The Role of minihalos in decoupling the spin temperature from the CMB temperature *

ABSTRACT — 21 cm tomography has the potential to explore the ubiquity of neutral hydrogen in the early universe. We have performed several high resolution cosmological simulations of early structure formation using the adaptive mesh refinement code FLASH to study the 21 cm radio signal prior to the epoch of reionization. The main objective of this research is to investigate the role of minihalos in decoupling the spin temperature from the CMB. We have also investigated the impact of X-ray heating and Lyman alpha resonance scattering on the 21 cm signal. We found that for the collisional coupling case, most of the gas remains cold and is not decoupled from the CMB. The 21 cm signal is seen in emission from high density peaks with overdensity ($\delta \geq 100$) and in absorption from dense filaments with $10 \leq \delta \leq 100$. In the case of X-ray feedback, gas is heated above the CMB and shines in 21 cm emission. We found that X-ray heating rate of $10^{-29}$ erg/s/atom is sufficient to drive the 21 cm signal into emission. For the Lyman alpha resonance scattering case, the spin temperature is efficiently decoupled from the CMB. Consequently, the 21 cm signal is seen in absorption or emission depending on the number of photons that pass through the Ly$\alpha$ resonance. We found that the 21 cm signal goes into emission with $N_{\alpha} \geq 10^{-14}$ s$^{-1}$ per H atom. Feedback mechanisms play a vital role in unlocking the spin temperature from the CMB.

*In preparation: Latif, M. A., Zaroubi S., Spaans M., Nusser A.
5.1 Introduction

Gas in the intergalactic medium (IGM) remained neutral after the epoch of recombination until the formation of the first luminous objects. It has been realized since a long time that neutral hydrogen in the IGM and gravitationally bound objects can be detected against the cosmic microwave background (CMB) radiation in the 21 cm hydrogen line (Field 1959a; Sunyaev & Zeldovich 1975; Hogan & Rees 1979; Scott & Rees 1990). The 21 cm signal is an important probe of the cosmic dark ages of the early universe. Its measurement will give insight into the thermal history of the universe, and the formation and evolution of the first objects. Now we are in an era where it is possible to detect this signal with (upcoming) radio telescopes like LOFAR and SKA.

The 21 cm signal is generated by the hyperfine splitting in the ground state of a neutral hydrogen atom. The absorption or emission of this signal is determined through the spin temperature. The spin and kinetic temperature of the cosmic gas remains coupled to CMB photons down to redshift 200 due to a small fraction of residual electrons from the recombination epoch. The gas temperature drops as $T_{\text{gas}} \propto (1 + z)^2$ below the CMB temperature $T_{\text{CMB}} \propto (1 + z)$ due to adiabatic cooling. The spin temperature follows the gas temperature down to redshift $z = 70$ due to collisions. The collision rates reduced as compared to the radiative coupling rate due to Hubble expansion at redshifts lower than 70 and the spin temperature starts to track the CMB temperature. Therefore, the 21 cm signal will be zero at $z \geq 200$ and in absorption at $20 \leq z \leq 200$. It becomes invisible at lower redshifts unless the spin temperature is decoupled from CMB temperature.

There are two mechanisms by which the spin temperature can be decoupled from the CMB temperature. The first one is the Wouthuysen-Field process, also called Lyman alpha pumping, in which redistribution of hyperfine level population takes place through absorption or emission of Lyman alpha photons (Wouthuysen 1952; Field 1959b). The second mechanism is collisional coupling in which collisions between hydrogen atoms can exchange the spin states (Field 1959a; Purcell & Field 1956). Coupling of the spin temperature to the gas temperature takes place in this way.

The 21 cm signal from the early universe has been studied in connection to mini-halos and intergalactic medium (IGM) (Iliev et al. 2002; Shapiro et al. 2006; Furlanetto & Loeb 2004; Ciardi & Madau 2003; Yue et al. 2009; Kuhlen et al. 2006; Furlanetto & Oh 2006; Baek et al. 2009; Santos et al. 2008; Tozzi et al. 2000; Furlanetto et al. 2006; Loeb & Zaldarriaga 2004). The IGM is expected to be cold in the absence of first radiation sources and a 21 cm signal will be in absorption against the CMB or coupled to the CMB. As first sources of radiation appear, they can raise the temperature of IGM gas through X-ray heating and resonance scattering of UV radiation, and turn the 21 cm signal into absorption or emission (Madau et al. 1997). Shock heating can heat the overdense gas in the IGM and convert the 21 cm line into emission (Furlanetto & Loeb 2004).

