Distinctive 21 cm Structures of the First Stars, Galaxies, and Quasars

Hidenobu Yajima$^{1,2,3}$ and Yuexing Li$^{2,3}$

$^1$SUPA, Institute for Astronomy, University of Edinburgh, Royal Observatory, Edinburgh, EH9 3HJ, UK
$^2$Department of Astronomy and Astrophysics, Pennsylvania State University, 525 Davey Lab, University Park, PA 16802, USA
$^3$Institute for Gravitation and the Cosmos, The Pennsylvania State University, University Park, PA 16802, USA

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ABSTRACT

Observations of the redshifted 21 cm line with upcoming radio telescopes promise to transform our understanding of the cosmic reionization. To unravel the underlying physical process, we investigate the 21 cm structures of three different ionizing sources, Pop III stars, the first galaxies and quasars, by using radiative transfer simulations that include both ionization of neutral hydrogen and resonant scattering of Ly$\alpha$ photons. We find that Pop III stars and quasars produce a smooth transition from an ionized and hot state to a neutral and cold one, owing to their hard spectral energy distribution with abundant ionizing photons, in contrast to the sharp transition in galaxies. Furthermore, Ly$\alpha$ scattering plays a dominant role in producing the 21 cm signal as it determines the relation between hydrogen spin temperature and gas kinetic temperature. This effect, also called Wouthuysen-Field coupling, depends strongly on the ionizing source. It is the strongest around galaxies, where the spin temperature is highly coupled to that of the gas, resulting in extended absorption troughs in the 21 cm brightness temperature. On the other hand, in the case of quasars, since Ly$\alpha$ photons cannot propagate far from the source due to its large H$\text{II}$ region and limited traveling time, only emission of the 21 cm is produced, while for Pop III stars, the 21 cm signal falls in between, showing both emission and absorption region around a small H$\text{II}$ bubble. We predict that future surveys from large radio arrays such as MWA, LOFAR and SKA may be able to detect the 21 cm signals of primordial galaxies and quasars, but unlikely Pop III stars due to its small angular diameter.

Key words: radiative transfer – diffuse radiation – galaxies: evolution – galaxies: formation – galaxies: high-redshift – quasars: supermassive black holes

1 INTRODUCTION

The epoch of reionization (EoR), during which high energy photons produced by the first luminous objects reionized the neutral hydrogen in the intergalactic medium (IGM), was an important milestone in the cosmic history (Loeb & Barkana 2001). The latest measurements from the Planck satellite suggest that the Universe was reionized at redshift $z \sim 11$ (Planck Collaboration 2013), in agreement with the seven-year results of Wilkinson Microwave Anisotropy Probe (WMAP) (Komatsu et al. 2011), while studies of Gunn-Peterson absorption (Gunn & Peterson 1965) of high-redshift quasars (QSOs) suggest that reionization began as early as $z \sim 15$ and ended at $z \sim 6$ (Fan et al. 2006a). The reionization history strongly constrained not only the formation of the first generation of galaxies and QSOs, but also their feedback and impacts on structure formation at later times (Bromm & Yoshida 2011).

Over the past few years, impressive progress has been made in detecting distant objects. Recent observations using both broad-band colors (e.g., Bouwens et al. 2012; Ellis et al. 2013) and narrow-band Ly$\alpha$ emission (e.g., Ouchi et al. 2010; Kashikawa et al. 2011) have detected hundreds of galaxies at $z \gtrsim 6$. Meanwhile, over two dozen luminous QSOs have been detected at $z \sim 6$ (e.g., Fan et al. 2006a; Willott et al. 2010b; Mortlock et al. 2011). While it is generally believed that early star-forming galaxies played an important role in reionizing the Universe (Robertson et al. 2010), the ionization process and the actual contributions from different ionizing sources remain poorly understood.
The 21 cm hyperfine line of neutral hydrogen has been proposed to be a powerful tool to probe the EoR, as it traces the thermal history of the IGM and the ionization structures (e.g., Morales & Wyithe 2010; Pritchard & Loeb 2012). Recent advances in radio instrumentation and techniques will soon make it possible to measure the highly redshifted 21 cm signal from gas during the first billion years after the Big Bang, as a number of radio interferometers are currently being built or planned, such as Murchison Widefield Array (MWA; Lonsdale et al. 2008), the Low Frequency ARray (LOFAR; Haverkorn et al. 2013), the Precision Array to Probe the Epoch of Reionization (PAPER; Parsons et al. 2010), the Giant Meter-wave Radio Telescope (GMRT; Paturel et al. 2011), and Square Kilometre Array (SKA; Dewdney et al. 2009).

In order to understand and interpret observations from these instruments, it is critical to understand the 21 cm structures from different ionizing sources. It has been suggested by advanced numerical simulations that the first stars (the so called metal-free Pop III stars) started to form in mini-halos of order $M_c \sim 10^{6} M_\odot$, as early as $z \sim 30$ (Abel et al. 2002; Bromm et al. 2002; Yoshida et al. 2008; Turk et al. 2009; Clark et al. 2011). The first galaxies are believed to form in low-metallicity halos via gas accretion or mergers around $z \sim 15$ thanks to feedback and metal enrichment from Pop III stars (Wise & Abel 2007; Wise et al. 2008; Wise & Abel 2008; Greif et al. 2014; Pawlik et al. 2011; Wise et al. 2012). Meanwhile, the massive black holes (BHs) may form from remnants of massive Pop III stars or direct collapse of gas clumps or supermassive stars (e.g., Volonteri & Begelman 2010), leading to the emergence of the first QSOs (Li et al. 2007; Di Matteo et al. 2008; Baek et al. 2009) which calculate the gas spin temperature and ionization state (Furlanetto & Oh 2006; Baek et al. 2009). These objects provided strong UV radiation that reionized the neutral hydrogen.

