The observational signature of the first H II regions

Thomas H. Greif, Jarrett L. Johnson, Ralf S. Klessen and Volker Bromm

1 Zentrum für Astronomie der Universität Heidelberg, Institut für Theoretische Astrophysik,
Albert-Ueberle-Straße 2, 69120 Heidelberg, Germany
2 Department of Astronomy, University of Texas, Austin, TX 78712, USA
3 Texas Cosmology Center, University of Texas, Austin, TX 78712, USA
4 Fellow of the International Max Planck Research School for Astronomy and Cosmic Physics at the University of Heidelberg

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ABSTRACT
We use three-dimensional smoothed particle hydrodynamics simulations together with a dynamical ray-tracing scheme to investigate the build-up of the first H II regions around massive Population III stars in minihaloes. We trace the highly anisotropic breakout of the ionizing radiation into the intergalactic medium, allowing us to predict the resulting recombination radiation with greatly increased realism. Our simulations, together with Press-Schechter type arguments, allow us to predict the Population III contribution to the radio background at $\sim 100$ MHz via bremsstrahlung and 21-cm emission. We find a global bremsstrahlung signal of around 1 mK, and a combined 21-cm signature which is an order of magnitude larger. Both might be within reach of the planned Square Kilometer Array experiment, although detection of the free-free emission is only marginal. The imprint of the first stars on the cosmic radio background might provide us with one of the few diagnostics to test the otherwise elusive minihalo star formation site.

Key words: cosmology: observations – cosmology: theory – early Universe – stars: formation

1 INTRODUCTION
One of the most important questions in modern cosmology is to understand how the first stars, the so-called Population III (Pop III), ended the cosmic dark ages at redshifts $z \lesssim 30$ (Barkana & Loeb 2001; Bromm & Larson 2004; Ciardi & Ferrara 2003). Their emergence led to a fundamental transformation in the early Universe, from its simple initial state to one of ever-increasing complexity. The emission from the hot, $T_{\text{eff}} \sim 10^5$ K, photospheres of Pop III stars began the reionization of primordial hydrogen and helium in the intergalactic medium (IGM), although this process was completed only later on, when more massive galaxies formed (Fan et al. 2004). In addition, the supernova explosions that ended the lives of massive Pop III stars distributed the first heavy elements into the IGM (Bromm et al. 2003; Greif et al. 2007; Tornatore et al. 2007; Wise & Abel 2008). This latter process might have had a significant impact on the physics of early star formation, as metal-enriched gas can cool more efficiently than primordial gas (Bromm & Loeb 2003; Omukai et al. 2005; Jappsen et al. 2007, 2009).

Based on numerical simulations, a general consensus has emerged that the first stars formed in dark matter minihaloes at $z \sim 20–30$, in isolation or at most as a small stellar multiple, and with typical masses of $M_* \sim 100 M_\odot$ (for a recent review, see Bromm et al. 2009). It is crucial to observationally test this key prediction. However, it has become evident that this will be very challenging. Even the exquisite near-IR ($\sim nJy$) sensitivity of the upcoming James Webb Space Telescope (JWST) will not suffice to directly image such massive, single Pop III stars (Bromm et al. 2001; Gardner et al. 2006), unless they explode as energetic pair-instability supernovae (Heger & Woosley 2002; Scannapieco et al. 2003). The direct spectroscopic detection of recombination line emission from the H II region surrounding the Pop III star, as well as from the relic H II region left behind once the star had died, is beyond the capability of JWST as well, although such line emission might be detectable from primordial stellar populations inside more massive host haloes (Schaerer 2002, 2003; Johnson et al. 2008).

An alternative approach is to search for the global signature from many Pop III stars that formed in minihaloes over large cosmic volumes (Haiman & Loeb 1997). One such probe is the optical depth to Thomson scattering of cosmic microwave background (CMB) photons off free electrons along the line of sight, determined by the five-year Wilkinson Microwave Anisotropy Probe (WMAP) measurement to be $\tau_c \approx 0.09 \pm 0.02$ (Komatsu et al. 2009). This
signal, however, is dominated by ionizing sources that must have formed closer to the end of reionization, with only a small contribution from Pop III stars formed in minihaloes (Greif & Bromm 2006; Schleicher et al. 2008). A second empirical signature is the combined bremsstrahlung emission from the H II regions in their active and relic states around those minihaloes that hosted Pop III stars. The resulting free-free radio emission leads to spectral distortions that might be detectable in the Rayleigh-Jeans part of the CMB spectrum. Recently, the ARCADE 2 experiment has attempted to measure such a free-free contribution from the epoch of the first stars (Komatsu et al. 2009). We use an artificially high fluctuation power of $\sigma_8 = 1.6$ to accelerate structure formation in our relatively small box, although the cosmological mean is given by $\sigma_8 = 0.81$. We take the chemical evolution of the gas into account by following the abundances of H, H$^+$, H$^{-}$, H$_2$, H$_2^+$, He, He$^+$, He$^{++}$, and e$^-$, as well as the three deuterium species D, D$^+$, and HD. We include all relevant cooling mechanisms, i.e. H and He collisional ionization, excitation and recombinination cooling, bremsstrahlung, inverse Compton cooling, and collisional excitation cooling via H$_2$ and HD (Glover & Jappsen 2007). We explicitly include H$_2$ cooling via collisions with protons and electrons, which is important for the chemical and thermal evolution of relic H II region gas (Glover & Abel 2008).

