The 21cm Signature of Early Relic H\textsc{ii} Regions

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ABSTRACT

We calculate the spin temperature and 21 cm brightness of early H\textsc{ii} regions around the first stars. We use outputs from cosmological radiation-hydrodynamics simulations of the formation and evolution of early H\textsc{ii} regions. In the pre-reionization era, H\textsc{ii} regions around massive primordial stars have diameters of a few kpc. The gas within the H\textsc{ii} regions is almost fully ionized, but begins recombining after the central stars die off. The relic H\textsc{ii} regions are then seen as bright emission sources in hydrogen 21 cm. We make brightness temperature maps of the H\textsc{ii} regions, accounting for radiative coupling with Lyman-\(\alpha\) photons in a simplified manner. The spin temperature in the relic H\textsc{ii} region is close to the gas kinetic temperature, generally several hundred to several thousand degrees. We show that the relic H\textsc{ii} region can be as bright as \(\delta T_b \sim 100\) mK in differential temperature against the cosmic microwave background for an angular resolution of sub-arcseconds. While individual early H\textsc{ii} patches will not be identified by currently planned radio telescopes, the collective fluctuations from early H\textsc{ii} regions might imprint signatures in the 21 cm background.

Key words: cosmology:theory - early universe - intergalactic medium

1 INTRODUCTION

Reionization of hydrogen in the intergalactic medium (IGM) is an important landmark in the history of the universe. It is generally thought that the sources of ionizing photons are early generations of stars and galaxies formed at \(z > 6\). Recent observations provided important constraints on the epoch of reionization; the Gunn-Peterson troughs are found in the spectra of distant quasars at \(z = 6 - 7\) (White et al. 2003; Fan et al. 2006), while the large-scale polarization of cosmic microwave background (CMB) measured by the WMAP satellite suggests that reionization may have begun at \(z > 10\) (Page et al. 2007; Komatsu et al. 2008).

Observing 21 cm emission or absorption from hydrogen atoms in the high redshift IGM is a promising way of revealing the detailed process of reionization. There have been a number of studies on 21 cm signature of large-scale reionization by galaxies (McQuinn et al. 2006; Iliev et al. 2006; see Furlanetto et al. 2006 for a review). These studies are aimed at making forecasts for near-future radio observations such as LOFAR, and thus consider large-scale structures of ionized/neutral IGM at \(z \sim 6 - 10\).

There have been also theoretical studies on 21 cm signatures from pre-reionization epochs. Kuhlen et al (2006) study the 21 cm signature of early mini-quasars. They show that X-rays from the mini-quasar raise the gas kinetic temperature and enhance 21 cm signals. Chen & Miralda-Escudé (2004; 2008) argue that X-rays from the first stars heat the surrounding gas and couple the spin temperature to its kinetic temperature, generating a large Lyman-\(\alpha\) absorption sphere. Shapiro et al (2006) estimate the 21 cm fluctuations caused by cosmological “mini-halos” and by the IGM. They conclude that the 21 cm emission from mini-halos dominates over that from the diffuse IGM at \(z \lesssim 20\). Furlanetto & Oh (2006) argue, however, that mini-halos generate only small 21 cm fluctuations. Clearly, it is important to identify dominant sources of 21 cm fluctuations at high-redshifts. None of these works, however, consider 21 cm signals from early relic H\textsc{ii} regions, which are hot and (partially) ionized even after the central sources’ lifetimes, and hence can be bigger and brighter than cosmological mini-halos. Interestingly, in the standard theory of cosmic structure formation based on cold dark matter, there is a large gap between the time when the first stars are formed (Tegmark et al. 1997; Yoshida et al. 2003; 2008) and when the IGM is completely ionized. Hence it is expected that there were early relic H\textsc{ii} regions during the reionization process. Although individual H\textsc{ii} regions are too small to be detected even by future radio telescopes, their collective signals may imprint distinguishable fluctuations. In this paper, we study the 21 cm signature of
early relic H II regions around the first stars using cosmological simulations. We assume that massive primordial stars are formed in early low-mass dark matter halos and ionize a large volume of the surrounding IGM in their short lifetime of a few million years. We compute the spin temperature and 21 cm differential temperature fluctuations of the relic H II regions.