Although, the cosmic mean density of the gas is very low at higher redshift (10-20), which makes the collisional coupling weak. Still, the gas in overdense and high temperature regions will be coupled through collisions. Specifically, gas density in
the minihalos with virial temperature \(< 10^4\) K is high enough (\(> 10\) times the over-density of the universe) to decouple the spin temperature from gas temperature (Iliev et al. 2002; Shapiro et al. 2006). Such halos are formed in abundance and sufficient amounts of the gas has collected in them. So, a 21 cm signal is also expected from the minihalos. If the fraction of free electrons is between 10 -30 % in the IGM, they can decouple the spin temperature from the CMB even in moderately underdense regions due to their higher collisional cross-sections for the 21 cm transition (10 times higher) than atoms (Nusser 2005).

X-ray feedback can heat the IGM and drive the 21 cm signal into emission (Pellepessy et al. 2007; Ciardi et al. 2010; Madau et al. 1997; Furlanetto et al. 2006; Chuzhoy et al. 2006; Chen & Miralda-Escudé 2008). Kuhlen et al. (2006) performed numerical simulations to study the influence of X-ray heating on the spin and brightness temperature of IGM. They found that X-rays heat the IGM and the emission of 21 cm is strongly enhanced. Zaroubi et al. (2007) used analytical models to calculate the heating of the IGM by miniquasars and found that heating by X-rays can unlock the spin temperature from CMB up to distances of a few Mpc (comoving), depending on the mass and lifetime of an accreting black hole. Ripamonti et al. (2008) found that X-rays from early black holes can heat the gas to \(\gtrsim 10^3\) K and induce the 21 cm emission signal, which should be detectable with the telescope LOFAR.

Resonance scattering of Lyman alpha photons from the first generation of stars can decouple the spin temperature from the CMB even in low density regions where collisional coupling is not efficient. The influence of Lyman alpha coupling has been studied before (Madau et al. 1997; Ciardi & Madau 2003; Gnedin & Shaver 2004; Ciardi & Salvaterra 2007; Ciardi et al. 2010; Baek et al. 2009; Pritchard & Furlanetto 2006; Hirata 2006). Chen & Miralda-Escudé (2004) found that by including thermal motions heating by Lyman alpha scattering is reduced by a few orders of magnitude compared to previous estimates (Madau et al. 1997). Chuzhoy & Shapiro (2007) showed that resonance scattering of Lyman alpha photons can heat the IGM above the CMB temperature and may drive the 21 cm signal into emission at redshifts lower than 15.

The prime objective of this research is to investigate the role of minihalos in decoupling the spin temperature from the CMB. In order to accomplish this goal, we have performed high resolution three-dimensional cosmological simulations of structure formation prior to the epoch of reionization. Our resolution is high enough to resolve the gas dynamics on small scales as this is crucial for obtaining realistic results. It is higher than previous simulations performed in this regard (Shapiro et al. 2006). We have also studied the impact of radiation feedback from the first radiation emitting objects on the 21 cm signal emanating from cosmic neutral gas. We have performed a parameter study to find the minimum UV/X-ray background flux required to decouple the spin temperature.

The structure of this paper is as follows. In section 2, we discuss simulation setup and numerical methods used. In section 3, we discuss the physics included in our simulations to study the 21 cm signal. In section 4, we present the results obtained from cosmological simulations. Finally, in section 5, we summarize our conclusions and discuss future prospects.
5.2 Simulations

The simulations have been performed using the code FLASH (Dubey et al. 2009). It is an adaptive-mesh, module based, Eulerian, parallel multiphysics simulation code. It utilizes the message passing interface (MPI) library for inter processor communication to run on massively parallel systems. It is designed for general compressible flow problems found in numerous astrophysical environments. FLASH has two exchangeable discretization grids, a uniform grid (UG) and an adaptive mesh refinement (AMR) grid. We use the piece-wise parabolic method (PPM) to solve the hydrodynamic equations, which is a higher order version of Gudnov method, details can be found in Colella & Woodward (1984). PPM does not use artificial viscosity which makes it preferable over other methods for resolving shocks and contact discontinuities. FLASH uses active particles to follow the dynamic evolution of the dark matter for cosmological simulations. It makes use of the particle-mesh (PM) technique for this goal. For self-gravity calculations, we use the parallel version of the fast Fourier transform (FFT) which is suitable for uniform grids and multigrid solvers for adaptive grids.