We run the simulations until the first minihalo in the box has collapsed to a density of $n_H = 10^4$ cm$^{-3}$, at which point the gas has cooled to $\sim 200$ K and becomes Jeans-unstable (Abel et al. 2002; Bromm et al. 2002). The first halo that fulfills this criterion collapses at $z \approx 20$ and has a virial mass of $\sim 9.4 \times 10^5$ M$_\odot$ and a virial radius of $\sim 90$ pc. Highly resolved simulations have shown that at later times, the gas condenses further under the influence of self-gravity to $n_H \sim 10^{21}$ cm$^{-3}$, where it becomes optically thick and forms a protostellar seed (Yoshida et al. 2008). Due to its residual angular momentum, the central clump flattens and likely evolves into an accretion disk. In our case, we find a flattened structure already at a density of $n_H = 10^5$ cm$^{-3}$ (see Fig. 1). Subsequently, the star grows to as massive as $\sim 100$ M$_\odot$ within its lifetime of a few million years (Bromm & Loeb 2004). However, we note that under certain conditions the disk may fragment to form multiple objects of smaller masses (Clark et al. 2008). Unfortunately, the details of the accretion phase and the concomitant radiative feedback are poorly understood, although some analytic investigations have been carried out (Tan & McKee 2004; McKee & Tan 2008). Under these circumstances, it seems best to initialize the calculation of the H II region at the onset of the initial Jeans-instability, when the density exceeds $n_H = 10^4$ cm$^{-3}$.

2.2 Ray-tracing scheme

The procedure used to calculate the Strömgren sphere around the star for a given time-step $\Delta t$ is similar to the ray-tracing scheme used in Johnson et al. (2007). We first designate an individual SPH particle as the source of ionizing radiation and create a spherical grid with typically $10^5$ rays and 500 logarithmically spaced radial bins around the source particle. The minimum radius is set by the smoothing length of the central particle, while the maximum radius is chosen appropriately to encompass the entire H II region.
This approach may seem crude compared to existing methods that use adaptive grids (e.g. HEALPIX; Górski et al. 2003), but the increased angular and radial resolution towards the center tend to mirror the existing density profile. However, one must proceed with care if the ionization front encounters dense clumps far from the source, where the resolution may no longer be sufficient.

In a single, parallel loop, the Cartesian coordinates of all particles are converted to spherical coordinates, such that their density and chemical abundances are mapped to the bins corresponding to their radius, zenith angle and azimuth, denoted by $r$, $\theta$ and $\phi$, respectively. The volume element of a particle intersects with the volume element of a bin, the particle contributes to the bin proportional to $\Delta r \Delta \theta \Delta \phi$, where

$$\Delta r = h, \Delta \theta = h/r \text{ and } \Delta \phi = h/r \sin \theta.$$  

If the volume element of a particle intersects with the volume element of a bin, the particle contributes to the bin proportional to the density of the particle squared. This dependency ensures that overdense regions are not missed if the bin size is much larger than the smoothing length, which could occur far from the source where the grid resolution is poor. Accidental flash-ionization of minihaloes is thus avoided. Once the above steps are complete, it is straightforward to solve the ionization front equation along each ray:

$$n_e r_i^2 \frac{d\tau}{dr} = \frac{\dot{N}_{\text{ion}}}{4\pi} - \alpha_B \int_0^{r_i} n_e n_e r^2 dr,$$  

where $r_i$ denotes the position of the ionization front, $\dot{N}_{\text{ion}}$ the number of ionizing photons emitted per second, $\alpha_B$ the case B recombination coefficient, and $n_e$, $n_p$ and $n_i$ the number densities of neutral particles, electrons and positively charged ions, respectively. We assume that the recombination coefficient remains constant at its value for $10^6$ K, which is roughly the temperature of the H II and He II region.

The numbers of H II and He II ionizing photons are given by

$$\dot{N}_{\text{ion}} = \frac{\pi L_*}{\sigma T_{\text{eff}}} \int_{\nu_{\text{min}}}^{\infty} \frac{B_\nu}{\nu} d\nu,$$  

where $h$ from now on denotes Planck’s constant, $\sigma$ denotes Boltzmann’s constant, and $\nu_{\text{min}}$ is the minimum frequency corresponding to the ionization threshold of H I and He II. We assume that massive Pop III stars emit a blackbody spectrum $B_\nu$ (in erg s$^{-1}$ cm$^{-2}$ Hz$^{-1}$ sr$^{-1}$) with an effective temperature $T_{\text{eff}} = \text{dex}(4.922, 4.975, 4.999)$ K and luminosity $L_* = \text{dex}(5.568, 6.095, 6.574)$ L$_\odot$ for a 50, 100 and 200 $M_\odot$ star, respectively (Schaerer 2002). This yields

$$\dot{N}_{\text{ion, H II}} = [2.80, 9.14, 26.99] \times 10^{49} \text{ s}^{-1}$$  

and

$$\dot{N}_{\text{ion, He II}} = [0.72, 4.14, 15.43] \times 10^{48} \text{ s}^{-1}.$$  

We do not distinguish between the H II and He II region, which is a good approximation for massive Pop III stars (Osterbrock & Ferland 2006). The lifetimes of the stars are given by $t_* = 3.7$, 2.7 and 2.2 Myr, respectively. We neglect the effects of stellar evolution, which might lead to a decrease of the number of ionizing photons emitted at the end of the main sequence (Marigo et al. 2001; Schaerer 2002), although recent investigations have shown that rotating Pop III stars remain on bluer evolutionary tracks and this effect might not be so strong (Yoon & Langer 2003; Woosley & Heger 2006; Vázquez et al. 2007).