To date, a number of theoretical works have studied the 21 cm signals of Pop III stars (Chen & Miralda-Escude 2004; 2005; Torki et al. 2009), galaxies (McQuinn et al. 2006; Kuhlen et al. 2006; Mellema et al. 2006; Semelin et al. 2007; Baek et al. 2010; Volonteri & Begelman 2010), and QSOs (Furlanetto & Oh 2006; Baek et al. 2009) combined cosmological simulations and post-processing Lyα RT to calculate the 21 cm signals from UV and X-ray sources. They found that the absorption phase of the 21 cm survives throughout the EoR even in the presence of strong X-ray sources, and that the brightness temperature fluctuation of the 21 cm signal evolves strongly with redshift, with a higher amplitude in the early reionization phase.

In order to investigate the Wouthuysen-Field effect from different ionizing sources and the resulting 21 cm structures, we here carry out a comparative study of the ionization history of three types of sources: Pop III stars, primordial galaxies and QSOs. We perform RT calculations, which include both ionization and Lyα scattering, on individual source embedded in the IGM. Different intrinsic spectral energy distribution (SED) appropriate for each source type is used. We follow the evolution of the ionization structures and temperature to derive the 21 cm signals.

The paper is organized as follows. In §2, we describe our model and method of the simulations. In §3, we present the results, which include the structure of ionization, temperatures and the 21 cm signal around different sources, and their time evolution. We discuss in §4 the detectability of the 21 cm structures of these sources by upcoming facilities such as MWA, LOFAR and SKA, and summarize in §5.

## 2 Model & Method

In this work, we carry out RT calculations that include ionization and Lyα scattering on three types of ionizing sources embedded in the IGM: Pop III stars, galaxies and QSOs. The IGM is modeled as spherical shells around the source. The boundary of the sphere is set to be $R = 7 R_\odot$, where $R_\odot$ is the radius of Strömgren sphere, and it is linearly divided into 300 bins.

For each source type, we consider a range of masses in the redshift range $z = 7 - 20$. For Pop III stars, $M_{\text{star}} = 10^4 - 10^5 M_\odot$; for galaxies, $M_{\text{star}} = 10^9 - 10^{10} M_\odot$, and for QSOs, $M_{\text{star}} = 10^8 - 10^{12} M_\odot$, where $M_{\text{star}}$ is total stellar mass. For Pop III stars with $M_{\text{star}} > 10^5 M_\odot$, we assume multiple star formation of $100 M_\odot$ in a halo (e.g., Greif et al. 2012), or a cluster of halos with Pop III stars.

### 2.1 The 21 cm Signal

The fluctuation in 21 cm intensity (or fluctuation of brightness temperature) from different regions of the IGM at a given redshift $z$ depends sensitively on the gas properties, including density, velocity gradients, gas temperature, gas spin temperature and ionization state (Furlanetto & Oh 2006). We follow the procedure of previous works (e.g., Furlanetto & Oh 2006; Baek et al. 2009) which calculate the fluctuation of brightness temperature as

$$\delta T_b = 28.1 \chi_{\text{HI}} (1 + \delta) \left( \frac{1 + z}{10} \right)^{1/2} \frac{T_S - T_{\text{CMB}}}{T_S} \text{ mK},$$

where $\chi_{\text{HI}}$ is the neutral hydrogen fraction, $\delta$ is over density, $T_S$ and $T_{\text{CMB}}$ are the gas spin and CMB temperature respectively. The IGM is assumed to be uniform, i.e., $\delta = 0$, as recent simulations suggest small clumpiness in the IGM.
at high redshift (Pawlik et al. 2009). The contribution of the gradient of the proper velocity is not considered in this work.

The gas spin temperature is controlled by Thomson scattering of CMB photons, Lyα photon pumping, and collisions by the gas particles, as formulated by Furlanetto & Oh (2006):

\[
T_{S}^{-1} = \frac{T_{\text{CMB}}^{-1} + x_{C}T_{\text{gas}}^{-1} + x_{\alpha}T_{\text{Ly}\alpha}^{-1}}{1 + x_{C} + x_{\alpha}},
\]

where \(T_{C}\) is the color temperature of the Lyα line, \(T_{\text{gas}}\) is the kinetic temperature of the gas, \(x_{\alpha}\) and \(x_{C}\) are the coupling coefficients by Lyα photon scattering and gas collision, respectively, which are calculated for each spherical shell from RT simulations of ionizing and Lyα photons as follows

\[
x_{\alpha} = \frac{4P_{\alpha}T_{\star}}{27A_{10}T_{\text{CMB}}}, \quad (3)
\]

\[
x_{C} = \frac{T_{\star}}{A_{10}T_{\text{CMB}}}(C_{\text{H}} + C_{p} + C_{e}). \quad (4)
\]

where \(T_{\star} = 0.068\, \text{K}, A_{10} = 2.85 \times 10^{-15}\, \text{s}^{-1}\) is the spontaneous emission factor of the 21 cm transition. \(P_{\alpha}\) is the number of scatterings of Lyα photons per atom per second, \(C_{\text{H}}, C_{p}\) and \(C_{e}\) are the de-excitation rates due to collision with neutral atoms, protons, and electrons, respectively. We use the fitting formula given by Liszt (2001) and Kuhlen et al. (2006) for the de-excitation rates. Since \(T_{C}\) quickly settles into \(T_{\text{gas}}\) owing to the recoil effect of Lyα photon scattering, \(T_{C} = T_{\text{gas}}\) is assumed in our calculations. The spin temperature depends sensitively on the coupling due to Lyα scattering and collision. When the coupling is strong, the it decouples from the CMB temperature and becomes \(T_{S} \sim T_{\text{gas}}\).