We use the COSMICS code by Bertshinger (1995) to create Gaussian random field initial conditions and import them into FLASH. We take three-dimensional periodic boxes 100 kpc in size with different sets of initial conditions. In order to select massive halos, we make use of the constraint realization implemented in the grafic (part of the COSMICS software) package. We perform simulations with $512^3$ grid cells. We take $512^3$ dark matter particles for our simulations. We run FLASH in UG mode as resolution is uniform across the entire simulation box. We perform our simulations in accordance to the $\Lambda$CDM model with WMAP 5-year parameters of $\Omega_m = 0.2581$, $H_0 = 72 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_b = 0.0441$ and a scale invariant power spectrum with preferred value of $\sigma_8 = 0.8$. We initiate the simulations at $z=140-160$ and stop at $z=10$. The initial redshift is determined by the COSMICS package. Particle mass resolution in these cases is about 0.5 M$_\odot$. We use periodic boundary conditions both for hydrodynamics and gravity. We use a primordial composition for the gas with 75% hydrogen and 25% helium by mass.

5.3 Included Physics

The absorption or emission of the 21 cm line is associated with a spin temperature ($T_s$), which can be expressed in terms of relative populations of two spin states (parallel and anti-parallel) as given by

$$
\frac{n_1}{n_0} = \frac{g_1}{g_0} \exp(-T_s/T_*),
$$

(5.1)

where $n_1$ is the number density of atoms in the triplet state and $n_0$ is number density of atoms in the singlet state, $g_1$ and $g_0$ are the statistical weights these states. $T_* = 0.0868 K$ is the temperature corresponding to the energy difference between two the states. The 21 cm signal can be seen in absorption if $T_s < T_{CMB}$ and in emission if $T_s > T_{CMB}$. There are various mechanisms by which the spin temperature can be decoupled from the CMB temperature. These are absorption by CMB photons (CMB pumping), Lyman alpha transitions followed by decay to hyperfine states of
HI (Lyman alpha pumping) and collisional excitation of the ground state of neutral hydrogen (collisional coupling). These pumping mechanisms collectively determine the spin temperature as given by

$$T_s = \frac{T_{\text{CMB}} + (y_\alpha + y_c)T_K}{1 + y_\alpha + y_c},$$  \hspace{1cm} (5.2)

where $T_K$ is the kinetic temperature of the gas, $y_\alpha$ is the Lyman alpha pumping coefficient and $y_c$ is the collisional coupling constant (Purcell & Field 1956; Field 1959a). It can be seen from equation 5.2 that $T_s$ deviates from $T_{\text{CMB}}$ only if some coupling mechanism exists. The Lyman alpha pumping efficiency depends on the intensity of the UV flux. For the no heating case, we assume that sources of radiation are not abundant enough in the early universe to build up a sufficient UV flux, so $y_\alpha = 0$. The efficiency of the collisional pumping mechanism depends on the density and temperature of the local gas. The collisional coupling efficiency is expressed as

$$y_c = \frac{T_s}{T_K A_{10}} (C_H + C_e + C_p),$$  \hspace{1cm} (5.3)

where $A_{10} = 2.55 \times 10^{-15}$ s$^{-1}$ is the Einstein spontaneous emission coefficient. $C_H$, $C_e$ and $C_p$ are the collisional de-excitation rates due to atoms, electrons and protons, respectively. $C_H = \kappa (1 - 0) n_H$, where $n_H$ is the number density of hydrogen atoms. We use the function given in Kuhlen et al. (2006) to calculate the value of $\kappa (1 - 0)$, which fits very well for $10 < T < 3000$ K and can be extrapolated to $10^4$ K, $\kappa = 3.1 \times 10^{-11} T_k^{0.357} \exp(-32/T_k) \text{ cm}^3 \text{ s}^{-1}$. Similarly, $C_e = n_e \gamma_e$ and $C_p = n_p \gamma_p$, where $n_e$ and $n_p$ are the number density of electrons and protons, respectively, and where the values of $\gamma_e$ and $\gamma_p$ can be found from Kuhlen et al. (2006). The 21 cm line can be observed by performing a differential brightness temperature ($\delta T_b$) measurement, given by