2 NUMERICAL SIMULATIONS

We use the outputs of a cosmological simulation of Yoshida et al. (2007, hereafter Y07). Briefly, they carried out three-dimensional radiation hydrodynamics calculations of the formation and evolution of early H II / HeII regions around the first stars. Primordial gas chemistry such as hydrogen recombination is followed in a non-equilibrium manner in the simulation. We generate the same realization as that of Y07 but for a slightly lower value of the normalization of the density fluctuation amplitude, \( \sigma_8 = 0.8 \).

The other cosmological parameters are the same as in Y07, \( (\Omega_m, \Omega_b, \Omega_\Lambda, H_0) = (0.26, 0.04, 0.7, 70(\text{km} \cdot \text{s}^{-1} \cdot \text{Mpc}^{-1})) \), which are consistent with the standard ΛCDM model (Komatsu et al. 2008). Lowering the value of \( \sigma_8 \) simply shifts the formation epoch of the first star to a later time. The main properties of the H II region are almost the same as those presented in Y07. In our simulation, the first star-forming cloud is located at \( z = 22 \). We embed a Population III star with a mass of 100 \( M_\odot \). In order to focus on the evolution of an early H II region, we assume that the central star dies without triggering supernova explosion. Such a massive star may also leave behind a remnant black hole. We defer detailed studies on the feedback effects from supernovae and from early remnant black holes to future work.

We note that early Population III remnant black holes do not accrete the surrounding gas and emit X-rays efficiently, due to photoevaporation of gas from the host halo by the progenitor star, as well as photo-heating by the accreting black hole itself (Y07; Johnson & Bromm 2007; Alvarez et al. 2008). We further assume that UV radiation background and UV radiation from other sources do not exist and that the central star is the first radiation source. We follow the thermal evolution of the relic H II region for over one hundred million years under these assumptions.

3 21 CM SIGNATURES FROM EARLY H II REGIONS

The 21 cm line is produced via the transition between the triplet and the singlet sublevels of the hyperfine structure of the ground level of a neutral hydrogen atom. This wavelength corresponds to a frequency of 1420 MHz and a temperature of \( T_s = 0.068K \). The transition between the levels occurs through three processes: absorption of CMB photons, collisions with other particles (hydrogen atoms, free electrons and protons), and scattering of UV photons.

The spin temperature is expressed as a weighted mean of these processes as (Field 1958)

\[
T_s = \frac{T_s + T_{\text{CMB}} + x_e T_e + x_\alpha T_\alpha}{1 + x_e + x_\alpha},
\]

where \( T_K \) is the gas kinetic temperature, \( T_e \) is the color temperature of Lyman-\( \alpha \) photons, and \( x_e \) and \( x_\alpha \) are coefficients for collisional and radiative coupling, respectively.

We do not consider a cosmological UV background radiation because the 21 cm differential brightness temperature of relic H II regions is not significantly affected by the strength of radiative coupling. Also, we do not include the effect of heating by X-ray photons from the first stars. The gas outside the H II region can be significantly heated by X-ray induced secondary electrons. However, for a 100 \( M_\odot \) star, the size of the heated region is only slightly larger than the extent of the H II region (Chen & Miralda-Escudé 2008, Figures 3-5). Hence ignoring the X-ray heating effect does not affect significantly our results; in this case it would boost the observable signal by a factor of order unity. For very massive stars (> 300\( M_\odot \)), which are hotter and generate more X-rays, the signal from the X-ray heated region could be significantly larger.

The coupling coefficient for collisions, \( x_c \), is given by

\[
x_c = \frac{T_c}{A_{10} T_K} (C_H + C_e + C_p),
\]

where the spontaneous emission rate \( A_{10} \) is \( 2.85 \times 10^{-13} \text{s}^{-1} \), and \( C_H, C_e \) and \( C_p \) are the de-excitation rates for collisions with neutral atoms, free electrons and protons, respectively.

We use fitting functions of Zygelman (2005) and Liszt (2001) for H-II collisions and e-H collisions, respectively. For p-H collisions, we use the coefficient 3.2 times as large as that for H-H collisions (Smith 1966).