### 2.2 Intrinsic SEDs of Ionizing Sources

We consider different SEDs for the three types of sources, PopIII stars, galaxies and QSOs in our calculations. For PopIII stars, we assume a black body spectrum, and follow the formulae from Bromm et al. (2001) to calculate the effective temperature and bolometric luminosity of a star with mass \(M\):

\[
T_{\text{PopIII}}^{\text{eff}} = 1.1 \times 10^{5}\left(\frac{M}{100\, M_{\odot}}\right)^{0.025} \text{K}. \quad (5)
\]

\[
L_{\text{PopIII}}^{\text{bol}} = 10^{4.5} \frac{M}{M_{\odot}} L_{\odot}. \quad (6)
\]

The primordial galaxies in our model are assumed to consist of only metal poor, young stars which follow a Salpeter initial mass function (IMF) Salpeter (1955). We assume a stellar age of 5 Myr and a metallicity of \(Z = 0.1\, Z_{\odot}\), which are consistent with observations of high-redshift Lyα emitting galaxies (e.g., Lai et al. 2007; Hakunietz et al. 2002; Ota et al. 2011; Nakajima et al. 2012). The SEDs of galaxies are then generated using the stellar population synthesis code PEGASE v.2.0 (Fioc & Rocca 1997) for a given stellar mass with the above parameters of stellar age, metallicity and IMF.

The SED of QSOs is estimated by adding a broken power-law spectrum of massive black holes to the galaxy’s SED. The power-law spectrum is assumed following (Laor & Draine 1993; Marconi et al. 2004; Hopkins et al. 2003), with a peak at \(\lambda \sim 300\, \text{Å}\). The SED of galaxies drops sharply at wavelengths shortward of the Lyman limit \(\lambda \sim 912\, \text{Å}\), while that of QSO has a power-law tail at from X-ray to Lyman limit owing to radiation from an accreting BH. As we will show later, the difference in the SEDs at \(\lambda < 912\, \text{Å}\) would result in different ionization structure of hydrogen by the three ionizing sources. On the other hand, both galaxies and QSOs have much higher Lyα flux at \(\lambda = 1216\, \text{Å}\) than Pop III stars, which would lead to stronger effects of Lyα scattering.

### 2.3 Ionization and Heating of the IGM

We calculate the ionization of hydrogen and helium in the IGM by central sources using one-dimensional RT of ionizing photons. In this work, we focus on the early phase when radiation field is localized, hence the radiation background from external sources is not included. The time evolution of the ionization of hydrogen and helium is estimated by the
following equations:

\[
\frac{dX_{\text{HI}}}{dt} = -\Gamma_{\text{HI}} + \Gamma_C^{\text{HI}} X_{\text{HI}} n_e + \alpha_B^{\text{HI}} X_{\text{HI}} n_e,
\]

(8)

\[
\frac{dX_{\text{HeI}}}{dt} = -\Gamma_{\text{HeI}} + \Gamma_C^{\text{HeI}} X_{\text{HeI}} n_e + \alpha_B^{\text{HeI}} X_{\text{HeI}} n_e,
\]

(9)

\[
\frac{dX_{\text{HeII}}}{dt} = -\frac{dX_{\text{HeI}}}{dt} - \Gamma_{\text{HeII}} + \Gamma_C^{\text{HeII}} X_{\text{HeII}} n_e + \alpha_B^{\text{HeII}} X_{\text{HeII}} n_e,
\]

(10)

where \(X_{\text{HI}}, X_{\text{HeI}}, X_{\text{HeII}}\) are ionization fraction of neutral hydrogen, neutral helium, ionized hydrogen and ionized helium, respectively, \(n_e\) is the electron density, \(\alpha_B\) is case B recombination rate, \(\Gamma_C\) is collisional ionization rate. We use the fitting formula of [Gnedin & Ostriker (1997)] for \(\alpha_B\), and that of [Cen (1992)] for \(\Gamma_c\). The photo-ionization rate \(\Gamma^\alpha\) in each shell is estimated by

\[
\Gamma_H^\alpha = \frac{1}{m_{\text{H}} V_{\text{shell}}} \int_{\nu_{\text{limit}}}^{\nu_{\text{Ly}\alpha}} L(\nu) \frac{e^{-\tau(\nu)}}{h\nu} \left(1 - e^{-\Delta\tau_H(\nu)}\right) \, d\nu
\]

(11)

where \(V_{\text{shell}}\) is the volume of the gas shell, \(\nu_{\text{limit}}\) is the Lyman limit frequency, \(\tau\) is the optical depth from the central source to the shell, \(\Delta\tau\) is optical depth of the shell. The optical depth is calculated by

\[
\tau(\nu) = n_{\text{H}_2}\sigma_1(\nu) \int_0^{r_{\text{shell}}} dr' \chi_{\text{HI}}(r') + n_{\text{HeI}}\sigma_{\text{HeI}}(\nu) \int_0^{r_{\text{HeI}}} dr' \chi_{\text{HeI}}(r')
\]

+ \(n_{\text{HeII}}\sigma_{\text{HeII}}(\nu) \int_0^{r_{\text{HeII}}} dr' \chi_{\text{HeII}}(r')
\]

(12)

where \(\sigma\) is the ionization cross section. We use the fitting formula from [Cen (1992)], i.e., \(\sigma_{\text{HI}} = 6.3 \times 10^{-18} (\nu/\nu_{\text{limit}})^{-1.66} \), \(\sigma_{\text{HeI}} = 7.2 \times 10^{-18} (\nu/\nu_{\text{limit}})^{-2.05} + 0.66 (\nu/\nu_{\text{limit}})^{-3.05}\), and \(\sigma_{\text{HeII}} = 1.58 \times 10^{-18} (\nu/\nu_{\text{limit}})^{-3}\).