$$\delta T_b = 27 x_{HI}(1 + \delta) \left( \frac{0.023}{\Omega_B h^2} \right) \left( \frac{0.15 + z}{0.15} \right)^{1/2} \left( \frac{T_s - T_{\text{CMB}}}{T_s} \right),$$  \hspace{1cm} (5.4)

where $x_{HI}$ is neutral fraction of hydrogen and $\delta$ is fractional overdensity. The formula given in equation 5.4 is valid for the optically thin case.

X-rays play a vital role in decoupling the spin temperature from CMB. Due to their long mean free paths, they can heat the IGM up to larger distances and are assumed to provide a uniform background. X-rays enhance the collisional coupling by raising the gas temperature above the CMB up to few thousand Kelvin (Madau et al. 1997). Ciardi et al. (2010) found that, without overproducing the unresolved X-ray background, the 21 cm signal should be seen in emission at redshift $\leq 11.5$. Moreover, IGM heating is always dominated by X-rays. In order to include the X-ray feedback by mini-quasars, we have followed the method described in Zaroubi et al. (2007). We calculated the mass evolution of black holes from redshift 35 down to redshift 6. Knowing the mass of black holes as a function of redshift, the heating rate is calculated. Further details can be found in the above mentioned article.

In the absence of other coupling mechanisms, Lyman alpha pumping is a very efficient mechanism in decoupling the spin temperature from the CMB. The Lyman
alpha photons can also travel long distances and quickly build up a homogeneous background. Large numbers of UV photons are produced by population III stars with frequencies below the hydrogen Lyman limit. These photons, when emitted between Lyα and Lyβ frequencies, continuum photons are redshifted into the Lyman alpha resonance and heat the gas. In contrast to this, photons emitted between Lyγ and the Lyman limit (injected photons) cool the gas. Chen & Miralda-Escude (2004) found that inclusion of atomic thermal motions reduces the heating rate compared to previous calculations (Madau et al. 1997). Consequently, cooling prevails at temperatures above 10 K. Chuzhoy & Shapiro (2007) showed that photon absorption in resonances higher than Lyman alpha proceeds via the 2s level instead of the 2p level. Therefore, the number of injected photons and the cooling efficiency are reduced. Consequently, the gas temperature increases up to \( \sim 100 \) K. We have considered the recoil effect that follows when Lyman alpha photons scatter resonantly with the gas. We have followed Chuzhoy & Shapiro (2007) to study the influence of this effect on the 21 cm signal. Further details can be found in the above mentioned article. The Lyman alpha pumping coefficient is calculated using

\[
y_\alpha = P_{10} \frac{T_s}{T_K A_{10}}. \tag{5.5}
\]

\( P_{10} \sim 10^9 J_\alpha \) is the radiative de-excitation rate due to Lyman alpha photons. \( J_\alpha \) is the intensity of Lyman alpha photons of in units of \( 10^{-21} \text{erg/cm}^2/\text{s}/\text{Hz}/\text{sr} \).

### 5.4 Results

#### 5.4.1 minihalos

We start our simulations with cosmological initial conditions at redshift 150. We see that density perturbations decouple from the Hubble flow and begin to collapse under self-gravity. Initially density fluctuations evolve linearly and follow the adiabatic equation of state. We notice that gas remains cold until redshift 20. As nonlinear evolution of density fluctuations proceeds, gas collapses in the dark matter potentials and gets shock heated. Shock heating becomes dominant at redshifts lower than 20. The density-temperature phase diagram is shown in figure 5.1. It can be seen from the phase diagram that most of the gas remains cold and only small fraction of the gas is shock heated. Gas is collapsed to \( 10^3 \) times the overdensity \( \delta \) of the universe. The maximum gas kinetic temperature in our simulation box is a few 100 K, which comes from shock heated regions.