The radiative coupling included in equation 1 is known as the Wouthuysen-Field effect. It is extremely difficult to evaluate accurately the coupling coefficient for the incident UV radiation, \( x_\alpha \), because one needs to solve, in principle, full radiation transfer equations including the effect of absorption and re-emission of Lyman-\( \alpha \) photons, the Hubble flow, and the injection of new photons. By noting that tight radiative coupling is easily achieved under many cosmological conditions (e.g., Furlanetto et al. 2006), we assume that Lyman-\( \alpha \) photons produced by recombination are sufficient for effective radiative coupling, and examine the overall effect by setting a constant \( x_\alpha = 0.5 \) within H II regions. We compute the color temperature, \( T_c \), by solving the following equation

\[
T_c = T_K \left( \frac{1 + T_{se}/T_K}{1 + T_{se}/T_s} \right),
\]

where \( T_{se} = (2/9)T_K\nu_{21}^2/\Delta \nu_{\Omega \alpha}^2 \), which is obtained by solving the radiative transfer equation for scattering of UV photons for large optical depths (Furlanetto et al. 2006). Here, \( \nu_{21} \) is the frequency of 21 cm line, \( \Delta \nu_{\Omega \alpha} = \sqrt{(2kT_K)/(m_{\text{HI}}c^2)}\nu_\alpha \) is the Doppler width of Lyman-\( \alpha \), and \( \nu_\alpha \) is the central Lyman-\( \alpha \) frequency (2.47 \times 10^{13} \text{ Hz})

We determine the color temperature and the spin temperature by solving equations 1 and 3 iteratively.

We briefly describe the evolution of the H II region. Shortly after the central star dies, the kinetic temperature in the H II region is higher than several thousand Kelvin.

\[1^{1}\text{ Although the simulation of Y07 includes He atoms and ions, we ignore the collisions between H atoms and He species because the number fraction of He is small.} \]
While high density regions within the H\textsc{ii} region recombine and cool quickly, a large fraction of the H\textsc{ii} region has a low density ($n < 0.01 \text{cm}^{-3}$), and thus recombination and gas cooling occur rather slowly. The gas temperature remains a few thousand Kelvin at 30 Myrs, and the ionization fraction is down to about 10%, 5% at 30 Myrs and 50 Myrs after the star dies, respectively.

Figure 1 shows the 21 cm spin temperature against gas density at a time shortly after the ionizing source has been turned off. To see the effect of radiative coupling, we calculate the spin temperature ignoring (left panel) and accounting for (right panel) radiative coupling. At low densities, the spin temperatures are close to the CMB temperature for both cases, because the collisional coupling is weak. The gas within the H\textsc{ii} regions has been once photo-ionized, and so the gas kinetic temperature is high, which brings the spin temperature above ~100 K for the case without radiative coupling (left) and above ~$10^3$ K with radiative coupling (right). Clearly, radiative coupling raises the spin temperatures of intermediate-density, ionized gases. We see another branch in the high density, low spin temperature portion in this phase diagram. It corresponds to the gas outside the relic H\textsc{ii} region, which has been neutral and hence has a low kinetic temperature. Note that there are also neutral regions where the spin temperatures are slightly lower than CMB temperature because of effective collisional coupling.

We now observe the simulated H\textsc{ii} region in 21 cm. The radiative transfer equation for 21 cm radiation for brightness temperature, $T_b$, is given by

$$T_b = T_{\text{CMB}} e^{-\tau} + T_S (1 - e^{-\tau}).$$

In practice, we discretize the equation as in Kühlen et al. (2006) to calculate the brightness temperature for our simulated H\textsc{ii} region. The observed flux of 21 cm line can be expressed by the differential brightness temperature against the CMB temperature as $\delta T_b = (T_b - T_{\text{CMB}})/(1 + z)$. To make maps of $T_b$ and $\delta T_b$, we use a cubic region of $100 h^{-1}$ comoving kpc on a side, centered at the H\textsc{ii} region, and then divide the box into $128^3$ cells. Then the angular resolution of the map is about 0.02 arcseconds. We use the central slice of with a $7.8h^{-1}$ comoving kpc depth along the line of sight to make the maps shown in Figure 2. The corresponding spectral width is 190 Hz at $z=20$. Note that the required angular and spectral resolution are out of reach of any planned instruments; however, the collective effect of such relic H\textsc{ii} regions might be detectable.

Figure 2 shows the mass-weighted mean spin temperature at two output times, when the ionizing source died (top panels) and about 30 Myrs after (bottom panels). The bright, colored area is almost fully ionized (i.e. H\textsc{ii} region) and the radius of the H\textsc{ii} region is about $50 h^{-1}$ comoving kpc. At the top panels, the spin temperature ranges from a few tens Kelvin ($\sim T_{\text{CMB}}$) to several thousand Kelvin. The plotted region is 100 $h^{-1}$ comoving kpc on a side.