To obtain a discretisation of the ionization front equation, we replace the integral on the right-hand side of equation (1) by a discrete sum:

$$\int_0^{r_i} n_e n_e r^2 dr \simeq \sum_{i} n_e n_e r_i^2 \Delta r_i,$$  

where $\Delta r_i$ is the radial extent of bin $i$, and the sum extends from the origin to the position of the ionization front at

![Figure 1](image-url). Sequential zoom-in on the first star-forming minihalo at $z_* \simeq 20$. Shown is the density-squared weighted average of the hydrogen density along the line of sight, just after the formation of the first Jeans-unstable clump in a $\simeq 9.4 \times 10^9$ $M_\odot$ minihalo. The flattening of the core due to angular momentum conservation during the collapse is marginally visible, with the consequence that ionizing radiation from the central source breaks out anisotropically (see Fig. 3).
the end of the current time-step $\Delta t$. The above equation describes the advancement of the ionization front due to an excess of ionizing photons compared to recombinations. Similarly, the left-hand side of equation (1), which models the propagation of the ionization front into neutral gas, is discretized by

$$n_a r_i^3 \frac{dr_i}{dt} \simeq \frac{1}{\Delta t} \sum_i n_n x_i r_i^2 \Delta r_i,$$

where the sum now extends from the position of the ionization front at the previous time-step to its position at the end of the current time-step. We perform the above steps separately for the H II and He III region, since they require distinct heating and ionization rates. For the He II region, we replace the quantities $n_n$ and $x_n$ in equation (1) with $n_n = \int n_{\text{HeII}} + n_{\text{HeIII}}$, where $f_X$ is the number density of species $X$ relative to $n_H$. We adopt a case B recombination rate of $\alpha_B = 1.3 \times 10^{-12}$ cm$^3$ s$^{-1}$ for He II recombinations to He I (Osterbrock & Ferland 2006). Applying the same prescription to the H II region, we find $n_n = \int n_{\text{HII}} + n_{\text{HeII}}$ and $x_n = (f_{\text{HII}} + f_{\text{HeII}}) n_H$. Similarly, we adopt a case A recombination rate of $\alpha_A = 2.6 \times 10^{-13}$ cm$^3$ s$^{-1}$ for hydrogen and helium recombinations from their first ionized states to the ground state (Osterbrock & Ferland 2006). We initialize the calculation of the H II region at the boundary of the He III region, since hydrogen and helium are maintained in their first ionization states by recombinations of He III to He II (Osterbrock & Ferland 2006). We note that the exact position of the ionization front is not restricted to integer multiples of our pre-defined radial bins, but may instead lie anywhere in between. For this purpose we adopt a simple linear scaling of the number of ionizations and recombinations as a function of the relative position of the ionization front. The most expensive step in terms of computing time is the assignment of the density and the chemical abundances to the grid, while the ray-tracing itself requires only a negligible amount of time.

### 2.3 Photoionization and photoheating

Once the extent of the H II and He III region have been determined, the SPH particles within these regions are assigned an additional variable that stores their distance from the source. This information is then passed to the chemistry solver, which determines the ionization and heating rates, given by

$$k_{\text{ion}} = \int_{r_{\text{min}}}^{\infty} F_{\nu} \sigma_{\nu} \frac{d\nu}{h\nu},$$

and

$$\Gamma = n_n \int_{r_{\text{min}}}^{\infty} F_{\nu} \sigma_{\nu} \left(1 - \frac{\nu_{\text{min}}}{\nu}\right) d\nu,$$

where $F_{\nu}$ and $\sigma_{\nu}$ denote the incoming specific flux and ionization cross section, respectively. For the case of a black-body,

$$F_{\nu} = \frac{L_\nu}{4 \pi r^2 c dr c},$$

where $r$ is the distance from the source. The resulting rates are given by

$$k_{\text{ion,HI}} = \frac{[0.45, 1.32, 3.69]}{(r/\text{pc})^2} \times 10^{-6} \text{ s}^{-1},$$

$$k_{\text{ion,HeI}} = \frac{[0.42, 1.43, 4.29]}{(r/\text{pc})^2} \times 10^{-6} \text{ s}^{-1},$$

$$k_{\text{ion,HeII}} = \frac{[0.67, 3.72, 13.57]}{(r/\text{pc})^2} \times 10^{-8} \text{ s}^{-1},$$

$$\Gamma_{\text{HI}} = n_H \frac{[0.40, 1.28, 3.74]}{(r/\text{pc})^2} \times 10^{-17} \text{ erg s}^{-1} \text{ cm}^{-3},$$

$$\Gamma_{\text{HeI}} = n_{\text{HeI}} \frac{[0.41, 1.57, 4.94]}{(r/\text{pc})^2} \times 10^{-17} \text{ erg s}^{-1} \text{ cm}^{-3},$$

$$\Gamma_{\text{HeII}} = n_{\text{HeII}} \frac{[0.72, 4.46, 17.13]}{(r/\text{pc})^2} \times 10^{-19} \text{ erg s}^{-1} \text{ cm}^{-3}$$

for a 50, 100 and 200 $M_\odot$ Pop III star, respectively. These are taken into account every time-step, while the ray-tracing is performed only every fifth time-step. Since the hydrodynamic time-step is generally limited to one-twentieth of the sound-crossing time through the kernel, our treatment of the coupled evolution of the ionization front and the hydrodynamic shock is roughly correct. The computational cost of runs with and without ray-tracing are typically within a factor of a few.