We have calculated the spin \( (T_s) \) and brightness \( (\delta T_b) \) temperature of the gas. The brightness temperature is shown in figure 5.2. The gas that is cooled due to the Hubble expansion has \( T_k << T_{CMB} \) and could not unlock its spin temperature from CMB. Our results show that \( \sim 80\% \) of the gas in our simulation is invisible against the CMB as its brightness temperature remains close to zero (0.1 mK). At \( \delta \geq 10 \) collisional coupling becomes important and decouples \( T_s \) from \( T_{CMB} \). We see that gas with \( 10 \leq \delta \leq 100 \) has \( T_s < T_{CMB} \) and the 21 cm line is seen in absorption. Such gas is mostly lying in the filaments and sheets of the cosmic web. At \( \delta \geq 100 \) the gas is heated due to adiabatic compression and shock waves. Its temperature is raised above the CMB and the 21 cm signal is seen in emission. We found that \( \sim 7\% \) of
Figure 5.1: The density-temperature phase diagram for the no heating case.

Figure 5.2: Projected brightness temperature for the no heating case. The values of temperature are in mK. Comoving 100 kpc corresponds to the angular resolution of 0.04 arcsec.
Figure 5.3: The density-temperature phase diagram for the X-ray heating case.

Figure 5.4: Projected brightness temperature for the X-ray heating case. The values of temperature are in mK. Grid and particle resolution is $512^3$ as in other cases. Comoving 100 kpc corresponds to the angular resolution of 0.04 arcsec.
Figure 5.5: The density-temperature phase diagram for the UV heating case.

Figure 5.6: Projected brightness temperature for the UV heating case. The values of temperature are in mK. Comoving 100 kpc corresponds to the angular resolution of 0.04 arcsec.
the gas mass is visible against the CMB. On other hand, the amount of gas seen in absorption is twice the amount of gas in emission. The average brightness temperature in the simulation box is 0.4 mK. In order to compare our results with Shapiro et al. (2006), we have performed a set of simulations with resolution comparable to them. The resulting $\delta T_b$ is shown in figure 5.9. We do see absorption in the 21 signal (although small i.e., -1 mK) at redshift 10 as $T_s$ becomes less than $T_{\text{CMB}}$. Kuhlen et al. (2006) also see absorption in the 21 cm signal at redshift 17.5 for their “NOBH” case.

5.4.2 X-ray heating

We have studied the impact of X-ray heating by mini-quasars on the 21 cm signal prior to the epoch of reionization. To compute the X-ray flux from mini-quasars, we have adapted the method given in the Zaroubi et al. (2007). The evolution of X-ray flux has been followed based on the growth of black hole mass as shown in figure 8 of above mentioned article. Moreover, we have assumed that black hole is shining at 10% of its Eddington luminosity at emission scale of 1 Mpc. We note that gas is heated due to X-rays and the kinetic temperature of the gas is raised above $T_{\text{CMB}}$. The density-temperature phase diagram is shown in figure 5.3. The temperature of the gas is increased up to a few times $10^3$ K. The equation of state is stiffened and the value of the polytropic exponent is increased above the adiabatic value ($\gamma \sim 1.9$). We see that X-ray heated gas does not collapse to high densities ($\delta > 100$) and does not cool efficiently to be detectable in 21 cm absorption. The brightness temperature of the gas is depicted in figure 5.4. It is seen that introduction of X-ray heating has efficiently decoupled the spin temperature from the CMB. Consequently, the entire gas volume is visible in 21 cm emission. Even gas with smaller density (equal to the average density of the universe) is visible against the CMB. Our results are in agreement with theoretical expectations Zaroubi et al. (2007); Ripamonti et al. (2008). The average value of $\delta T_b$ is 4 mK.

Kuhlen et al. (2006) also performed simulations and found that by including X-ray feedback emission of the 21 cm signal is enhanced. In order to find the minimum X-ray background flux required to efficiently decouple the spin temperature from the CMB, we performed several simulations with different values of X-ray feedback. The average brightness temperature corresponding to a given heating rate is listed in table 5.1. We found that at redshift 10 a heating rate $\geq 10^{-29}$ erg/s/atom is sufficient to decouple the spin temperature from the CMB and drive the 21 cm signal into emission. This value is comparable to the energy input per baryon as shown in figure 14 of Ripamonti et al. (2008).