The evolution of ionization would lead to change of gas temperature in each shell with time as follows,

\[
\frac{dT_{\text{gas}}}{dt} = \frac{2}{3k_B m}\left[k_B T_{\text{gas}} \frac{dn}{dt} + H - \Lambda\right]
\]

(13)

where \(k_B\) is the Boltzmann constant, \(n\) is the total number density of hydrogen and helium, \(H\) is the heating rate, and \(\Lambda\) is the cooling rate. We follow the procedures of [Maselli et al. (2003)] to calculate the heating and cooling rates: we consider photo-heating for \(H\), while for \(\Lambda\), we include recombination, collisional ionization and excitation cooling processes. The upper limit of gas temperature is set to be \(10^5\) K, and heating by Ly\(\alpha\) photon scattering is not included, as it was shown to be insignificant (Chen & Miralda-Escudé 2004).

We follow the evolution of ionization and temperature up to \(10^8\) yr, and calculate Ly\(\alpha\) radiation field and the 21 cm signal of the snapshot at \(t_{\text{snap}} = 10^6, 10^7\) and \(10^8\) yr, respectively. Our fiducial run uses the snapshot at \(t_{\text{snap}} = 10^7\) yr at redshift \(z = 10\).

2.4 Radiative Transfer of Ly\(\alpha\) Photons

The RT of Ly\(\alpha\) photons in IGM is a highly complex process. It depends strongly on the Ly\(\alpha\) resonant scattering, the density distribution and ionization state of the medium. The frequency change resulted from the scattering is difficult to estimate analytically. [Yajima et al. (2012a)] has developed a three-dimensional, Monte Carlo Ly\(\alpha\) RT code which couples continuum and ionization of hydrogen. Here we use the 1-D version of the code to numerically simulate the Ly\(\alpha\) RT in spherical shells of the IGM.

In the scattering process, the outgoing frequency in the laboratory frame \(\nu_{\text{out}}\) is calculated as

\[
\frac{\Delta\nu_{\text{out}}}{\Delta\nu_{\text{in}}} = 1 - \frac{\nu_{\text{in}} - \nu_0}{\nu_{\text{out}}} - \frac{\nu_{\text{out}} k_{\text{in}}}{\nu_{\text{in}}} + \frac{\nu_{\text{in}} k_{\text{out}}}{\nu_{\text{out}}}
\]

(14)

where \(\nu_{\text{in}}\) is the incoming frequency in the rest frame of scattering medium, \(\nu_0\) is the line center frequency \(\nu_0 = 2.466 \times 10^{15}\) Hz, \(\nu_{\text{in}}\) is the atom velocity, \(\Delta\nu_{\text{D}} = (v_{\text{in}}/c)\nu_0\) corresponds to the Doppler frequency width, \(v_{\text{in}}\) is the velocity dispersion of the Maxwellian distribution describing the thermal motions, i.e., \(v_{\text{in}} = (2k_B T/m_{\text{H}})^{1/2}\), and \(k_{\text{in}}\) and \(k_{\text{out}}\) are incoming and outgoing propagation direction, respectively.

We consider Ly\(\alpha\) photons from both continuum radiation of sources and recombination process in ionized IGM. The intrinsic Ly\(\alpha\) luminosity is estimated by

\[
L_{\text{Ly}\alpha} = \int_{\nu_{\text{Ly}\alpha}}^{1216\ \text{A}} \frac{L}{\lambda d\lambda} + 0.68 \sigma_{\text{HII}} n_{\text{HII}} n_e V_i
\]

(15)

where the continuum spectrum is considered in the frequency range from Ly\(\alpha\) line(1216 A) to Lyman limit (912 A), and the recombination term depends on the volume of the ionized bubble \(V_i\) and density of the ionized hydrogen and electrons. Photons in this continuum range can be absorbed by neutral hydrogen which is then excited to higher levels of the Lyman series, and those hydrogen atoms at \(n = 2\) level can transit to \(n = 1\) by emitting Ly\(\alpha\) photons. Since we focus on the early phase of ionization up to \(10^9\) yr in this work, which is shorter than the recombination time scale \((t_{\text{rec}} \sim 4 \times 10^8\) yr\), the ionized volume \(V_i\) in Equation 15 is generally smaller than the Strömgren sphere at ionization equilibrium. Hence, the total Ly\(\alpha\) emission is dominated by the continuum radiation from central sources.

We simulate the Ly\(\alpha\) RT using the structure of ionization and temperature at times \(t_{\text{snap}} = 10^6, 10^7\) and \(10^8\) yr, respectively, by assuming that the traveling time of the Ly\(\alpha\) photons \(t_{\text{travel}} = t_{\text{snap}}\). We performed a convergence test and found an optimal number of photon packets for the RT calculations, \(N_p = 10^9\), of which the number of Ly\(\alpha\) photons \(N_{\text{L}\alpha} = L_{\text{L}\alpha}/(h\nu_{\alpha} N_p)\). In these calculations, since we need to estimate the number of scattering of Ly\(\alpha\) photons in each shell precisely to derive the spin temperature, we cannot use the “core skipping” technique in the Ly\(\alpha\) RT which can accelerate the calculation, as used in most Ly\(\alpha\) RT simulations (e.g., Zheng & Miralda-Escudé 2002; Verhamme et al. 2003; Dijkstra et al. 2006; Laursen et al. 2007; Yajima et al. 2012b, 2013). Hence, the calculations are very expensive even with 10^7 photon packets. Each simulation took a few days running on 64 processors.