### 2.4 Photodissociation and photodetachment

The final ingredient in our algorithm is the inclusion of molecule-dissociating radiation. This effect turns out to be of only minor importance in the present study, but will render our algorithm capable of addressing a general set of early Universe applications. Molecular hydrogen is the most important coolant in low-temperature, primordial gas, but is easily destroyed by radiation in the Lyman-Werner (LW) bands between 11.2 and 13.6 eV. The small residual H$_2$ fraction in the IGM leads to a very small optical depth over cosmological distances, such that even a small background can have a significant effect (Haiman et al. 2004, Glover & Brand 2001, Johnson et al. 2007). In our implementation, we do not take self-shielding into account, which becomes important for H$_2$ column densities $\gtrsim 10^{14}$ cm$^{-2}$ (Draine & Bertoldi 1996). Such a high column density is difficult to achieve in minihaloes, and is more likely to occur within the virial radius of the first galaxies (Oh & Haiman 2002). However, the onset of turbulence in the first galaxies likely leads to a reduction of self-shielding via Doppler shifting (Wise & Abel 2007, Greif et al. 2008). For this reason we treat the photodissociation of H$_2$ in the optically thin limit, such that the dissociation rate in a volume limited by causality to a radius $r = ct_\nu$ is given by $k_{\text{H}_2} = 1.1 \times 10^8 F_{\text{LW}}$ s$^{-1}$, where $F_{\text{LW}}$ is the integral of the specific flux $F_{\nu}$ over the LW bands, resulting in

$$k_{\text{H}_2} = \frac{[1.27, 3.38, 9.07]}{(r/\text{pc})^2} \times 10^{-7} \text{ s}^{-1}$$

for a 50, 100 and 200 $M_\odot$ Pop III star, respectively. We do not explicitly include photodetachment of H$^-$ and photodissociation of H$^+_2$, which might be problematic outside of the H II region, where molecules survive collisional destruction.
However, in the context discussed here, this caveat is not important (see Johnson et al. 2007).

### 3 OBSERVATIONAL SIGNATURE

In the following, we discuss the direct observational signature of the first H II regions and relic H II regions in terms of recombination radiation, as well as their indirect signature in terms of a global radio background produced by bremsstrahlung and 21-cm emission.

#### 3.1 Build-up of H II and He III region

The build-up of the first H II regions by Pop III stars in minihaloes was treated in one dimension by Kitayama et al. (2004) and Whalen et al. (2004), and in three dimensions by Alvarez et al. (2006), Abel et al. (2007) and Yoshida et al. (2007). The latter also treated the build-up of a smaller He III region, which is created by the very hard spectrum of massive Pop III stars. The consensus was that recombinations initially balanced ionizations within the virial radius of the host halo, leading to the formation of a D-type ionization front. Breakout occurred after the density dropped sufficiently for the ionization front to race ahead of the hydrodynamic shock, becoming R-type. The hydrodynamic response of the gas is self-similar, since minihaloes approximately resemble singular isothermal spheres (Shu et al. 2004; Alvarez et al. 2006). The relevant parameters are set by the temperature of the singular isothermal sphere and the H II region, which in our case are $T \approx 200$ and $\approx 10^4$ K, respectively.

In Fig. 2, we compare the density profile of the Shu et al. (2002) solution to the simulation for the case of a 100 $M_\odot$ Pop III star. Interestingly, we find a clear deviation from the ideal, spherically symmetric solution already during the D-type phase, which is caused by the anisotropic collapse of the minihalo. Due to angular momentum conservation, the gas spins up and forms a flattened, disk-like structure in terms of a global radio background produced by bremsstrahlung and 21-cm emission.

#### 3.2 Recombination radiation from individual H II and He III regions

The strongest direct signature of the first H II and He III regions is likely generated by recombination radiation, since ionizing photons are absorbed by dense gas in the host halo. We have concentrate on the Hα and He II $\lambda 1640$ lines, since more energetic photons are scattered out of resonance by the neutral IGM, creating extended haloes around high-redshift sources (e.g. Loeb & Rybicki 1999). The resulting fluxes may then be compared to the expected sensitivity of the Mid-Infrared Instrument (MIRI) on JWST at $\sim 10$ $\mu$m wavelengths (Gardner et al. 2008). The spatial resolution is limited by diffraction, such that a scale of $\approx 1$ kpc at $z = 20$ is marginally resolved, which allows us to approximate the region of emission as a point source. Using the simulation output, the total luminosities are given by

$$L_{\text{H}\alpha} = j_{\text{H}\alpha} \sum_i m_i \rho_i \left( \frac{X \rho_i}{m_\text{H}} \right)^2 f_{e,i} f_{\text{H}\alpha,i},$$

and

$$L_{1640} = j_{1640} \sum_i m_i \rho_i \left( \frac{X \rho_i}{m_\text{H}} \right)^2 f_{e,i} f_{1640,i},$$

where $j_{\text{H}\alpha}$ and $j_{1640}$ are the emissivity of the Hα and He II $\lambda 1640$ lines at $10^4$ K (Osterbrock & Ferland 2006), $X = 0.76$ is the primordial mass fraction of hydrogen, $m_\text{H}$ is the mass of the hydrogen atom, $m_i$ and $\rho_i$ are the mass and density of particle $i$, respectively, and the sum is over all particles in the simulation box. From the total luminosity, we determine the observed flux with the inverse-square law