5.4.3 Lyman alpha pumping

We have also investigated the influence of resonant scattering of Lyman alpha photons on the 21 cm signal emanating from cosmic neutral gas. We see that heating due to continuum photons dominates up to 100 K. Cooling due to injected photons becomes efficient at temperatures higher than 100 K. The density-temperature phase diagram is shown in figure 5.5. It can be seen from the figure that the minimum temperature of the gas is close to the CMB and the maximum temperature is around a few hundred K. The temperature of the gas becomes constant at higher densities
as cooling due to injected photons dominates. Gas is collapsed up to few thousand times the overdensity of the universe. The brightness temperature for this case is depicted in figure 5.6. It can be seen that Lyman alpha pumping has efficiently decoupled the spin temperature of the gas from the CMB. Consequently, the 21 cm signal is rendered in emission. The average value of brightness temperature in the simulation volume is around $\sim 10$ mK. We found that a value of the Lyman alpha background intensity of $J_{\alpha} = 1$ (in units of $10^{-21}$ erg/cm$^2$/s/Hz/sr) is high enough to unlock the spin temperature. Our results again agree with the theoretical expectations (Ciardi & Salvaterra 2007; Chuzhoy & Shapiro 2007). Number of photons which are emitted between Ly$\alpha$ and Ly$\beta$ frequencies redshift into Ly$\alpha$ resonance and heat the gas. We found that for $N_{\alpha} \geq 10^{-14}$ s$^{-1}$ per H atom (number of photons that pass through the Lyman alpha resonance per H atom per unit time) the 21 cm signal shines in emission.

We carry out several simulations by varying the value of $N_{\alpha}$, we find that absorption or emission of the 21 cm signal relies on the value of $N_{\alpha}$. The values of brightness temperature corresponding to different values of $N_{\alpha}$ are listed in table 5.2. The density-temperature phase diagram for $N_{\alpha} = 10^{-16}$ is shown in figure 5.7. The projected brightness temperature corresponding to figure 5.7 is depicted in figure 5.8. It is found that $N_{\alpha} \geq 10^{-14}$ s$^{-1}$ per H atom is required to drive the 21 cm signal into emission. We also note that $J_{\alpha} \sim 10^{-21}$ efficiently decouples the spin temperature. Even, $J_{\alpha} = 10^{-22}$ can decouple the spin temperature, but the signal strength is reduced (see table 5.2). This agrees with previous estimates of the Lyman alpha intensity required to unlock the spin temperature from the gas (Ciardi & Madau 2003).

So far we have studied the impact of a background flux by the first stars on the spin temperature of the gas. Here, we consider a case where a star is formed inside the halo at redshift 25 and examine its influence on the 21 cm signal. The mass of the star is 100 M$_{\odot}$; such a massive star can form in the $10^6$ M$_{\odot}$ halos (Yoshida et al. 2006; Abel et al. 2000). Its luminosity is $\sim 10^6$ L$_{\odot}$ and its effective temperature is 10$^4.975$ K (see table 3 of Schaerer (2002)). Its life time is $2.8 \times 10^6$ years. The density-temperature phase diagram for this case is shown in figure 5.10. It can be seen from the figure that gas is heated up to a few thousand Kelvin by stellar radiation and cools due to an adiabatic expansion. The corresponding brightness temperature is shown in figure 5.11. The 21 cm signal in the surroundings of the star is found in emission. The gas far away from the star is seen in absorption. The average signal from the simulation box is -26 mK. We have also found that a stellar heating rate of $5.0 \times 10^{-25}$ erg/baryon/s ($\sim 500$ M$_{\odot}$) is required to drive the 21 cm signal into net emission. The corresponding phase diagram and brightness temperature are shown in figures 5.12 and 5.13, respectively. The average brightness temperature for this case is 23 mK. We also explored a few cases with low mass stars. Due to the weak dependence of a star’s temperature on its mass (Schaerer 2002), the effect on the brightness temperature is modest for stars between 40 and 100 M$_{\odot}$. For a 10 M$_{\odot}$ star the average signal in the simulation box remains in absorption (i.e., -400 mK).
Table 5.1: X-rays case. The values of the heating rates are listed for redshift 10.

<table>
<thead>
<tr>
<th>Heating rate (erg/s/baryon)</th>
<th>$&lt;\delta T_b&gt;$ (mK)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^{-26}$</td>
<td>4</td>
</tr>
<tr>
<td>$10^{-29}$</td>
<td>1</td>
</tr>
<tr>
<td>$10^{-30}$</td>
<td>0.3</td>
</tr>
</tbody>
</table>

Table 5.2: Lyman alpha scattering case.

