The aftermath of the first stars: massive black holes

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ABSTRACT
We investigate the evolution of the primordial gas surrounding the first massive black holes formed by the collapse of Population III stars at redshifts $z > 20$. Carrying out three-dimensional hydrodynamical simulations using GADGET, we study the dynamical, thermal and chemical evolution of the first relic H II regions. We also carry out simulations of the mergers of relic H II regions with neighbouring neutral minihaloes, which contain high-density primordial gas that could accrete on to a Population III remnant black hole. We find that there may have been a significant time delay, of the order of $\sim 10^8$ yr, between black hole formation and the onset of efficient accretion. The build-up of supermassive black holes, believed to power the $z \gtrsim 6$ quasars observed in the Sloan Digital Sky Survey, therefore faces a crucial early bottleneck. More massive seed black holes may thus be required, such as those formed by the direct collapse of a primordial gas cloud facilitated by atomic line cooling. The high optical depth to Lyman–Werner (LW) photons that results from the high fraction of H$_2$ molecules that form in relic H II regions, combined with the continued formation of H$_2$ inside the dynamically expanding relic H II region, leads to shielding of the molecules inside these regions at least until a critical background LW flux of $\sim 10^{-24}$ erg s$^{-1}$ cm$^{-2}$ Hz$^{-1}$ sr$^{-1}$ is established. Furthermore, we find that a high fraction of deuterium hydride (HD) molecules, $X_{\text{HD}} \gtrsim 10^{-7}$, is formed, potentially enabling the formation of Population II.5 stars, with masses of the order of $\sim 10^5$ M$_\odot$, during later stages of structure formation when the relic H II region gas is assembled into a sufficiently deep potential well to gravitationally confine the gas again.

Key words: molecular processes – stars: formation – H II regions – galaxies: formation – cosmology: theory – early Universe.

1 INTRODUCTION

What were the feedback effects from the first generation of stars in the Universe? The first stars, which formed in dark matter (DM) minihaloes of mass $\sim 10^6$ M$_\odot$, at redshifts of $z \sim 20$, were likely very massive, having characteristic masses of the order of $\sim 100$ M$_\odot$ (Bromm, Coppi & Larson 1999, 2002; Nakamura & Umemura 2001; Abel, Bryan & Norman 2002). These massive Population III stars would have radiated at temperatures of $\sim 10^5$ K (e.g. Bond, Arnett & Carr 1984), generating enough ionizing photons to completely ionize the minihaloes in which they were formed and to contribute to the reionization of the Universe (e.g. Barkana & Loeb 2001; Alvarez, Bromm & Shapiro 2006).

In addition to the radiation emitted by the first stars during their lifetimes, those Population III stars with masses $40 \lesssim M_\star \lesssim 140$ M$_\odot$ or $M_\star \gtrsim 260$ M$_\odot$ are predicted to have collapsed to form black holes directly, possibly providing the seeds for the first quasars (Madau & Rees 2001; Heger et al. 2003; Madau et al. 2004; Ricotti & Ostriker 2004; Kuhlen & Madau 2005), although more massive seed black holes may have been formed after the epoch of the first stars in DM haloes with virial temperatures $\gtrsim 10^4$ K (Bromm & Loeb 2003; Begelman, Volonteri & Rees 2006; Spaans & Silk 2006).

The growth of the first black holes must have been rapid enough to account for the powerful quasars observed at redshifts of $z \gtrsim 6$ (e.g. Fan et al. 2004, 2006), believed to be fuelled by accretion on to supermassive black holes (SMBHs) with masses $\sim 10^9$ M$_\odot$ (e.g. Haiman & Loeb 2001; Volonteri & Rees 2005, 2006). How such vigorous accretion of matter could have taken place poses an important question, as it has been shown that the radiation from the first stars heats and evacuates the gas residing within the $\sim 10^6$ M$_\odot$ minihaloes in which they are born (Kitayama et al. 2004; Whalen, Abel & Norman 2004; Alvarez et al. 2006). Notwithstanding some possible contribution to the accreted mass from self-interacting DM (SIDM) particles (see Spergel & Steinhardt 2000; Hu et al. 2006), the baryonic mass around these primordial massive black holes (MBHs) must have been efficiently replenished soon after the birth of the black hole. In the course of hierarchical structure formation, this continued accretion of matter is naturally accomplished through mergers of the black hole’s parent halo with its neighbouring haloes.
side relic HII regions, as well as in partially ionized shells just ahead by deuterium hydride (HD) molecules inside relic HII regions may. Neighbouring minihaloes may not, in fact, have been significantly extinguished (e.g., Ricotti, Gnedin & Shull 2001, 2002a, b; see also Ahn & Shapiro 2006). The former possibility has recently received considerable attention (Oh & Haiman 2003; Nagakura & Omukai 2005; O'Shea et al. 2005; Johnson & Bromm 2006). O'Shea et al. (2005) have reported that second-generation star formation could have occurred in the ionized minihaloes neighbouring the first stars, owing to the formation of H2 molecules in the recombinating primordial gas (see Shapiro & Kang 1987; Ferrara 1998; Ricotti et al. 2001, 2002a, b). However, Alvarez et al. (2006) find that neighbouring minihaloes are self-shielded to the ionizing radiation of the first stars, and thus that star formation in neighbouring minihaloes may not, in fact, have been significantly enhanced. Also, it has been shown that the activation of cooling by deuterium hydride (HD) molecules inside relic HII regions may provide an avenue for the formation of Population II.5 (Pop II.5) stars, with masses of the order of 10 M⊙ and formed from strongly ionized primordial gas (Mackey, Bromm & Hernquist 2003; Johnson & Bromm 2006; see also Nagakura & Omukai 2005). However, it remains to fully elucidate the formation process of Population II.5 stars within the first relic HII regions if, indeed, the radiation from the first stars evacuates the gas contained in their parent haloes and, yet, does not substantially ionize the gas in its neighbouring minihaloes.

Here we present the results of three-dimensional numerical simulations of the recombination of the first relic HII regions, investigating the possibility of Population II.5 star formation in such regions. We assume, for this case, the first star to have a mass of 100 M⊙ and to collapse directly to a black hole. Additionally, we simulate the merger of this parent halo with a neighbouring neutral minihalo which has not yet experienced star formation, in order to determine the necessary conditions for the black hole to begin accreting gas at the Eddington limit, and so to grow to a mass of 10^9 M⊙ by a redshift of z ~ 6. In future work, we will study the feedback from a pair-instability supernova, the other possible fate predicted for single primordial stars with masses > 100 M⊙ (e.g., Rakavy & Shaviv 1967; Bond et al. 1984; Heger et al. 2003). The details of our numerical methodology are given in Section 2. The results of our simulations of the recombination of the relic HII region appear in Section 3. Our results from the simulation of the merging of the relic HII region with a pre-collapse halo are presented in Section 4, while the implications of these results for the growth of the remnant black hole appear in Section 5. Finally, in Section 6 we summarize our results and present our conclusions.