3 RESULTS

We performed a set of RT simulations on three types of ionizing sources, PopIII star, primordial galaxy and QSO, in the redshift range \(z = 7 - 20\). A wide range of masses were considered for these sources, i.e., \(M_{\text{star}} = 10^5 - 10^7 M_{\odot}\) for Pop III stars or cluster of Pop III stars, \(M_{\text{star}} = 10^8 - 10^{10} M_{\odot}\) for galaxies, and \(M_{\text{star}} = 10^8 - 10^{12} M_{\odot}\) for QSOs.
3.1 Structures of Ionization and Temperature

The propagation of the ionization front of a Pop III star, a primordial galaxy, and a QSO are shown in Figure 2 in comparison with the analytical solution from Spitzer (1978). The position of the ionization front is measured where the ionized hydrogen fraction $X_{\text{HII}} = 0.5$. The size of the ionized region from the galaxy and QSO follows the analytical one closely, but that of the Pop III star appears to be smaller, owing to helium ionization by Pop III stars. As shown in Figure 3, the SED of Pop III stars peaks around the Ly-$\alpha$ number of Ly-$\alpha$ photons is consumed by helium ionization, resulting in a HeII region compared to the analytical solution $ii$. Moreover, the hard SEDs of Pop III stars and QSOs can also produce ionized HeII regions, which is absent in the modeled galaxy without accreting black holes. The size of the ionized HeII region is $\sim 0.2$ of the HII bubble in Pop III stars and $\sim 0.1$ in QSOs.

Similarly, the temperatures show different structures from these different sources. The kinetic temperature of the gas, $T_{\text{gas}}$, shows a smooth transition from hot ($\sim 10^4$ K) to cold ($\sim$ a few K) state around the Pop III star and the QSO, in contrast to the sharp transition in the galaxy, due to partial ionization and heating from photoionization. The spin temperature $T_S$ shows different patterns in these sources. As indicated in Equation 2, $T_S$ depends strongly on the coupling efficiency due to Ly-$\alpha$ scattering and gas collision. If the coupling is strong, $T_S$ is coupled to $T_{\text{gas}}$ which is in general different from the CMB temperature $T_{\text{CMB}}$. As shown in the middle panels of Figure 3 for the Pop III star, $T_S$ is weakly coupled to $T_{\text{gas}}$ within the HII region due to small number of Ly-$\alpha$ scatterings resulted from low number of Ly-$\alpha$ photons in its SED. As the Ly-$\alpha$ scattering becomes sparse beyond the HII region, $T_S$ is decoupled from $T_{\text{gas}}$ and it takes the value of $T_{\text{CMB}}$. For the galaxy, $T_S$ is completely coupled to $T_{\text{gas}}$ due to strong Ly-$\alpha$ scattering, it is thus completely decoupled from $T_{\text{CMB}}$. For the QSO, $T_S$ is completely coupled to $T_{\text{gas}}$ within the HII region, but outside of which it decouples from $T_{\text{gas}}$ and becomes $T_{\text{CMB}}$ due to sharp decline of Ly-$\alpha$ scattering.

As a result of the different ionization and temperature structures around the three sources, the 21 cm signal shows different features, as shown in $\delta T_S$ in the lower panels in Figure 3. The modeled galaxy shows a narrow emission ring surrounded by an extended absorption trough owing to efficient coupling between $T_S$ and $T_{\text{gas}}$. In the case of Pop III star and QSO, since the traveling of most Ly-$\alpha$ photons is confined in the transition region with numerous resonant scatterings within the limited $t_{\text{evo}} = 10^7$ yr, the $T_{\text{gas}}$ at transition region is higher than $T_{\text{CMB}}$, so they both show extended emission in $\delta T_S$ in the transition region, and the
Figure 5. Two dimensional map of the differential brightness temperature of Pop III stars (M_{\text{star}} = 10^3 M_\odot), galaxy (M_{\text{star}} = 10^6 M_\odot) and QSO (M_{\text{star}} = 10^8 M_\odot) at t_{\text{evo}} = 10^7 yr. The box size is 1 Mpc in physical scale.

Figure 4. Coupling coefficients \( x_\alpha \) (by Ly\( \alpha \) photon scattering, solid line) and \( x_\text{C} \) (by gas collision, dotted line) as a function of distance from the central source at redshift \( z = 10 \) for a Pop III star (top panel), a galaxy (middle panel), and a QSO (bottom panel), respectively. The radius is normalized by Strömgren sphere radius \( R_S \). The dashed line represents unity. When the coupling coefficient is higher than unity, the spin temperature can decouple from the CMB temperature. The vertical dash-dot line indicates the location of the ionization front at \( \chi_{\text{HII}} = 0.5 \), while the long-dash-dot line indicates the location where \( T_{\text{gas}} = T_{\text{CMB}} \). In region beyond the long-dash-dot line, if the coupling coefficient is higher than unity, then it would cause absorption, as is the case of the galaxy model.

Figure 6. Dependence of the 21 cm structures on the source mass for Pop III stars (green triangles), galaxies (red squares), and QSOs (blue circles). Upper panel: size of the ionized bubble \( R_{\text{HII}} \) at \( t_{\text{evo}} = 10^7 \) yr, defined as the position at \( \chi_{\text{HII}} = 0.5 \). Middle panel: surface area of emission \( S_{\text{em}} \) (filled symbols) and absorption ring \( S_{\text{abs}} \) (open symbols). Lower panel: ratio of \( S_{\text{abs}}/S_{\text{em}} \) as a function of stellar mass of the source. The dot lines are artificial lower limits.