$$F = \frac{L}{4\pi D_L^2},$$

where $D_L$ is the cosmological luminosity distance. In Fig. 4, we show the observed flux for a 50, 100 and 200 $M_\odot$ Pop III star as a function of time. The emission peaks before breakout, when the density in the host halo is still high, reaching a maximum flux of $\approx 10^{-23}$ erg s$^{-1}$ cm$^{-2}$. Once the star turns off, the Hα emission drops quite rapidly over the course of a few 10 Myr, while the He II $\lambda 1640$ emission drops almost instantaneously in the 100 and 200 $M_\odot$ cases, due to the high recombination coefficient of He III to He II. It is noteworthy that the emission in the He II $\lambda 1640$ line is generally not much lower than that in the Hα line, which may be used as an indicator for massive Pop III stars (Bromm et al. 2001; Oh 2001; Tumlinson et al. 2001; Schaerer 2002). For a 10 σ detection with an exposure time of 100 hours, the spectrograph on MIRI exhibits a typical limiting sensitivity of $\approx 10^{-18}$ erg s$^{-1}$ cm$^{-2}$ (Panagia 2005), implying that the first H II regions are typically five orders of magnitude too faint for a direct detection. We must therefore resort to indirect methods that rely on their cumulative signal. One such signature is the cosmic infrared background (CIB), where the redshifted Lyα recombination photons from $z \approx 10 - 20$ might contribute at a detectable level (Santos et al. 2002; Kashlinsky et al. 2003). Minihaloes, however, are not
expected to be important sources for the CIB, as opposed to more massive dark matter haloes that host the first galaxies (Greif & Bromm 2006). This leads us to consider the radio background as a key diagnostic of the Pop III minihalo formation site.

3.3 Radio background produced by bremsstrahlung

The first H ii regions in their active as well as relic states also emit bremsstrahlung via thermal motions of electrons in an ionized medium. In line with our conclusions of the previous section, the signature from an individual source is much too faint to be detected. However, the cumulative radio signal might be strong enough to be detected by the upcoming SKA. We will here further explore this possibility (for a review of earlier work, see Furlanetto et al. 2006).

Solving the cosmological radiative transfer equation, it is straightforward to derive a simple expression for the observed radio background $J_\nu$ (in erg s$^{-1}$ cm$^{-2}$ Hz$^{-1}$ sr$^{-1}$):

$$J_\nu = \int_0^{t_{\text{H},0}} \frac{j_\nu}{(1+z)^2} c \, \text{d}t,$$

where $t_{\text{H},0}$ is the present Hubble time and $j_\nu$ is the specific emissivity of bremsstrahlung, given by

$$j_\nu = \epsilon_\text{ff} \langle n_e^2 \rangle \left( T / 10^5 \text{ K} \right)^{-1/2},$$

where $\epsilon_\text{ff} \simeq 10^{-39}$ erg s$^{-1}$ cm$^{-3}$ Hz$^{-1}$ sr$^{-1}$, $\langle n_e^2 \rangle$ is the volume-averaged electron density, and $T$ is the temperature (Rybicki & Lightman 1979). We universally assume $T = 10^5$ K, since the relic H ii region cools quite rapidly to $\sim 10^3$ K via inverse Compton losses and adiabatic expansion once the star has died (e.g. Greif et al. 2005, Yoshida et al. 2007). Furthermore, we assume $j_\nu = 0$ at $z < 6$, since photoheating during reionization evaporates minihaloes (Dijkstra et al. 2004). This leads to:

$$J_\nu = c \epsilon_\text{ff} \int_6^{-} \frac{\langle n_e^2 \rangle}{(1+z)^2} \left| \frac{d}{dz} \right| \left| \text{d}z \right|,$$

where we relate $\langle n_e^2 \rangle$ to the number density of minihaloes according to:

$$\langle n_e^2 \rangle \simeq t_{\text{rec}} n_{\text{H},b}^2 v_{\text{HII}} \left| \frac{dN_{\text{ps}}}{dN_{\text{ps}}} \right| \frac{dN_{\text{ps}}}{dz}.$$

Here, $t_{\text{rec}} = (\alpha_B n_{\text{H},b})^{-1}$ denotes the recombination time for hydrogen atoms, $\alpha_B$ the case B recombination rate for $T = 10^5$ K, $n_{\text{H},b}$ the background density, $N_{\text{ps}}$ the number of minihaloes per comoving volume, $v_{\text{HII}} = N_{\text{ion}} / n_{\text{H},b,0}$ the comoving volume of an individual H ii region in its active as well as relic state, which is independent of redshift, and $N_{\text{ion}} = N_{\text{ion}} t_*$ the total number of ionizing photons emitted per Pop III star (see Section 2). In the above equation, we have implicitly assumed that (rellic) H ii regions survive for a recombination time, and that all ionizing photons escape into the IGM, which is a good approximation for massive Pop III stars in minihaloes (Alvarez et al. 2004). We note that in the range of redshifts considered here, the recombination time is larger than the stellar lifetime and smaller than the age of the Universe. In principle, one must also account for the clustering of minihaloes (biasing), which reduces the net volume filling factor of H ii regions (Mo & White 1996, Iliev et al. 2003, Gao et al. 2007, Reed et al. 2003, Greif & Bromm 2006). However, it is extremely difficult to determine the importance of this effect, since (i) the actual overlap depends on the relative separation of minihaloes, and (ii) previous ionization allows a nearby H ii region to become larger than usual. We therefore neglect biasing, but keep in mind that the actual signal may be somewhat lower.