2 METHODOLOGY

2.1 Chemical network

We employ the parallel version of the GADGET code for our three-dimensional numerical simulations. This code includes a tree, hierarchical gravity solver combined with the smoothed particle hydrodynamics (SPH) method for tracking the evolution of the gas density, ionization fronts, and star formation. However, the chemical network is quite complex, and we have included many species, such as H, H+, H2, D, D+, D2, HD, HD+, He, He+, and He++. In this paper, we focus on the study of Population II.5 stars, which are expected to form in the ionized minihaloes of the first stars (Springel, Yoshida & White 2001). Along with H2, H2+, H, H+, He, He+ and He++, we have included the five deuterium species D, D2, D+, D2+, HD and HD+, using the same chemical network as in Johnson & Bromm (2006).

As a test of the reliability of the chemical network incorporated into GADGET, we have simulated the idealized case of the homologous collapse of a ~ 10^6 M⊙ spherical cloud with an initial uniform density of n_e ~ 2 cm^-3. The chemical species are initialized with their primordial abundances, as given in Galli & Palla (1998). The temperature of the gas, initially a uniform 200 K, was chosen so that there would be little pressure support of the gas against gravitational collapse, allowing the cloud to collapse essentially in free fall. We then followed the thermal and chemical evolution of the gas near the centre of the sphere, where the density profile is approximately flat. We compare our simulation results with those obtained from the one-zone model, employed in previous work (see Johnson & Bromm 2006). In this one-zone calculation, a cloud of uniform density collapses homologously under its own gravity, its density evolving according to

\[ \frac{dn}{dt} = \frac{3}{2} (24\pi G \mu m_\text{H})^{1/2} n^{3/2} \left[ 1 - \left( \frac{n_i}{n} \right)^{1/3} \right]^{1/2}, \]

where n is the density at time t after the onset of the collapse, m_\text{H} is the mass of the hydrogen atom, and \mu is the mean molecular weight. Fig. 1 shows a comparison of the evolution of the density and of the abundances of H2, HD, and free electrons found from our GADGET simulation with that found from the calculation using our one-zone model. The agreement is very good, giving us confidence in the accuracy of our chemical network.

2.2 First ionizing source

The initial conditions for our three-dimensional SPH calculation are given by a cosmological simulation of high-z structure formation that evolves both the DM and baryonic components, initialized...
The properties of the primordial gas in the minihalo identified to host the first star, as functions of distance from the centre. The values shown for the central density, temperature, $e^-$ fraction and $H_2$ fraction are very close to the canonical values generally found in simulations of Population III star formation (e.g. Bromm & Larson 2004).

According to the Lambda cold dark matter (ACDM) model at $z = 100$, in carrying out the cosmological simulation used in this study, we adopt the same parameters as in earlier work (Bromm, Yoshida & Hernquist 2003). We thus use a periodic box of size $L = 100 h^{-1}$ kpc comoving and a number of particles $N_{DM} = N_{SPH} = 128^3$. The SPH particle mass here is $\sim 8 M_\odot$.

We identified the first SPH particle to achieve a density above $10^{15.5} \text{ cm}^{-3}$ within our cosmological box at $z \sim 19.5$, finding it at the centre of a minihalo with a total mass of $\sim 10^6 M_\odot$. Fig. 2 presents the properties of the primordial gas as a function of distance from the minihalo centre. The gas temperature rises as particles are adiabatically heated as they fall into the potential well of the halo, and then drops nearer the centre of the halo where the $H_2$ fraction rises to $\sim 10^{-3.4}$ and molecular cooling can thus efficiently cool the gas to $\sim 200 \text{ K}$ (e.g. Bromm & Larson 2004).

Having identified the location of the first star, we placed a point source of ionizing radiation at that location in our cosmological box. This was affected by including the following heating rates and ionization rate coefficients in our calculations of the thermal and chemical evolution of the gas:

$$\Gamma_{H_\alpha} = n_{H_\alpha} \frac{8.23 \times 10^{-18}}{r^2} \text{ erg cm}^{-3} \text{ s}^{-1},$$

$$\Gamma_{HeI} = n_{HeI} \frac{1.9 \times 10^{-17}}{r^2} \text{ erg cm}^{-3} \text{ s}^{-1},$$

$$\Gamma_{HeII} = n_{HeII} \frac{3.16 \times 10^{-19}}{r^2} \text{ erg cm}^{-3} \text{ s}^{-1},$$

$$k_{HeI} = \frac{8.96 \times 10^{-7}}{r^2} \text{ s}^{-1},$$

$$k_{HeII} = \frac{1.54 \times 10^{-6}}{r^2} \text{ s}^{-1},$$

$$k_{HeIII} = \frac{2.72 \times 10^{-8}}{r^2} \text{ s}^{-1},$$

where $r$ is the distance from the star in pc, and the subscripts denote the chemical species subject to photoionization and photoheating. These heating rates and ionization coefficients are derived from the models given in Schaerer (2002) for the case of a $\sim 100 M_\odot$ Population III star, assuming the stars emit a blackbody spectrum (see also Bromm, Kudritzki & Loeb 2001). We also carried out a simulation of the ionization and heating of the gas assuming a stellar mass of $200 M_\odot$, and the resulting density, temperature and radial velocity profiles around the central ionizing source, for each case, are shown in Fig. 3. The profiles show the situation after 3 and 2 Myr of photoheating and photoionization, for the 100 and 200 $M_\odot$ cases, respectively (see e.g. Schaerer 2002). The higher effective temperature and luminosity of the 200 $M_\odot$ star result in both a harder spectrum and more ionizing photons, and so in a higher heating rate of the surrounding gas from photoionization. Thus, as can be seen in Fig. 3, the temperature of the gas at a given distance from the central source is at least several $\sim 10^4$ K higher for the case of the 200 $M_\odot$ star than for that of the 100 $M_\odot$ star. Also, due to the shorter lifetime of the 200 $M_\odot$ star, the shock that arises from the steep temperature and density gradients encountered during the photoheating of the gas has not moved as far out from the central star for the 200 $M_\odot$ case, although the shock velocity is higher in this case.

Although we neglect the detailed radiative transfer of the ionizing photons here, we succeed at reproducing the basic features of the temperature and density profiles of the gas around the ionizing source that have been found in previous radiative transfer calculations (Kitayama et al. 2004; Whalen et al. 2004; Alvarez et al. 2006). Also, we heat and ionize the gas only within 500 pc of the central source, which is roughly consistent with an inhomogeneously ionized region around the first star of the order of $\sim 1$ kpc, as found.
by Alvarez et al. (2006), without impinging on neighbouring minihaloes in our cosmological box. We require that our H II region not encompass any neighbouring minihaloes because these can be self-shielded to ionizing radiation even if they reside inside the H II region, and so we cannot accurately follow the chemical evolution of the gas inside those minihaloes while the central ionizing source is on. Since we do not explicitly follow the propagation of the ionization front with time, we also do not resolve the time-dependent effects on the chemistry and thermal evolution of the gas that can give rise to, for instance, the formation of shells of H II molecules just outside the I-front (see Ricotti et al. 2001, 2002a,b). Despite the inability of our method to capture the detailed structure of the H II region, we do expect that we can capture the essential chemical and thermal evolution of the relic H II region as a whole in our simulations, as it expands, cools and recombines after we remove the central source from the calculation.