QSO shows only emission in \( \delta T_b \) due to the large size of its H\( \text{II} \) bubble.

The 21 cm structure of QSOs from our model differs from that of Alvarez et al. (2010), which showed extended absorption shell in the outer cold region under the assump-
tion of $\delta T_b = T_{\text{gas}}$. In addition, Datta et al. (2012) used the assumption of $\delta T_b = 4.6 \times 10^7 K n_{\text{HI}} \sqrt{z + 1}$, which leads to absorption even in the highly ionized region around QSOs. In the case of Pop III stars, the absorption feature from our calculations is shaler than that of Chen & Miralda-Escude (2008). This is caused by a smaller $P_s$ due to limited traveling time of Ly$a$ photons.

To further illustrate the physical process behind the emission and absorption features of the 21 cm signal, we show in Figure 4 the radial profiles of the coupling coefficients caused by Ly$a$ scatterings, $x_{\alpha}$, and by gas collisions, $x_C$, respectively. When the coupling coefficient is higher than unity, the spin temperature can decouple from the CMB temperature. As can be seen, the $x_C$ is around unity in high-temperature region, and becomes very small in region with neutral hydrogen gas. As a result, gas collision has little effect on the change of $T_S$, the $\delta T_b$, in neutral region. On the other hand, the $x_{\alpha}$ shows much higher value than unity even in the outer neutral region, and it monotonically decreases with distance, because the scattering cross section decreases due to high relative velocity, and Ly$a$ cannot propagate to outer region within the limited traveling time. In the case of Pop III stars, the $x_{\alpha}$ is $\sim 1 - 100$ in the partially ionized and moderately high temperature region $T_{\text{gas}} > T_{\text{CMB}}$. Therefore, in such a region, $T_S$ is much higher than $T_{\text{CMB}}$, resulting in emission in $\delta T_b$. However, at the location of $T_{\text{gas}} \sim T_{\text{CMB}}$, the $x_{\alpha}$ becomes $\sim 1$, and less in the cold region, leading to the shallower absorption structure. The $x_{\alpha}$ of the QSO case shows similar trend with the one of Pop III star. However, since its Hii bubble is larger than that of a Pop III star, most of Ly$a$ photons cannot reach the point of $T_{\text{gas}} = T_{\text{CMB}}$, resulting in no absorption feature. In the case of galaxy, however, the $x_{\alpha}$ appears to be very large ($\sim 10^4$) at the location of $T_{\text{gas}} = T_{\text{CMB}}$, and it drops to $\sim 1$ at $R \sim 100$ kpc, resulting in extended absorption region between $R \sim 20 - 100$ kpc.

3.2 The 21 cm Structures

The resulting 21 cm maps of the Pop III star, galaxy, and QSO at $z = 10$ are shown in Figure 6 respectively. Clearly, the 21 cm structures of these different sources are distinctively different. The $\delta T_b$ of the PopIII star shows a ring structure with emission in the inner region and absorption in the outer region. The galaxy shows very thin emission ring but a deep, extended absorption region, while the QSO shows extended emission only.

To further investigate the dependence of 21 cm structures on the source properties, we show the emission and absorption structures of the three sources at different stellar mass in Figure 5 as represented by the radius of ionized bubble $R_{\text{HI}}$, the surface area of emission ($S_{\text{em}}$) and absorption ($S_{\text{abs}}$), and their ratio.

First of all, the size of the ionized region increases with the mass of the source, as shown in Figure 6 (top panel). This can be understood since the total number of ionizing photons is simply proportional to the total stellar mass in our models, $R_{\text{HI}} \propto M_{\text{star}}^{1/3}$. The $R_{\text{HI}}$ is in the range of $R_{\text{HI}} \sim 24 - 260$ kpc for PopIII stars, $\sim 20 - 650$ kpc for galaxies, and $\sim 0.2 - 4.5$ Mpc for QSOs. The size of the ionized region by QSOs is consistent with that from Wytche et al. (2005). Pop III stars have higher ionizing power because their hard SEDs produce more ionizing photons and higher effective temperature $\sim 10^5$ K. Of course, the ionized region would appear as a "zero-signal hole" ($\delta T_b \sim 0$ mK) in the 21 cm structure.

The middle panel of Figure 6 shows the surface areas of the emission ($S_{\text{em}}$) and absorption ($S_{\text{abs}}$) regions in a two dimensional slice passing the central sources. For all models, the $S_{\text{em}}$ monotonically increases with the stellar mass of the source, the $S_{\text{abs}}$, however, is clearly different depending on the source type and the size of ionized region. The $S_{\text{abs}}$ of galaxies are much higher than the $S_{\text{em}}$, which produces the strong absorption trough as seen in Figure 5. In the QSOs, $S_{\text{abs}}$ is very small $t_{\text{evo}} = 10^7$ yr since Ly$a$ photons cannot propagate to the cold, neutral gas region. The ratio between $S_{\text{abs}}$ and $S_{\text{em}}$ is shown in the lower panel of Figure 6. The ratio is in the range of $\sim 1 - 10$ for Pop III stars, $\sim 5 - 160$ for the galaxies, and below 1 for the QSOs.

The results demonstrate that Pop III stars, the first galaxies, and the first QSOs have clearly different 21 cm structures, owing to different temperature and ionization structures resulting from different photon SEDs and the propagation of Ly$a$ photons in these regions.