In equation (23), the number density of minihaloes is given by

$$N_{\text{ps}}(z) = \int_{M_{\text{min}}}^{M_{\text{max}}} n_{\text{ps}}(z, M) \, dM,$$

where $n_{\text{ps}}$ is the well-known Press-Schechter mass function (Press & Schechter 1974). The minimum mass required for efficient cooling within a Hubble time may be found in Yoshida et al. (2002) and Trenti & Stiavelli (2009).
Figure 3. The H\textsc{ii} region created by a 50, 100 and 200 M\textsubscript{\odot} Pop III star (from top to bottom) after 50 kyr, 300 kyr, and at the end of their lifetime (from left to right). Shown is the density-squared weighted average of the temperature along the line of sight. The spiral structure of the central clump as well as the resulting anisotropic breakout of the ionization front are clearly visible. For increasing stellar mass and ionizing photon output, breakout occurs earlier and is more isotropic. Once the ionization front becomes R-type, spherical symmetry is asymptotically restored and the H\textsc{ii} region expands to a final radius of $r_{\text{HII}} \simeq 1.9, 2.7$ and $3.7$ kpc after $3.7, 2.7$ and $2.2$ Myr, respectively.
while the maximum mass is set by the requirement that cooling must be dominated by molecular hydrogen, i.e. the virial temperature must not exceed $T \approx 10^4$ K for atomic hydrogen cooling, resulting in (e.g. Barkana & Loeb 2001)

$$M_{\text{max}} \approx 2.5 \times 10^7 \, M_\odot \left( \frac{1+z}{10} \right)^{-3/2}.$$  

We have found that our results are only marginally affected by the upper mass limit, but depend sensitively on the lower mass limit, since most minihaloes reside at the lower end of the halo distribution function.

After combining the above equations, we obtain

$$J_\nu \approx \frac{c \, e \, n_\text{ion}}{10} \, n_\text{H}_\alpha (z = 6) ,$$  

which, for an IMF consisting solely of 100 $M_\odot$ Pop III stars, yields

$$J_\nu \approx 300 \text{ mJy sr}^{-1} .$$  

The brightness temperature, $T_b = c^2 J_\nu / 2 k_B B^2$, is given by

$$T_b \approx 1 \text{ mK} \left( \frac{\nu}{100 \, \text{MHz}} \right)^{-2} .$$  

In the following, we investigate whether a signal of this magnitude is observable by the upcoming SKA.

The sensitivity of radio instruments is generally defined by the ratio of the effective collecting area $A_e$ to the system temperature $T_{\text{sys}}$. For the SKA with its proposed aperture array configuration at low frequencies, $A_e / T_{\text{sys}} \approx 5 \times 10^3$ m$^2$ K$^{-1}$ at 100 MHz. In this range, the system temperature is dominated by Galactic synchrotron emission, for which a useful approximation is given by $T_{\text{sys}} \approx 180$ K $\left( \nu / 180 \, \text{MHz} \right)^{-2.6}$ (Furlanetto et al. 2006), resulting in $T_{\text{sys}} \approx 800$ K and $A_e \approx 4 \times 10^6$ m$^2$. The minimum angular resolution for an array filling factor of unity at 100 MHz is approximately 15 arcmin. At higher resolutions, the sensitivity decreases much too rapidly for effective imaging.

In Fig. 5, we compare the sensitivity of the SKA for a 10$\sigma$ detection, a bandwidth of $\Delta \nu_{\text{obs}} = 1$ MHz, and an integration time of 1000 h to the brightness temperature and specific flux expected for free-free emission. Although the figure implies that the free-free signal is detectable by the SKA, we have neglected biasing as well as radiative feedback in the form of a global LW background, which attenuates star formation in minihaloes (Johnson et al. 2007, 2008). Another complicating issue is the overlap with 21-cm emission, which makes it nearly impossible to isolate the contribution from bremsstrahlung. In consequence, we do not believe that this signal will be observable in the near future.

3.4 Radio background produced by 21-cm emission

Perhaps the most promising observational signature comes from 21-cm emission of the relic H II region gas once the star has died, a prospect that was already investigated by Tokutani et al. (2009). An emission signal requires the spin temperature $T_S$ of neutral hydrogen to be greater than the temperature of the CMB, with its relative brightness determined by $T_S$ and the size of the relic H II region. The spin temperature is set by collisional coupling with neutral hydrogen atoms, protons and electrons, as well as radiative coupling to the CMB. Furthermore, it may be modified by the so-called Wouthuysen-Field effect, which describes the mixing of spin states due to the absorption and re-emission of Ly$\alpha$ photons (Wouthuysen 1952, Field 1959). The color temperature of the Ly$\alpha$ background is determined by the ratio of excitations to de-excitations, which approaches the kinetic gas temperature at high redshifts, where the optical depth to Ly$\alpha$ scattering is very large (Furlanetto et al. 2006). In this case, adopting the Rayleigh-Jeans approximation and assuming $T_S \gg T_\gamma$, where $T_\gamma = h \nu_{\text{Ly}\alpha} / k_B = 68$ K is the temperature associated with the 21-cm transition, the spin temperature may be written as (Madau et al. 1997)

$$T_S = T_\gamma \left( \frac{y_e + y_\alpha}{1 + y_e + y_\alpha} \right) T_\gamma ,$$  

where $T_\gamma$ is the temperature of the CMB. The collisional coupling coefficient $y_e$ is approximately given by

$$y_e \approx 1.$$  

1 http://www.skatelescope.org
that the free-free signal of the first \( H_\text{ii} \) regions will be observable in the near future.