We used the version of GADGET which integrates the entropy equation for our photoionization calculation, as we also do later for our simulations of the relic H II region. As opposed to the integration of the energy equation, this formulation of GADGET conserves both energy and entropy and is much more successful at resolving the thermal evolution of gas that experiences shocks or strong local energy injection (Springel & Hernquist 2002).

### 2.3 Recombination and molecule formation

With the formation of a black hole by direct collapse of the 100 $M_\odot$ Population III star, the relic H II region left behind begins to recombine and cool. We implement this by simply setting the photoionization coefficients and heating rates to zero, for the case of the 100 $M_\odot$ central star. Thus, the temperature, density and radial velocity profiles shown in Fig. 3 are the initial conditions for our simulation of the relic H II region. We follow the thermal and chemical evolution of the relic H II region for $\sim$100 Myr, considering in particular the production of molecules and the cooling of the primordial gas.

#### 2.3.1 Photodissociation of molecules

Molecular hydrogen can easily be dissociated by absorption of Lyman–Werner (LW) photons with energies between 11.2 and 13.6 eV (e.g. Haiman, Rees & Loeb 1997; Bromm & Larson 2004, and references therein). Although it is well established that an external LW background could be produced by stars born in neighbouring minihaloes (e.g. Haiman et al. 1997; Ciardi et al. 2000; Haiman, Abel & Rees 2000; Machacek, Bryan & Abel 2001), we assume that at the death of our first star a negligible ultraviolet background has been established by emission from stars elsewhere in the Universe. Thus, to evaluate the effect that photodissociation has on the molecule fraction in the first relic H II region, we consider as the only source of dissociating radiation two-photon emission from the $2^1S \rightarrow 1^1S$ transition in recombining helium atoms from within the relic H II region itself (Johnson & Bromm 2006). Given the much larger Einstein A coefficient for two-photon emission from $2^1S$ than from $2^3S$, 51.3 s$^{-1}$ for the $2^3S \rightarrow 1^3S$ transition versus $2.2 \times 10^5$ s$^{-1}$ for the $2^1S \rightarrow 1^1S$ transition, this should be a sound approximation (Mathis 1957; Osterbrock & Ferland 2006).

To include a prescription for the photodissociation rates of H$_2$ and HD in our code, we assume for simplicity that the relic H II region is spherically symmetric and that it is optically thin to the LW photons. With this latter assumption, we obtain an upper limit for the dissociation rate, as the molecule fraction can approach $10^{-3}$ in relic primordial H II regions, which may lead to an appreciable optical depth to LW photons (see e.g. Ricotti et al. 2001; Oh & Haiman 2003; Kuhlen & Madau 2005; O’Shea et al. 2005). We estimate the total number of He recombinations, He$^+ + e^- \rightarrow$ He + h$v$, per second within the H II region that lead to population of the $2^1S$ state, $Q_{2^1S}^t$, according to

$$Q_{2^1S}^t \approx \frac{\alpha_B n_e n_{HeII} m_{SPH}}{3 \mu m_{HeII}},$$

(8)

where the sum is over all SPH particles in the H II region. Here $n_e$ is the number density of free electrons, $n_{HeII}$ is the number density of He II, $n$ is the total number density, $m_{SPH}$ is the mass per SPH particle, $\mu$ is the mean molecular weight and $\alpha_B$ is the Case B total He recombination coefficient to singlet states. We take it that $Q_{2^1S}^t \lesssim 1/3$ of the recombinations to the singlet levels of He I result ultimately in population of the $2^1S$ state, which is accounted for by the factor of 1/3 in the above formula (see Pottasch 1961; Osterbrock & Ferland 2006). For the LW flux at the edge of the H II region, we find

$$J_{LW} \sim 10^{-6} \frac{Q_{2^1S}^t}{4\pi R^2},$$

(9)

where $R$ is the radius (in cm) of the He II region, $J_{LW}$ is the LW flux in units of $10^{-21}$ erg s$^{-1}$ cm$^{-2}$ Hz$^{-1}$ sr$^{-1}$, and we have conservatively estimated the probability of LW photon emission per two-photon transition $2^1S \rightarrow 1^1S$ as $\lesssim 0.4$ (see Osterbrock & Ferland 2006). We compute the time-scale for the photodissociation of H$_2$ and HD as

$$t_{diss} \sim 10^8 \text{yr} \left( \frac{Q_{2^1S}^t}{10^{45} \text{s}^{-1}} \right)^{-1},$$

(10)

where we have taken $R \sim 500$ pc and used $t_{diss} \sim 10^8 \text{yr} (J_{LW}/10^{-4} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ Hz}^{-1} \text{ sr}^{-1})^{-1}$ (see Oh & Haiman 2003; Johnson & Bromm 2006). Inverting this time-scale, we find a typical rate for the dissociation of H$_2$ and HD of

$$k_{diss} \sim 10^{-16} \text{s}^{-1} \left( \frac{Q_{2^1S}^t}{10^{45} \text{s}^{-1}} \right)^{-1},$$

(11)

which is included in the calculation of the molecule fraction in our simulations.

To give an estimate of the importance of the dissociation of molecules due to two-photon emission, we calculate $t_{diss}$ for the simplified case of a spherical recombining H II region of uniform density. In this case, we have the total number of recombinations to He I which ultimately result in the $2^1S$ state given by

$$Q_{2^1S}^t \sim \frac{4\pi}{9} R^2 n_e n_{HeII} \left( \frac{R}{500 \text{ pc}} \right)^3 \left( \frac{n_{HeII}}{\text{cm}^{-6}} \right).$$

(12)

Using equation (10), we find

$$t_{diss} \sim 10^3 \text{ yr} \left( \frac{n_{HeII}}{\text{cm}^{-6}} \right)^{-1},$$

(13)

which clearly shows that at high densities and at times when He recombination is still ongoing, the photodissociation of any molecules that have formed may be important, even in the absence of an externally generated LW background. However, for our case of a relic H II region surrounding a minihalo, since it is predominantly at lower temperatures ($\lesssim 5000$ K) that molecules are formed, at which times much of the H II has already recombined, and since our H II region is expanding to lower densities with time, we expect that dissociation of molecules due to two-photon emission will be unimportant, at least during the later evolutionary stages.
Molecular hydrogen could also be dissociated by radiation generated during the accretion of gas on to the remnant black hole. However, as we show in Section 5, we find that the accretion rate on to the black hole is low, comparable to that found by O’Shea et al. (2005), for at least a few 10 Myr after the collapse of the central ionizing star. O’Shea et al. estimate that this accretion rate results in a photodissociation rate of $H_2$ which is at least an order of magnitude below the formation rate of $H_2$ in the relic H II region. We thus neglect the possible effects of photodissociating radiation due to accretion on to the remnant MBH.

2.4 Merging minihaloes

In order to determine which, and how quickly, neighbouring minihaloes will collapse following the formation of a Population III remnant black hole, we consider the situation in which the relic H II region surrounding the remnant black hole merges with a neighbouring DM halo and its accompanying, ionized and dense gas component. Since we are simulating the evolution of the relic H II region and the infalling neutral minihalo after the death of the Population III star, in these merger simulations we do not include any photoheating or photodissociating terms in our calculations of the thermal and chemical history of the gas. We initiate the merger by placing the spherical relic H II region, immediately following the collapse of the central star, with properties shown in Fig. 3, adjacent to a second spherical region of radius 500 pc at the centre of which is a minihalo which is still neutral, not yet having hosted star formation. The region containing the neutral minihalo is selected and cut out from elsewhere in the same cosmological box, and is then placed adjacent to the relic H II region in a new, otherwise empty simulation box. The initial separation between the centres of the two minihaloes is 1 kpc proper for all merger simulations carried out here.