3.3 Time Evolution of the 21 cm Structure

The evolution of the $\delta T_b$ signal at different time is shown in Figure 7. As the ionizing bubble grows with time, the Ly$a$ photons propagate into more extended cold region with scattering, resulting in stronger absorption signal. At $t_{\text{evo}} = 10^6$ yr, the $\delta T_b$ of Pop III stars and QSO have no absorption area. At $t_{\text{evo}} = 10^8$ yr, all simulations show 21 cm absorptions. Note that for Pop III stars, the evolution
Figure 8. The evolution of the size of the ionizing bubble $R_{\text{HII}}$, surface area of emission $S_\text{em}$ and absorption $S_\text{abs}$, and their ratio $S_\text{abs}/S_\text{em}$, at different time for Pop III stars (green triangles), galaxies (red squares), and QSOs (blue circles). The mass of these three different sources is $M_{\text{star}} = 10^3, 10^6, 10^8 M_\odot$, respectively. The symbols are the same as in Figure 6.

of ionization may not last $10^8$ yr due to their short lifetimes and fast metal enrichment (e.g., Wise et al. 2012). However, since the recombination time scale of IGM is longer than $10^8$ yr, the Ly$\alpha$ photons can travel in the relic H$\text{II}$ region and the cold region outside, which may produce similar absorption features as in Figure 7.

Figure 8 shows the evolution of the size of the ionizing bubble $R_{\text{HII}}$, surface area of emission $S_\text{em}$ and absorption $S_\text{abs}$, and their ratio $S_\text{abs}/S_\text{em}$, at different times $t_{\text{evo}} = 10^6, 10^7$ and $10^8$ yr for Pop III stars, galaxies, and QSOs, respectively. As $R_{\text{HII}}$, $S_\text{em}$ and $S_\text{abs}$ at $t_{\text{evo}} = 10^6, 10^7$ and $10^8$ yr are shown in Figure 8. As shown in Figure 2, the $R_{\text{HII}}$ increase with $t_{\text{evo}}$, $R_{\text{HII}} \propto (1 - \exp(-t_{\text{evo}}/t_{\text{rec}}))^{1/3}$, where $t_{\text{rec}}$ is recombination time scale. The $S_\text{em}$ and $S_\text{abs}$ of Pop III stars and galaxies show slow increase with time, and the ratio of the two becomes nearly constant after $\sim 10^7$ years. In the case of QSO, however, $S_\text{abs}$ increases dramatically after $\sim 10^7$ years, leading to a strong absorption feature.

The probability distribution function (PDF) of the 21 cm emission volume is shown in Figure 9. As time evolves, more Ly$\alpha$ photons propagate to cold gas region, and produce the extended tail of the PDF with absorption signal. At $t_{\text{evo}} = 10^7$ yr, the PDF of Pop III stars is confined in $\delta T_b > -100$ mK, and it extends to $\delta T_b < -100$ mK at $10^8$ yr. In the case of QSO, the PDF is mostly confined in $\delta T_b > -100$ mK.

3.4 Detectability

The detectability of the 21 cm emission from the first luminous objects with future instruments is of great inter-

Figure 10. Detectability of the 21 cm signal from Pop III stars, the first galaxies and quasars at $z = 10$ with upcoming missions MWA, LOFAR, and SKA. The elliptical shade regions represent the mean $\delta T_b$, which is estimated in the spherical top hat beam with the size from the source to the outer edge of $|\delta T_b| = 1$ mK. The $\delta T_b$ maps with the width of $\Delta \nu = 1, 2, 3$ and 4 MHz are used to estimate the maximum and minimum values of the elliptical shades. The yellow shaded regions indicate the sensitivity of upcoming facility with $A_{\text{eff}} = 10^4, 10^5$ and $10^6$ m$^2$ estimated by equation (16), while the width of which corresponds to the integration time from 100 to 1000 hours with $\Delta \nu = 1$ MHz. The red, green and blue shapes indicate our simulation results.
est. Here we calculate the detectability of the 21 cm emission from the Pop III stars, first galaxies and quasars with upcoming observatories such as MWA, LOFAR, and SKA. The noise per resolution element is estimated by (Furlanetto et al. 2009) as follows,

$$\Delta T \sim 20 \, \text{mK} \left(\frac{10^4 \, \text{m}^2}{A_{\text{eff}}}\right) \left(\frac{10'}{\Delta \theta}\right) \times \left(\frac{\text{MHz} \, 100 \, \text{hr}}{t_{\text{int}}}ight)^{1/2}, \quad (16)$$

where \(A_{\text{eff}}\) is the effective collecting area, \(\Delta \theta\) is the angular diameter, \(\Delta \nu\) is the bandwidth, and \(t_{\text{int}}\) is the integration time.

For the redshifted 21-cm line at \(z \sim 10\), the contribution from the polarized Galactic synchrotron foreground is dominant to the system temperature, and it has \(T \sim 180(\nu/180 \, \text{MHz})^{-2.6}\). The sensitivity curves are shown in Figure 10. The yellow shade with \(A_{\text{eff}} = 10^4 \, \text{m}^2\) roughly corresponds to the sensitivity of MWA and LOFAR, while that with \(A_{\text{eff}} = 10^6 \, \text{m}^2\) corresponds to the sensitivity of SKA.

Here, we take the size of outer emission or absorption spheres, i.e., twice of distance \(L_{\text{edge}}\) from central sources to outer edge of \(\Delta T_\text{b}\) = 1 mK. Hence, the circles shift to larger size depending on the ionizing ability of the sources used in this work. The \(< \delta T >\) is estimated by taking the absolute value of mean of \(\Delta T_\text{b}\) at \(t_{\text{evo}} = 10^7 \, \text{yr}\) within the circle with the radius \(L_{\text{edge}}\). We calculate the \(\delta T_\text{b}\) map with the thickness of \(\Delta \nu = 1, 2, 3\) and 4 MHz around central sources. The major and minor axes of these ellipsicals are the minimum and maximum values of the outer shells of 21 cm emission/absorption and \(< \delta T >\).