For the SKA, we have here neglected biasing and radiative feedback, which act to reduce the signal. For this reason we do not believe that the free-free signal of the first \( H_\text{ii} \) regions in their active or relic states will be observable in the near future.

\[
y_c = \frac{T_e}{A_{21} T} (n_{\text{HII}} \kappa_{\text{HI}} + n_e \kappa_e)
\]

where \( A_{21} = 2.85 \times 10^{-15} \text{ s}^{-1} \) is the Einstein A-coefficient for the 21-cm transition, and \( \kappa_{\text{HI}} \) and \( \kappa_e \) are the effective single-atom rate coefficients for collisions with neutral hydrogen atoms and electrons, respectively. Good functional fits in the temperature range \( 100 \text{ K} \lesssim T \lesssim 10^4 \text{ K} \) are given by

\[
\kappa_{\text{HI}} = 10^{-11} T^{1/2} \text{ cm}^3 \text{ s}^{-1}
\]

and

\[
\kappa_e = 2 \times 10^{-10} T^{1/2} \text{ cm}^3 \text{ s}^{-1}
\]

which we have obtained from the rates quoted in Kuhlen et al. (2006). At \( z \lesssim 20 \), the electron fraction in the IGM remains above \( f_e = 0.1 \) for most of the lifetime of the relic \( H_\text{II} \) region. In this case, the collisional coupling coefficient is given by

\[
y_c \simeq 0.015 \left( \frac{f_e}{0.5} \right) \left( \frac{T}{10^3 \text{ K}} \right)^{-1/2} \left( \frac{1 + z}{10} \right)^3 .
\]

A derivation of the Ly\( \alpha \) coupling coefficient \( y_o \) requires radiative transfer of local as well as global Ly\( \alpha \) radiation, which is beyond the scope of this work. We therefore consider two limiting cases: one in which we only consider collisional coupling, and the other in which a strong Ly\( \alpha \) background drives the spin temperature towards the gas temperature (i.e. \( y_o \gg 1 \text{ or } T_S = T \)).

The differential brightness temperature with respect to the CMB may then be derived as follows. In the Rayleigh-Jeans limit and for \( T_S \gg T_\gamma \), the monochromatic radiative transfer equation for a ray passing through a cloud, evaluated in its comoving frame, may be written in terms of the brightness temperature \( T_b \):

\[
T_b = T_\gamma e^{-\tau} + \int_0^\tau T_S e^{-\tau'} d\tau',
\]

where the optical depth at the 21-cm line is given by

\[
d\tau = \frac{3c^2 A_{21} n_{\text{HI}}}{32\pi v_{21}^2} \phi(v_{21}) \frac{T_e}{T_S} \text{d}s .
\]

Here, \( \phi(v_{21}) \) is the normalized line profile at the resonance frequency \( v_{21} \) and \( ds \) is the distance traveled by the ray. In our case, the line profile is dominated by thermal broadening, with a Doppler width given by

\[
\Delta v_D = v_{21} \sqrt{\frac{2k_b T}{m_n c^2}} .
\]

The amplitude of the line profile at the resonance frequency may be replaced by the Doppler width, i.e. \( \phi(v_{21}) = \Delta v_D^{-1} \). With this definition, equation (35) yields the differential brightness temperature \( \delta T_b = T_b - T_\gamma \), which becomes particularly simple for a constant spin temperature and the fact that the relic \( H_\text{II} \) regions considered here are optically thin: \( \delta T_b = (T_S - T_\gamma) \tau \).

The observed differential brightness temperature is then simply given by \( \delta T_{b,\text{obs}} = \delta T_b / (1 + z) \).

In Fig. 6, we show the observed differential brightness temperature for a 100 M\( \odot \) star and the two limiting cases discussed above. Note that we have only taken into account ionized gas along the line of sight. For collisional coupling, the observed differential brightness temperature is of order a few 10 mK for \( z \approx 100 \text{ Myr} \), while for perfect coupling the signal is elevated by an order of magnitude to a few 100 mK for well over \( z \approx 100 \text{ Myr} \). In reality, the expected signal lies between these extremes and is a function of redshift, since collisional coupling becomes weaker as the background density drops, while Ly\( \alpha \) coupling becomes stronger as the Ly\( \alpha \) background rises. At \( z \leq 20 \), where the observationally accessible signal is produced, the Ly\( \alpha \) background is likely strong enough for the latter to be more important (Pritchard & Furlanetto 2007).

Next, we determine the radio background produced by the integrated 21-cm emission of relic \( H_\text{II} \) regions. The differential specific flux observed at the redshifted 21-cm line from a single relic \( H_\text{II} \) region with differential brightness temperature \( \delta T_b \) is given by

\[
\delta F_\nu = \frac{2k_b T_{21}}{c^2} (1 + z)^{-3} \Delta \Omega \delta T_b ,
\]

where \( \Delta \Omega = A/D_A^2 \) denotes the solid angle subtended by the relic \( H_\text{II} \) region, \( A = \pi r_{\text{HII}}^2 \) its area, \( r_{\text{HII}} = (3N_{\text{halo}}/4\pi n_{\text{HII}})^{1/3} \) its radius, and \( D_A \) the angular diameter distance. The average differential specific flux \( \langle \delta F_\nu \rangle \) within a beam size \( \Delta \Omega_{\text{beam}} \) and bandwidth \( \Delta \nu_{\text{obs}} \) is then given by

\[
\langle \delta F_\nu \rangle = \delta F N_{\nu_{\text{obs}}} \frac{d^2 \nu(\nu)}{\text{d}\nu} \frac{\Delta \nu_{\text{obs}}}{\Delta \Omega_{\text{beam}}} ,
\]
Figure 6. The observed differential brightness temperature of the relic H\thinspace ii region around a 100 M\sun\ Pop III star, shown 20, 50 and 100 Myr after the star has turned off. We delineate the range of possible values by showing the result for collisional coupling only (top row), as well as perfect coupling to the Ly\alpha background, resulting in $y_{\alpha} \gg 1$ or $T_S = T$ (bottom row). In the first case, the observed differential brightness temperature is of order a few 10 mK for $\approx 100$ Myr, while in the second case the signal is of order a few 100 mK for well over $\approx 100$ Myr. We note that the latter is likely more relevant at $z \lesssim 20$, where the observationally accessible signal is produced (see Furlanetto 2006; Pritchard & Furlanetto 2007).