The reason why we must choose these initial conditions, and why we may not simply continue running our cosmological simulation of the relic H II region and wait for a merger to occur, is that we are limited by the size of the cosmological box. Our box size is $\sim 100 h^{-1}$ kpc, which is too small to contain the large wavelength density modes that drive the mergers of minihaloes. Thus, we carry out the mergers in an empty box, imparting a relative velocity of $8 \text{ km s}^{-1}$ to the merging haloes, comparable to the virial velocity of the resulting system, setting them on trajectories for a direct collision.

We assume that the molecules in the infalling, pre-collapse halo have been destroyed by the $H_2$ photodissociating LW flux from the nearby Population III star which has formed the relic H II region. We carry out simulations in which the neighbouring halo has peak gas densities of $0.1, 1, 10$ and $100 \text{ cm}^{-3}$, corresponding to different degrees of pre-collapse. In the case of the $0.1 \text{ cm}^{-3}$ peak density neighbouring halo, the free-fall time will be comparable to the timescale for the completion of the merger and so we can neglect the possibility of this minihalo collapsing to form a star before the completion of the merger. However, given that we assume that there are no molecules in the neighbouring halo at the outset of the merger, we expect that collapse will be delayed even for the higher density cases, as cooling will be suppressed until molecules have reformed (see Mesinger, Bryan & Haiman 2006).

Although the initial conditions for these simulations are idealized, as we have not followed the merger of the haloes in a fully cosmological context but instead in a box containing only the relic H II region and the infalling minihalo, we are able to discern the crucial aspects in the thermal and chemical evolution of the gas in the vicinity of the remnant Population III black hole. We do note, however, that additional effects that we do not consider here, such as the formation of an $H_2$ shell and the driving of a shock through a partially ionized minihalo, can become important for cases in which significant portions of the infalling minihalo are ionized (see Ahn & Shapiro 2006). A more sophisticated treatment of radiative transfer will be required to more accurately follow the evolution of the gas (see Ahn & Shapiro 2006; Susa & Umemura 2006).

3 EVOLUTION OF PRIMORDIAL GAS IN RELIC H II REGIONS

The results of our recombination simulation are presented in Fig. 4 at three representative times after the death of the central star. As can be seen in the panels showing the temperature as a function of the density, the gas initially cools largely by adiabatic expansion, as at temperatures below $\sim 10^{4}$ K the gas closely follows the adiabatic relation $T \propto n^{\frac{4}{3}}$, delineated in the panels on the right-hand side. As the gas recombines, the cooling rate due to collisional excitation of the newly formed hydrogen atoms is enhanced and the temperature of the gas drops to $\sim 10^{3}$ K, at which point the cooling rate decreases when molecular hydrogen becomes the main coolant, aside from adiabatic cooling, which continues as the gas expands into the intergalactic medium (IGM).

The HD fraction in the highest density regions of the recombinating gas increases to $X_{\text{HD}} \sim 10^{-7}$ after $\sim 10$ Myr since the death of the central star, and to $X_{\text{HD}} \sim 10^{-6}$ after 100 Myr. Thus, the HD fraction quickly rises above the critical value of $X_{\text{HD, crit}} \sim 10^{-8}$ for efficient cooling of primordial gas in local thermodynamic equilibrium (LTE) to the temperature of the cosmic microwave background (CMB) (see Johnson & Bromm 2006). Because LTE can only be achieved at much higher densities than those that persist in the relic H II region we consider here, radiative cooling to the CMB floor would only be a viable possibility if densities are somehow increased to the point that LTE can be established. This would happen if the gas is at some point incorporated into a larger DM halo and becomes gravitationally bound once more. That the HD fraction is so high, however, means that the potential for Population II.5 star formation does exist, in principle, if the gas becomes gravitationally bound and thus available for star formation (see also Nagakura & Omukai 2005).

We evaluate the recombination time after 100 Myr by taking the density of $H^+$ and of free electrons to be $n_{H^+} \sim n_e \sim 10^{-4} \text{ cm}^{-3}$, as can be seen from the lower left-hand panel of Fig. 4. Then, assuming at these low densities a Case A recombination coefficient of $\alpha_A \sim 6 \times 10^{-13} \text{ cm}^3 \text{s}^{-1}$, we obtain a recombination time of $t_{\text{rec}} \sim 500$ Myr. This is more than twice the Hubble time at these redshifts, and suggests that the free electron fraction left over from the ionization caused by the first stars may have remained an important catalyst for molecule formation even after hundreds of millions of years since the death of the central star (see e.g. Shapiro & Kang 1987; Yamada & Nishi 1998; Nagakura & Omukai 2005; O’Shea et al. 2005).

The optical depth to LW photons becomes unity for $H_2$ column densities of $10^{19} \text{ cm}^{-2}$ (e.g. Draine & Bertoldi 1996; Osterbrock & Ferland 2006), and for our relic H II region we estimate

$$\tau_{\text{LW}} \sim \frac{n_{H_2}X_{H_2}R}{10^{14} \text{ cm}^2}.$$  

(14)

where $X_{H_2}$ is the molecule fraction, $R$ is the radius of the relic H II region and $n_{H_2}$ is the number density of hydrogen nuclei. We find that the molecule fraction approaches $X_{H_2} \sim 10^{-3}$ and that the number density becomes $n_{H_2} \sim 10^{-3} \text{ cm}^{-3}$. Taking the radius of the H II region...
Figure 4. The evolution of the relic H II region. From left to right, the panels show the free electron fraction, the H$_2$ fraction, the HD fraction and the temperature as functions of density at $\sim$1 Myr (top row), $\sim$10 Myr (middle row) and $\sim$100 Myr (bottom row) after the collapse of the central star to a black hole. The long dashed line in the rightmost panels denotes the temperature of the cosmic background radiation, $T_{\text{CMB}}$, while the short dashed line denotes the line $T \propto n^{2/3}$, along which gas evolves adiabatically. Here, we plot only the SPH particles that were subjected to the photoionizing radiation of the central star, that is, particles within $\sim$500 pc of the central star.

region to be $\sim$1 kpc, we find that the optical depth to LW photons becomes of the order of $\tau_{\text{LW}} \sim 10$. If the density of star-forming minihaloes is thus high enough, an appreciable suppression of the background LW flux may result from the high molecule fraction which arises in relic H II regions. This may provide an important degree of shielding from molecule-dissociating radiation and may lead to a higher overall efficiency of star formation in minihaloes with virial temperatures $\lesssim 10^4$ K (see Machacek et al. 2001; Ricotti et al. 2001; Oh & Haiman 2002; Machacek, Bryan & Abel 2003).