The results are shown in Figure 10. Pop III stars and QSOs show \(< \delta T >\) \(\sim 1 - 10 \, \text{mK}\), while galaxies are \(< \delta T >\) \(\sim 100 - 500 \, \text{mK}\). In Pop III case, there are absorption spheres comparable to emission ones. Hence the net signal becomes small due to the offset. For the QSO case, the emission spheres are relatively small to the central zero-signal holes, hence the net signal decreases. On the other hand, in the case of galaxy, there are deep extended absorption spheres relatively to the central holes and inner emission spheres. Thus, galaxies appear to have much stronger 21 cm signal than the Pop III stars and QSOs. The H\(\alpha\) regions around luminous QSOs can be detected by MWA and LOFAR with \(\sim 100 \, \text{hours}\) integration. For massive galaxies \(M_{\text{star}} \sim 10^{10} \, \text{M}_\odot\), it may need \(\sim 1000 \, \text{hours}\) integration by MWA and LOFAR. For galaxies and faint QSOs, SKA or A\(\text{eff} = 10^5 \, \text{m}^2\) class telescope will be needed to detect the H\(\alpha\) regions around them. In the case of Pop III stars, however, it appears to be difficult to detect the H\(\alpha\) region even with SKA.

Our results suggest that the LOFAR, MWA or SKA may be able to detect the 21 cm signal around galaxies or QSOs, and may distinguish the nature of sources by the difference of emission or absorption, and the size. Here, we optimistically assume that the beam size of observations is comparable to the size of outer emission/absorption shells. In practice, the beam size can be larger than the one used in our models. As a result, the net signal may decrease with the beam size. However, the decrease will follow the same gradient of the sensitivity curve \(\Delta \theta^{-2}\), hence it may not affect significantly the detectability in the above discussion.

### Figure 11
The differential brightness temperature of Pop III stars \((M_{\text{star}} = 10^3 \, \text{M}_\odot)\), galaxy \((M_{\text{star}} = 10^8 \, \text{M}_\odot)\) and QSO \((M_{\text{star}} = 10^8 \, \text{M}_\odot)\) at \(z = 7, 10\) and 20. The map shots at \(t_{\text{evo}} = 10^7 \, \text{yr}\).

#### 4 DISCUSSION
In this work, we focus on the 21 cm signal at \(z = 10\). However, the size of ionizing bubble and propagation distance of Ly\(\alpha\) change at different redshifts. We test the change of \(\delta T_\text{b}\) structure at \(z = 7\) and 20 with the same source properties. Figure 11 shows the \(\delta T_\text{b}\) structure at \(t_{\text{evo}} = 10^7 \, \text{yr}\) at different redshifts. The size of ionized bubbles decreases with increasing redshift, while the ionizing front more close to Strömgren radius in the same propagation time. As a result, the ratio of ionizing front is estimated by

$$\frac{R_{\text{b}}}{R_{\text{f}}} = \left(\frac{1 + z'}{1 + z}\right)^{-2} \left[\frac{1 - e^{-A(1+z')}}{1 - e^{-A(1+z')}}\right]^{1/3}, \quad (17)$$

where \(A = t_{\text{evo}} \alpha \text{G}_\odot \, \text{yr}^{-1}\). Hence, the size ratio of \(z = 7\) (20) to \(z = 10\) is \(\sim 1.2\) (0.5). For Pop III star at \(z = 20\), there is the deep extended absorption area. With decreasing redshift, the absorption signal becomes shallower, because the distance to cold-neutral region becomes far, leading to longer traveling time to there. In the case of galaxies, the 21 cm structure is almost same, however, the absorption area relatively small at lower redshift, because the H\(\alpha\) bubble is bigger and the transition from ionized to neutral becomes more smooth due to the lower density. Note that, In the QSO, the QSO at \(z = 20\) shows the absorption signal, despite the H\(\alpha\) region is much larger than the one of Pop III star at \(z = 7\) which does not show clear absorption signal. This is due to higher Ly\(\alpha\) luminosity of continuum spectrum than Pop III star.

### 5 SUMMARY
In this paper, We investigate the redshifted 21 cm signal from different ionizing sources by combining idealized mod-
els of the first stars, the first galaxies and quasars with radiative transfer simulations that include both ionization of neutral hydrogen and resonant scattering of Lyα photons. We find that the 21 cm signal depend significantly on the source SED and stellar mass. The Pop III stars and quasars produce a smooth transition from an ionized and hot state to a neutral and cold one, owing to their hard SED with abundant ionizing photons, in contrast to the sharp transition in galaxies. The HII bubble size is typically ~20 kpc for PopIII stars, ~100 kpc for galaxies, and ~5 Mpc for QSOs. Furthermore, Lyα scattering plays a dominant role in producing the 21 cm signal as it determines the relation between hydrogen spin temperature and gas kinetic temperature. The Lyα photons can produce both emission and absorption region around small HII bubble of PopIII stars, extended absorption region around the first galaxies, and emission only around QSOs.

We predict that future surveys from large radio arrays such as MWA, LOFAR and SKA may be able to detect the 21 cm signals of primordial galaxies and quasars, but unlikely Pop III stars due to its small angular diameter.

These results are based on idealized models of the first stars, the first galaxies and quasars. We will investigate the 21 cm structures in more realistic situation including inhomogeneous density, metal enrichment and black hole growth by using cosmological simulations in future works.

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