBHs, respectively. The dashed line is the constraints on the BH mass density from the SXRB derived by Salvaterra et al. (2005).

Figure 2. Redshift evolution of the ratio between the IMBH and star contributions to the hydrogen ionizing photons, assuming the LE SED (10.4 eV < E < 100 keV) for the IMBH emission. The escape fractions of ionizing photons from stars are taken to be $f_{\text{esc}} = 0.05$, 0.2 and 0.5 for the solid, dashed and short-dashed lines, respectively.
Figure 3. Redshift evolution of the volume filling factor of $Q_{\text{HII}}$ and $Q_{\text{HeIII}}$ due to the ionizing photons from IMBHs and MBHs, assuming the LE SED ($10^{14}$ eV < $E$ < 100 keV) for the IMBH emission.

Figure 4. Redshift evolution of the volume filling factor of $Q_{\text{HII}}$ and $Q_{\text{HeIII}}$ for three different escape fractions $f_{\text{esc}}$ of ionizing photons from stars. Here, both accreting BHs and stars are included. The IMBH spectrum has a spectral index of $\alpha = 1$. The upper panel refers to the HE case for the BH emission, while the lower panel refers to the LE case.
Figure 5. Redshift evolution of the Thomson scattering optical depth for three different escape fractions $f_{\text{esc}}$. The upper and lower panels refer to the HE and LE cases for the IMBH emission, respectively. The black bar represents the WMAP-7 result, i.e., $\tau_e = 0.088 \pm 0.015$.

Figure 6. Redshift evolution of the volume filling factor of $Q_{\text{HII}}$ and $Q_{\text{HeIII}}$, assuming the mini-quasar emission with a quasar-like spectrum ($\alpha = 1.7$). The upper and lower panels refer to the HE and LE cases for the IMBH emission, respectively. Here, HeII reionization completes much earlier at $z \gtrsim 3.5$ for both HE and LE cases.
Figure 7. Redshift evolution of the Thomson scattering optical depth, assuming the mini-quasar emission with a quasar-like spectrum ($\alpha = 1.7$). The upper and lower panels refer to the HE and LE cases for the IMBH emission, respectively. The black bar represents the WMAP-7 result, i.e., $\tau_e = 0.088 \pm 0.015$. 

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