We carried out simulations both with and without the photodissociating two-photon emission from recombining He II included, and we found that this photodissociating radiation had little effect on the molecule abundances. To estimate the level of LW background radiation necessary to efficiently photodissociate H$_2$ molecules, we evaluate the H$_2$ formation time-scale at $\sim$10 Myr after the death of the central star. Taking representative values for the temperature, number density and abundances of the chemical species after 10 Myr of recombination, we find a formation time-scale for H$_2$ of $t_{\text{form}} \sim 10^7$ yr. The continued formation of H$_2$ is driven by the high abundances of H, H$^-$ and e$^-$, which are the reactants in the following reaction sequence that is the most important for the production of H$_2$ (e.g. Kang & Shapiro 1992):

$$\text{H} + \text{e}^- \rightarrow \text{H}^- + h\nu,$$

$$\text{H} + \text{H}^- \rightarrow \text{H}_2 + \text{e}^-.$$  \hspace{1cm} (15)  \hspace{1cm} (16)

Equating the formation time-scale for H$_2$ with the dissociation time-scale for H$_2$, given by $t_{\text{diss}} \sim 10^8$ yr ($J_{\text{LW}}/10^{-4}$)$^{-1}$, we find a critical value for the background LW flux, below which molecules in the relic H II region will not be photodissociated efficiently, of the order of $J_{\text{LW, crit}} \sim 10^{-3}$ (see also Oh & Haiman 2003). This is comparable to the background LW flux that is expected to have been established by the first generations of stars at redshifts $z \gtrsim 15$ (e.g. Greif & Bromm 2006). Taking into account the optical depth to LW photons of the order of $\tau_{\text{LW}} \sim 10$, we find that the most heavily self-shielded molecules in the centre of relic H II region could only be dissociated by a background LW flux, emanating from outside the relic H II region, at least of the order of $J_{\text{LW, crit}} \sim 10^{-3}$. This value would, however, decrease with time if the molecules nearer to the periphery of the relic H II region were dissociated by the external LW background flux, and so become unavailable for shielding the inner molecules from the dissociating radiation. We note also that if the gas in the relic H II region has large velocity gradients, owing to turbulence that we do not resolve in these simulations, then the optical depth to LW photons may be lower than the value we find here by a factor of a few (see Draine & Bertoldi 1996; Osterbrock & Ferland 2006). This would not, however, affect the value that we find for $J_{\text{LW, crit}}$, as this is independent of the optical depth to LW photons.

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The values that we find for $J_{\lambda_{\text{Lyman}}, \text{cri}}$ and for $\tau_{\text{Lyman}}$ suggest that the enhanced fractions of H$_2$ and HD inside relic H II regions could have persisted down to at least redshifts of $z \sim 15$, and so, in principle, would have been available for star formation at least down to these redshifts (see also Ricotti et al. 2002a). The high HD abundance, which becomes at least an order of magnitude above the critical abundance for cooling the primordial gas to the CMB temperature floor, could thus have led to Population II,5 star formation inside the first relic H II regions, if these regions became incorporated into more massive DM haloes that could gravitationally bind, and so increase the density of, the recombinating primordial gas.

4 EVOLUTION OF PRIMORDIAL GAS IN MERGING MINIHALOES

To discern the conditions under which the Population III remnant black hole could efficiently accrete the dense, cold gas supplied by a neighbouring minihalo, we have tracked the evolution of the gas in such merging systems with a range of initial peak densities of the gas within the infalling neutral minihalo. Again, here we have assumed that the LW flux from the now-collapsed Population III star has destroyed all of the molecules inside the neutral infalling halo, although molecules can reform during the merger, since there is no longer a LW flux from the original Population III star. The initial peak densities of the haloes we follow are 0.1, 1, 10 and $10^2$ cm$^{-3}$. Fig. 5 shows the evolution of the density structure in the merger between the relic H II region and a halo with a peak density of 10 cm$^{-3}$, as a representative case.

Fig. 6 shows the time evolution of a merger of a relic H II region, in which the central star has just collapsed to form a black hole, with a neutral pre-collapse minihalo which has a peak density of 0.1 cm$^{-3}$ at the time of the formation of the black hole, at four representative times. As in the case of the recombination of the relic H II region evolved in our 100 h$^{-1}$ kpc cosmological box, which did not experience a merger, the relic H II region gas expands and cools largely adiabatically. This expansion is evident in Fig. 5 as well. Also, as can be seen from the temperature rise in the pre-collapse halo, shown in black in Fig. 6, the expansion of the relic H II region, combined with the 8 km s$^{-1}$ relative velocity of the infalling halo with respect to the relic H II region, shock-heats the neutral gas within the infalling halo, contributing to the suppression of the density in the pre-collapse halo. The gas in the pre-collapse halo, furthermore, does not reform H$_2$ molecules efficiently, owing to the low density of the gas in this halo. The H$_2$ fraction stays below $10^{-6}$ for the entire 100-Myr duration of the merger, further preventing the gas from cooling and collapsing to higher densities.

Figure 5. The merging of the relic H II region with a neutral neighbouring minihalo with an initial central density of $\sim 10$ cm$^{-3}$. The H II region is on the right-hand side of the top left-hand panel at the beginning of the merger, while the pre-collapse halo with which it merges is on the left-hand side. The location of the remnant black hole, initially at the centre of the relic H II region, is shown by the black square in each panel. Here, we assume that the black hole has a ballistic trajectory, with a constant velocity of 4 km s$^{-1}$ to the left, equal to the initial velocity of the relic H II region. The highest density gas is shown in white and the lower density gas is shown in blue. The merger is shown at 1 Myr (top left-hand panel), 10 Myr (top right-hand panel), 50 Myr (bottom left-hand panel) and 100 Myr (bottom right-hand panel) after the death of the central star. The halo shown on the left-hand side collapses to a density of $\sim 10^3$ cm$^{-3}$ during the merger (see Fig. 7).
velocity, as can be seen in Fig. 3, and taking \( n_{\text{th}} \sim 10^{-2} \text{ cm}^{-3} \) as a typical value for the density of the relic H II region, as can be seen in Fig. 4, we find the following condition for the retention of the neutral gas in the potential well of the infalling halo:
\[
n_{\text{gas}} T \gtrsim 10^5 \text{ K cm}^{-3}.
\] (17)

The condition in equation (17) can be satisfied for primordial gas collapsing in a minihalo with a mass of \( \sim 10^6 \text{ M}_\odot \), provided that densities of at least \( n \sim 10^{-0.5} \text{ cm}^{-3} \) have been reached prior to the merger [see fig. 10 in Bromm et al. (2002)].

However, if the gas in the infalling minihalo collapses to form a star before the completion of the merger, then the gas in the minihalo will be heated and expand to lower densities, as shown in Fig. 3 (see also Abel, Wise & Bryan 2006). This final collapse to form a star will occur on the order of the free-fall time, \( t_{\text{ff}} \propto n^{-1/2} \), if the free-fall time is longer than the cooling time (e.g. Tegmark et al. 1997; Ciardi & Ferrara 2005). If the gas cannot cool efficiently, however, this collapse will be delayed. This may indeed be the case in regions near the first stars where the LW flux generated during their \( \lesssim 3 \text{ Myr} \) lives could destroy the H$_2$ molecules inside the pre-collapse haloes, depriving them of the coolants that allow for star formation (e.g. Yoshida et al. 2003).