Figure 3 shows the time evolution of the resulting 21 cm signal for the case with no radiative coupling. Regions where $\delta T_b \leq 0$ are colored in black. While a large volume surrounding the H\textsc{ii} region has $T_{\text{spin}} \sim T_{\text{CMB}}$ (see Figure 2), which appear in absorption. We also calculated the differential temperature for the case with efficient radiative coupling and find little difference with Figure 3. The clear difference in the spin temperature shown in Figure 2 does not affect the differential temperature. This is because, as long as $T_S$ is much higher than $T_{\text{CMB}}$, the observed brightness is determined by the column density of neutral hydrogen and the width of 21 cm line, which are independent of $T_S$ (e.g., Scott & Rees 1990). The large filamentary structure seen in Figure 3 is a neutral region which was not completely ionized by the central star because of its strong self-shielding. On average, its spin temperature is not high, hence the structure is not prominent in Figure 2 but it shows up clearly in differential
temperature because it has a large column density of neutral hydrogen (and hence a large 21 cm optical depth).

Figure 3 shows that the relic H\textsc{ii} region is a 21 cm emission source. In the relic H\textsc{ii} region, $\delta T_b$ is as high as several hundred mK, while in the surrounding neutral regions $\delta T_b$ can be as low as $\sim -10$ mK. The relic H\textsc{ii} region is bright for over 50 Myrs after the source died, because the number density of neutral hydrogen increases by recombination in the relic H\textsc{ii} region, while the spin temperature remains higher than $T_{\text{CMB}}$. The area-averaged $\delta T_b$ remains a few tens mK for over 100 Myrs (at the last output of our simulations).

4 DISCUSSION

We have studied the 21 cm signature from relic H\textsc{ii} regions at high redshifts. We have computed the spin temperature and 21 cm brightness temperature using radiation-hydrodynamics simulations. We have examined the effect of radiative coupling on the spin temperature under simplified assumptions. We have shown that, whereas the radiative coupling significantly affects the spin temperature, it has little effect on the 21 cm differential temperature. The relic H\textsc{ii} region is seen as a bright emission source in 21 cm, with the differential temperature being up to $\sim 100$ mK for very high angular resolutions. Previous works estimated the spin temperature and 21 cm signals of H\textsc{ii} regions, but they did not follow evolution by computing recombination, cooling and the expansion of H\textsc{ii} regions dynamically. We compared our results with those of Nusser (2005), which calculated the 21 cm signatures under the isobaric condition. The overall evolution is similar, but the H\textsc{ii} region in our simulation shines in 21 cm for a longer time because recombination occurs slowly in low density regions.

Early H\textsc{ii} regions are generally very small and thus the individual 21 cm sources will not be detected by the Low Frequency Array (LOFAR) and the Mileura Widefield Array (MWA) even by the next-generation low-frequency arrays such as the Square Kilometre Array (SKA). Minihalos similarly contain little mass, and are not individually detectable. A very large, percolated H\textsc{ii} regions or a group of nearby H\textsc{ii} regions may be detectable through the effect of strong gravitational lensing (Li et al. 2007). As we have shown, relic H\textsc{ii} regions are emission sources for a long time ($> 50$ Myrs, see Figure 2), and thus the number density of such 21 cm sources at a given frequency can be larger than Lyman-\textalpha{} spheres around short-lived stars. Therefore, early relic H\textsc{ii} regions could imprint distinct, strong collective signatures in the 21 cm background. In our future work, we will calculate the abundance and the clustering of the relic H\textsc{ii} regions and derive the 21 cm fluctuation amplitudes.

Finally, we comment that there are some other sources of 21 cm emission and absorption at high redshifts. Ripamonti et al. (2008) study the effect of X-rays from early black holes. They show that the differential brightness temperature is $\sim 20 - 30$ mK at $z < 12$. Zaroubi et al. (2007) show that X-ray heating produces a differential brightness temperature of the order of $\sim 5 - 10$ mK out to a few comoving Mpc distance from black holes. These brightness temperatures are smaller, at least locally, than that of relic H\textsc{ii} regions studied in the present paper. Thomas & Zaroubi (2008) consider both primordial black holes and Population III stars. They argue that the heating patterns around these objects is significantly different. A few other exotic models of ionization such as ultra-high energy cosmic rays and decaying dark matter particles are proposed (Shchekinov & Vasilev 2007). Such different sources can likely be distinguished by their different fluctuation spectra.

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