where $\delta F = \delta F_\nu \Delta \nu_D / (1 + z)$, $N_{\text{ps}}(z)$ is the Press-Schechter mass function defined in equation (24), $\Delta z = \Delta \nu_{\text{obs}} (1 + z)^2 / \nu_{21}$, and $d^3V(z)/dz \, d\Omega$ is the comoving volume per unit redshift and solid angle:

$$\frac{d^3V(z)}{dz \, d\Omega} = \frac{c \Delta \nu_\nu (1 + z)^2}{H(z)}, (41)$$

where $H(z)$ is the Hubble expansion rate. With the definition of the brightness temperature, the average differential antenna temperature $\langle \delta T_b \rangle$ is given by

$$\langle \delta T_b \rangle = \frac{\pi c}{\nu_{21}} \frac{(1 + z)^2 N_{\text{ps}}(z)}{H(z)} \Delta \nu_D\, r_{\text{HII}}(z) \, \delta T_b(z). (42)$$

Based on our argument above, we assume that the Ly\alpha background is strong enough for perfect coupling at all redshifts. In this case, and for $T \gg T_\gamma$, the average differential antenna temperature becomes independent of electron fraction and temperature:

$$\langle \delta T_b \rangle = \frac{9c^2 A_{21} T_\ast N_{\text{ion}}}{128\pi\nu_{21}^2 H_0 \sqrt{\Omega_m}} (1 + z)^{1/2} N_{\text{ps}}(z), (43)$$

where we have set $n_{\text{HII}} = n_{\text{H,b}}$ in equation (36). We note that the observed frequency is related to the redshift via $\nu_{\text{obs}} = \nu_{21} / (1 + z)$. We have further assumed that the relic H\thinspace ii region produced by each star-forming minihalo persists until the Universe is reionized (i.e. $z \approx 6$), which is a good approximation for perfect coupling and $T \gg T_\gamma$. Equation (43) thus provides a robust upper limit for the collective 21-cm emission from the first relic H\thinspace ii regions.

In Fig. 7, we compare the average differential antenna temperature and specific flux for a beam size of $\Delta \theta_{\text{beam}} = 15'$ to the sensitivity of the SKA, assuming a 10\sigma detection, a bandwidth of $\Delta \nu_{\text{obs}} = 1$ MHz, and an integration time of 1000 h. At all frequencies, the maximum 21-cm signal from the first relic H\thinspace ii regions is of order 10 mK, which is well detectable by the SKA. The effects of biasing and
radiative feedback will reduce this signal, but probably not enough to fall below the sensitivity of the SKA. Compared to free-free emission, the 21-cm signal is typically an order of magnitude stronger, and offers the best prospect for indirectly probing the first stars.

4 SUMMARY AND CONCLUSIONS

We have introduced a general-purpose radiative transfer scheme for cosmological SPH simulations that treats ionizing and photodissociating radiation from massive Pop III stars in the early Universe. Based on this methodology, we have investigated the build-up of the first H ii regions and relic H ii regions around Pop III stars formed in minihaloes, and predicted their contribution to the extragalactic radio background via bremsstrahlung and 21-cm emission. Although recombination radiation from individual H ii regions in their active as well as relic states is too faint to be directly detectable even with JWST, their collective radio emission might be strong enough to be within reach of the planned SKA. In particular, we have found that the integrated free-free emission results in a maximum differential antenna temperature of \( \lesssim 1 \) mK, while the 21-cm emission is an order of magnitude stronger. Considering the effects of biasing and negative radiative feedback, which would act to reduce the predicted signal, the free-free signal is likely beyond the capability of the SKA, while the 21-cm signal will most likely be observable, providing an excellent opportunity for indirectly probing the first stars.

We note that an analysis of the angular fluctuation power spectrum will be essential to isolate the 21-cm signal from other backgrounds (Furlanetto & Oh 2006), although the frequency-dependence of the 21-cm signal might already prove useful. Among these are neutral minihaloes, which appear in emission due to their enhanced density and temperature (Iliev et al. 2002), or IGM gas heated by X-rays from supernovae (Oh 2001), X-ray binaries (Glover & Brand 2003), or the first quasars (Madau et al. 2004; Kuhlen et al. 2006). A strong absorption signal might originate from cold, neutral gas if the Lyα background effectively couples the spin temperature to the gas temperature (Pritchard & Furlanetto 2007). In addition, there is the signal produced by stars (primordial or already metal-enriched) formed in the first dwarf galaxies (e.g. Naoz & Barkana 2008). All of these compete with each other, and more work is required to understand their relative importance. One important task is to extend the simulations to larger cosmological volumes, to measure the aggregate signal from many sources in a more robust way.

Minihaloes may not have been the dominant formation sites for primordial stars, in terms of producing the bulk of the radiation that drove reionization, or of being the source for the majority of the heavy elements present at high redshifts (Greif & Bromm 2006; Schleicher et al. 2008). Nevertheless, they are the ideal laboratory to test our current standard model of the first stars, by providing an exceedingly simple environment for the star formation process (Bromm et al. 2009). The next step in the hierarchical build-up of structure is already highly complex, due to the presence of metals, turbulent velocity fields, and possibly dynamically significant magnetic fields (Wise & Abel 2007, 2008; Greif et al. 2008; Schleicher et al. 2009). It is therefore crucial to empirically probe the minihalo environment, and the signature left in the radio background might provide us with one of the few avenues to accomplish this in the foreseeable future.

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