To find the highest densities that could be achieved during a merger of a neutral minihalo with a relic H II region, we compare the time-scale for completion of the merger, \( t_{\text{merge}} \), with the time-scale for the collapse of the neutral minihalo, \( t_{\text{collapse}} \), the latter found from our simulations of mergers involving minihaloes with peak densities of 1, 10 and \( 10^2 \text{ cm}^{-3} \) at the time of the formation of the black hole and the cessation of the radiation from the original Population III star. For each of these initial densities, the criterion given by equation (17) for neutral gas retention is satisfied. Cases for which \( t_{\text{merge}} \gtrsim t_{\text{collapse}} \) will give rise to mergers resulting in the highest densities of gas that can be accreted on to the black hole, as it is these minihaloes that will merge completely with the black hole before collapsing to form a second star. We define the merger time-scale as
\[
t_{\text{merge}} \sim \int_0^{r_{\text{MBH}}} \frac{dr}{2GM_{\text{halo}} \left( \frac{1}{r_{\text{MBH}}} - \frac{1}{r_{\text{H}}} \right)^{1/2}},
\] (18)

where \( r_{\text{MBH}} \) is the initial distance between the centres of the merging haloes at the time of the formation of the MBH in the relic H II region and \( M_{\text{halo}} \sim 10^6 \text{ M}_\odot \). We note, however, that this is only an approximation to the actual time that would be required for a merger to take place, as this formula assumes that the merging minihaloes start at rest with respect to each other at the time of the collapse of the first star, and this will not be the case in general (see e.g. Abel et al. 2006).

Fig. 7 shows the time evolution for a merger with a neutral peak density of \( 10 \text{ cm}^{-3} \), at four representative times, just as in Fig. 6. The gas in the pre-collapse halo, in this case, does reform H$_2$ molecules efficiently, owing to the high density of the gas in this halo. The H$_2$ fraction approaches \( \sim 10^{-3} \) after \( 100 \text{ Myr} \). Thus, gas cooling is efficient, and the density reaches \( n \sim 10^3 \text{ cm}^{-3} \) after \( \sim 100 \text{ Myr} \). Fig. 5 shows the evolution of the gas density structure in this merger, at the four representative times which are also shown in Fig. 7.

For the case of a merger with an initial peak density of \( 1 \text{ cm}^{-3} \), we find that the H$_2$ fraction becomes only of the order of \( 10^{-2} \), and the density in this minihalo thus does not increase beyond \( \sim 1 \text{ cm}^{-3} \) within \( 100 \text{ Myr} \), since molecular cooling is suppressed. We also find that for the case of a merging minihalo with an initial density

![Figure 7](https://academic.oup.com/mnras/article-abstract/374/4/1557/964615)

**Figure 7.** Same as in Fig. 6, except that the neutral gas has an initial peak density of \( \sim 10 \text{ cm}^{-3} \). The criterion in equation (17) for neutral gas retention is satisfied here, and the densest gas, in the centre of the infalling minihalo, retains its high density despite the outer layers of gas being shock-heated in the merger. Also, the H$_2$ fraction approaches \( 10^{-3} \) after \( 100 \text{ Myr} \) at these higher densities, so that the gas in the merging halo cools and collapses efficiently to a density of \( \sim 10^3 \text{ cm}^{-3} \). As the labels indicate, the four panels correspond to the same times since the death of the central star as the four panels in Fig. 5, which shows the evolution of the projected gas density.

of \( 100 \text{ cm}^{-3} \) the H$_2$ fraction becomes \( \sim 10^{-3} \) and the halo collapses after \( \sim 60 \text{ Myr} \). As expected, for higher initial peak densities in the infalling haloes, the time-scales for the collapse of these haloes become shorter, both because H$_2$ molecules are reformed more quickly and because the free-fall time is shorter for denser haloes (see also Mesinger et al. 2006).

Fig. 8 shows the requirements for infalling minihaloes to collapse to high densities on a time-scale that is longer than the time-scale
for their merging with a black hole inside a relic H II region. These infalling minihaloes, which have $t_{\text{merge}} \lesssim t_{\text{collapse}}$, are those that will contain high-density gas ($\gtrsim 10^2$ cm$^{-3}$) at the completion of the merger, which can lead to efficient accretion on to the black hole. As can be seen in Fig. 8, at the time of the death of the original Population III star, these minihaloes have densities $\gtrsim 10$ cm$^{-3}$ and lie within $r_{\text{MBH}} \sim 340$ pc of the halo hosting the first Population III star. Higher densities than this could be achieved, within a merger time-scale of the order of $\sim 100$ Myr and without forming a second star, in mergers with minihaloes that have initial densities of the order of $10^3$ cm$^{-3}$ only if the time-scale for completion of the merger is $t_{\text{merge}} \lesssim 60$ Myr, the time in which a $10^3$ cm$^{-3}$ peak density halo would collapse to form a star. As Fig. 8 shows, this would demand that such a dense minihalo be within $r_{\text{MBH}} \sim 240$ pc of the halo hosting the first Population III star at the time that this first Population III star collapses to form a black hole. Such minihaloes would lie well within the H II region of the Population III star and so may be strongly heated and partially ionized. However, the gas in such a halo is expected to remain neutral at densities $n \gtrsim 2$ cm$^{-3}$ (Alvarez et al. 2006; see also Abel et al. 2006; Susa & Umemura 2006), which justifies the assumption that we use in our simulations of neutral neighbouring minihaloes adjacent to the minihalo hosting the first Population III star, for haloes containing gas at densities $\gtrsim 10$ cm$^{-3}$.

5 BLACK HOLE ACCRETION AND FEEDBACK

In order for a black hole with a mass of $\sim 100 M_\odot$, such as may have been formed from the direct collapse of a Population III star at $z \sim 20$ (e.g. Heger et al. 2003), to attain a mass of $\sim 10^8 M_\odot$, such as have been inferred for the black holes that power quasars at $z \gtrsim 6$, an average accretion rate of $\gtrsim 1 M_\odot$ yr$^{-1}$ is required. Here we analytically estimate the accretion rate of a black hole that begins with a mass $m_i$, the resulting mass of the black hole $m$ as a function of time $t$ since its formation, and the luminosity that would be produced in the process of this accretion as a function of time, for a given density and temperature of accreted gas. We assume that the black hole accretes gas from a cloud with uniform density and temperature and with dimensions much greater than the accretion radius of the black hole, $r_{\text{acc}} \sim Gm/c_s^2$, where $c_s$ is the speed of sound in the gas. In this case, we can estimate the Bondi accretion rate as (Bondi 1952)

$$m_B \sim \frac{2\pi G(m)^2 m_B}{c_s^2}.$$  \hspace{1cm} (19)

Assuming that a fraction $\epsilon \simeq 0.1$ of the accreted mass is converted into energy and radiated away, so that the black hole grows according to $dm/dt \simeq (1 - \epsilon)m_B$, integrating from $t = 0$ and $m = m_i$ yields a time-dependent mass of the black hole of

$$m \sim \left[ \frac{1}{m_i} - \frac{2\pi(1 - \epsilon)m_i^2 G^2 n T^2}{(3kT)^2} \right]^{-1},$$  \hspace{1cm} (20)

where $T$ is the temperature of the gas at infinity and where we have used $c_s^2 = 3kT/m_i$.

Using equation (19) for the mass accretion rate, we compute the luminosity $L$ generated in the process of the black hole accreting mass, operating as a miniquasar, as

$$L = \frac{\epsilon}{1 - \epsilon} \frac{dm}{dt} c_s^2 = \frac{2\pi \epsilon G(m)^2 m_B c^2}{(1 - \epsilon)c_s^2}.$$  \hspace{1cm} (21)

where $c$ is the speed of light. Expressing this as a fraction of the Eddington luminosity of the black hole yields

$$L = \frac{\epsilon \sigma_T Gm c}{2(1 - \epsilon)c_s^3},$$  \hspace{1cm} (22)

where $\sigma_T$ is the Thomson cross-section. With equation (20), we thus find

$$L = \frac{\epsilon \sigma_T Gm c}{2(1 - \epsilon)(3kT)^2} \left[ \frac{1}{m_i} - \frac{2\pi(1 - \epsilon)m_i^2 G^2 n T^2}{(3kT)^2} \right]^{-1}.$$  \hspace{1cm} (23)

To use our analytical argument to estimate the early growth rate of the first black holes, we need to determine the densities and temperatures of the accreting gas. We can derive their typical range of values from our simulations of the thermal and dynamical evolution of the gas in the vicinity of the newly formed MBH (in Sections 3 and 4). We take it here that the accretion of DM particles contributes a negligible amount to the overall mass accretion rate, making the assumption that DM particles are collisionless. Consequently, DM particles within the virialized halo in which the black hole resides cannot lose angular momentum efficiently enough to fall into the MBH. If, however, DM particles were self-interacting and were thus not collisionless, the accretion of DM could enhance the growth of the black hole (see Hu et al. 2006).

We do not consider the effects of radiative feedback on the accretion rate of the black hole, although it has been shown that at high accretion rates the radiation emitted from quasars can inhibit further gas infall (see Di Matteo, Springel & Hernquist 2005; Springel, Di Matteo & Hernquist 2005). Indeed, radiative feedback from the accretion of matter on to the black hole may heat the accreting gas which surrounds the black hole to higher temperatures, which will in turn lower the accretion rate, as can be seen from equation (19). This assumption is partially justified by the low accretion rates and associated luminosities encountered in our simulations, although it is dependent on the uncertain efficiency with which the accreting gas may absorb the emitted radiation. We have also assumed that the black hole is not moving with respect to the accreting gas, as might be the case if the black hole receives a kick at its birth. These last two assumptions make our results for the accretion rates on to the black hole upper limits.

Finally, as for our assumption that the fraction of accreted mass that is converted to radiation, $\epsilon = 0.1$ will be an overestimate for accretion rates that are much below the Eddington accretion rate. In general, $\epsilon$ may be much lower, and so our results for the luminosity generated by the accretion on to black holes should also be considered upper limits.

Fig. 9 shows the mass of an initially 100 $M_\odot$ black hole as a function of time, using equation (20), for various densities of the accreting gas and assuming a temperature for the accreting gas of 200 K, which is the temperature of the highest density gas we find in our simulations of a relic H II region merging with a pre-collapse unionized minihalo. Also shown in Fig. 9 is the mass of the black hole as a function of time, assuming that it accretes at the Eddington limit at all times. This figure clearly shows that in order for a black hole with a mass of the order of $\sim 100 M_\odot$ to accrete at near the Eddington rate, it must accrete gas with a density $\gtrsim 10^2$ cm$^{-3}$. Since these densities are only found inside collapsing haloes, and are much higher than those of the gas in the expanding relic H II region around the black hole, for such a black hole to begin accreting at the Eddington rate it must merge with a minihalo that has a central density $\gtrsim 10^2$ cm$^{-3}$.
the collapse of a Population III star at a redshift at or near the Eddington limit starting shortly after its formation by a Population III remnant black hole may have led to accretion of gas with densities nearby pre-collapse minihaloes with a minihalo hosting a Population gas involved in the merger. This same time in the course of the merger. The accretion history of gas, residing in a region with a gas density of only $100 \text{ Myr}$, the remnant black hole accretes only much lower density gas, residing in a region with a gas density of only $10^{-2.5}\text{ cm}^{-3}$ at this same time in the course of the merger. The accretion history of a Population III remnant black hole thus sensitively depends on the location of that black hole, as well as on the highest densities of the gas involved in the merger.

One generic requirement for a Population III remnant black hole to accrete at the Eddington limit early enough to achieve a mass of $\sim 10^9 \text{ M}_\odot$ by $z \sim 6$ appears to be that it accrete the high-density gas within a merging pre-collapse minihalo which can lie only a few hundred parsecs from the black hole at the time of its formation, as Fig. 8 shows. Another requirement is that the peak density in this pre-collapse halo must be at least $n \sim 10 \text{ cm}^{-3}$ at the time when the original Population III star stops emitting LW photons and collapses to become a black hole, so that the density in this halo can rise to $\gtrsim 10^5 \text{ cm}^{-3}$. As Fig. 9 shows, this is the density that the accreted gas must have in order for accretion to take place at the Eddington limit for a black hole with a mass of the order of $100 \text{ M}_\odot$. If either of these requirements is not satisfied, and the black hole does not merge with a sufficiently dense or nearby minihalo, then the black hole will not begin accreting at the Eddington rate before it is incorporated into a larger halo that can gravitationally bind the hot gas in the relic HII region, and so begin to raise the density of this gas again. The time-scale for this to occur is $\sim 100 \text{ Myr}$ (see Yoshida 2006), which means that there would be a substantial delay of the order of the Hubble time at a redshift of $z \sim 30$ before a Population III relic black hole could begin efficiently accreting, unless it merges with a dense minihalo soon after its formation. Using equation (23), we find time-dependent luminosities of a miniquasar fuelled by a black hole remnant of a Population III star, expressed as a fraction of its Eddington luminosity, as shown in Fig. 10. Here we have assumed the same range of values for the density, and the same temperature, of the accreted gas as was assumed in Fig. 9. The same requirements for the black hole to begin accreting at the Eddington limit apply to the miniquasar, fuelled by accretion on to the black hole, to radiate at the Eddington luminosity. Thus, the Eddington luminosity will only be achieved within $\sim 100 \text{ Myr}$ for the case of a merger with a neighbouring pre-collapse halo with a central density above $\sim 10^3 \text{ cm}^{-3}$, and which lies within a few hundred parsecs from the black hole, at the time of the formation of the black hole. As Fig. 10 shows, black holes that do not accrete cold gas at densities $\gtrsim 10^2 \text{ cm}^{-3}$ will not radiate efficiently for well over a Hubble time at redshifts $z \gtrsim 20$. Therefore, it may be difficult for miniquasars to be strong ionizing sources which contribute substantially to the ionization at redshifts $z \gtrsim 15$, unless they are fuelled by the accretion of dense gas on to Population III seed black holes that merge with dense minihaloes soon after their formation (see Madau et al. 2004; Ricotti & Ostriker 2004; Kuhlen & Madau 2005). We note, however, that the number density of accreting black holes at these high redshifts is unknown, and if this number density...
is high enough then even inefficiently radiating miniquasars may be able to substantially reionize the Universe.

6 SUMMARY AND CONCLUSIONS

We have carried out three-dimensional numerical simulations of the evolution of the first relic H II regions and of the mergers of pre-collapse minihaloes with the minihaloes that host the first Population III remnant black holes at the centres of the first relic H II regions. Although the first Population III stars which form in minihaloes emit enough ionizing radiation to evacuate the primordial gas that resides in these haloes and to disperse it into the IGM, we find that the radiative feedback from the first stars, none the less, does have important effects that could help to foster continued star formation inside the relic H II regions that they leave behind. Namely, the recombination of these relic H II regions, due to their dynamical expansion, does not proceed to completion for over a Hubble time at the redshifts at which the first stars likely formed, \( z \gtrsim 20 \). The residual electron fraction that persists for long after the death of the central star in these regions allows for continued molecule formation, and thus high fractions of both \( \text{H}_2 \) and HD are produced.

Due to the large size of the first H II regions, of the order of a few kpc (e.g. Alvarez et al. 2006), and to the high \( \text{H}_2 \) fraction that is generated in the recombination of the ionized primordial gas after the death of the central star, of the order of \( 10^{-3} \), we find that shielding of molecules inside the first relic H II regions could have been significant, providing an optical depth to LW photons of the order of 10 (see also Haiman et al. 2000; Ricotti et al. 2001; Oh & Haiman 2002). With the effects of continued \( \text{H}_2 \) formation and of high optical depth to LW photons taken together, we have shown that molecules inside the first relic H II regions could have persisted at least down to redshifts of \( z \sim 15 \) before the background LW flux in the Universe grew strong enough to efficiently photodissociate \( \text{H}_2 \) in these regions. We have further shown that minihaloes with central densities of \( \gtrsim 10^2 \text{ cm}^{-3} \) that suffer complete destruction of \( \text{H}_2 \) molecules due to photodissociating flux from a Population III star can reform \( \text{H}_2 \) and collapse within 60 Myr after the death of the Population III star (see also Mesinger et al. 2006; Susa & Umemura 2006). Thus, second-generation Population III stars could have formed inside relic H II regions within minihaloes with central densities of at least this order of magnitude, and, furthermore, these sites of second-generation star formation could have been shielded from the background molecule-dissociating LW flux established by star formation elsewhere in the Universe.

In addition, we have shown that a very high fraction of HD molecules forms inside the first relic H II regions, reaching levels of the order of \( 10^{-7} \). As this fraction is well above the critical fraction of HD needed for efficient radiative cooling of the primordial gas to the temperature of the CMB, when this gas is in LTE, in principle, the first relic H II regions produce sufficient HD to allow the formation of Population II.5 stars. However, we emphasize that the primordial gas in the first relic H II regions must become gravitationally bound inside larger mass haloes in order for it to become dense enough to collapse and form stars, if indeed Population II.5 stars are to form inside these regions. Nagakura & Omukai (2005) investigate this possibility and find that stars could have formed from gas cooled by HD to temperatures \( \lesssim 100 \text{ K} \) inside haloes massive enough to bind dynamically expanding relic H II region gas. Three-dimensional numerical simulations of such larger mass systems are necessary to more reliably discern whether Population II.5 star formation can occur in the relic H II regions surrounding the first stars. Interestingly, recent three-dimensional radiation-hydrodynamics simulations reported by Yoshida (2006) suggest that the fragmentation scale of HD-enriched gas inside relic H II regions can become of the order of 10 M\(_{\odot}\), which corresponds to the characteristic mass expected for Population II.5 stars (Johnson & Bromm 2006).

The origin of the first SMBHs, which are observed to have masses of the order of 10\(^6\) M\(_{\odot}\) at \( z \sim 6 \), is an important and challenging question to address. In order for Population III remnant stellar black holes, with initial masses of the order of 100 M\(_{\odot}\) to grow to become the observed SMBHs, they must begin accreting at or near the Eddington rate very soon after their formation. Indeed, in order to explain the growth of SMBHs, much recent work draws on the assumption that this is the case (e.g. Li et al. 2006; Malbon et al. 2006). In particular, 100 and 500 M\(_{\odot}\) black holes must accrete at the Eddington limit for 800 and 700 Myr, respectively, in order to grow to 10\(^5\) M\(_{\odot}\). Additionally, recent work by Malbon et al. (2006) shows that it is indeed the accretion of gas that largely fuels the growth of MBHs at redshifts \( z \gtrsim 2 \), although at lower redshifts black hole mergers can become the dominant process for black hole growth. Because the radiation from the progenitor Population III stars which collapse to form such black holes evacuates the gas from their host haloes, mergers with neighbouring minihaloes must occur in order for the remnant black holes to accrete high enough density gas to accrete at or near the Eddington limit.

Our results indicate that there may have been a substantial time delay between MBH formation and the onset of efficient accretion in situations where Population III seed black holes do not merge with neighbouring neutral minihaloes with densities that are \( \gtrsim 10 \text{ cm}^{-3} \) at the time of black hole formation. In this case, efficient accretion cannot begin until the black hole is incorporated into a halo sufficiently massive to gravitationally bind the hot relic H II region gas (see Yoshida 2006), and this can take of the order of the Hubble time at \( z \sim 30 \), or \( \sim 100 \text{ Myr} \). It remains therefore an open question whether the SMBHs that power the \( z \gtrsim 6 \) quasars could have grown from stellar remnants, or whether more massive seed black holes were required (e.g. Bromm & Loeb 2003; Lodato & Natarajan 2006). More realistic, fully cosmological simulations which accurately track the dynamics and growth of accreting black holes over \( \sim 10^9 \text{ yr} \) will be required to further clarify the possible connection to the SMBHs observed at lower redshifts.

If the conditions we have found for accretion at the Eddington limit are not met, then the miniquasars fuelled by accretion on to the Population III remnant black holes will also not emit radiation at the Eddington limit until well after the formation of the black holes. This possibility of inefficient accretion on to these black holes has important consequences for theories of the reionization of the Universe by miniquasars, as it is often assumed that accretion at the Eddington rate is achievable for miniquasars at redshifts \( z \gtrsim 15 \) (see Madau et al. 2004; Ricotti & Ostriker 2004; Kuhlen & Madau 2005). Although, a sufficiently high number density of accreting black holes could still lead to significant reionization by miniquasars. If accretion on to miniquasars is inefficient, as discussed in Madau & Silk (2005), the generation of the observed near-infrared background excess by Population III stars (e.g. Santos, Bromm & Kamionkowski 2002; Kashlinsky 2005) may not necessarily imply an overproduction of X-rays emitted by miniquasars fuelled by accretion on to Population III remnant black holes. However, copious X-ray production could result from accretion of gas from a binary companion (see Belczynski, Bulik & Rudak 2004; Saigo, Matsumoto & Umemura 2004), even if the binary system resides in a low-density environment. Future work will have to include more detailed, fully cosmological simulations with a prescription for radiative feedback from...
Population III remnant black holes to self-consistently address these issues.

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