<table>
<thead>
<tr>
<th>$N_\alpha$ (s$^{-1}$ per H atom)</th>
<th>$&lt;\delta T_b&gt;$ (mK)</th>
<th>$&lt;\delta T_b&gt;$ (mK)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^{-14}$</td>
<td>10</td>
<td>2</td>
</tr>
<tr>
<td>$10^{-15}$</td>
<td>-47</td>
<td>-9</td>
</tr>
<tr>
<td>$10^{-16}$</td>
<td>-240</td>
<td>-40</td>
</tr>
</tbody>
</table>

5.5 Discussion and Conclusions

We have performed high resolution cosmological simulations of early structure formation to study the 21 cm signal emanating from the cosmic dark ages. We used the AMR code FLASH to carry out simulations from redshift 150 down to 10. Our resolution is sufficient to resolve small scale physics (particle mass resolution = 0.5 M$_\odot$).

The prime objective of this research was to investigate the role of minihalos in unlocking the spin temperature from the CMB. We have also probed the impact of X-ray heating and Lyman alpha resonant scattering in decoupling the spin temperature. We computed the spin and brightness temperature of the gas in the absence of any radiation sources and compared it with the X-ray and UV cases.

We found that collisional coupling is only efficient in regions with $\delta > 10$. The gas with $\delta > 100$ is visible in 21 cm emission and for $10 < \delta < 100$ gas is seen in 21 cm absorption. The bulk of the gas ($\sim 80\%$) remains coupled to the CMB and cannot unlock its spin temperature from the CMB. We also performed simulations with larger box sizes and found similar results ($512^3$ grid cells and $512^3$ particles). In the absence of external feedback it is difficult to decouple the diffuse gas and there should be some other mechanism like Lyman alpha pumping or X-ray heating. Furlanetto & Loeb (2004) suggested that shock heating can heat the IGM gas and can drive the 21 cm signal into emission. We do not see much shock heating in our simulations as predicted by these authors through the Press-Schechter formalism.

By the introduction of X-ray feedback, the temperature of the gas is increased above the CMB. Consequently, the gas is decoupled from the CMB and is visible in 21 cm emission. The inclusion of Lyman alpha coupling will enhance $\delta T_b$ fluctuations particularly in the vicinity of sources. We have assumed that X-ray photons provide a uniform background, which is not completely true. The soft X-ray component will
fluctuate on relatively small scales (Furlanetto et al. 2006). As X-rays heat the gas to \( \geq 10^3 \) K, it can have important implications for subsequent structure formation in minihalos. They can suppress the formation of halos and can partly ionize the gas (Oh & Haiman 2003).

In the case of Lyman alpha resonant scattering, the gas is heated to \( \sim 100 \) K. The continuum photons heat the gas while injected photons cool it. We conclude that Lyman alpha pumping is a very efficient mechanism in unlocking the spin temperature from the CMB. The coupling efficiency depends on the intensity of Lyman alpha photons. We have assumed in this study that there is no X-ray background. Its presence can heat the gas and enhance the emission of a 21 cm signal. Also, we have only considered the influence of Lyman alpha resonant scattering. Complete modeling of IGM heating by stars needs a dedicated study and is beyond the scope of this paper. Lyman alpha heating suppresses the collapsed gas fraction in minihalos by 50% (Ciardi & Salvaterra 2007). Hence, it could have important impact on the later structure formation and reionization process.

We have not performed a complete X-ray radiative transfer calculation. We have ignored the effect of Lyman alpha photons produced by X-rays. About 10-40 % of X-rays are converted in UV, see Meijerink & Spaans (2005); Maloney et al. (1996). This will be included in future calculations. High resolution cosmological radiative transfer simulations, including feedback effects in self consistent manner, should be performed to compute the 21 cm signal emanating from the cosmic dark ages of the early universe. We have not tried to match the resolution of our box with present/upcoming radio telescopes but instead focused on the underlying physics in the emission or absorption of the 21 cm signal. Our current simulation volume is too small to predict fluctuations in the 21 cm signal but we will address this in future work.

5.6 Acknowledgments

The FLASH code was in part developed by the DOE-supported Alliance Center for Astrophysical Thermonuclear Flashes (ACS) at the University of Chicago. Our simulations were carried out on the Gemini machines at the Kapteyn Astronomical Institute, University of Groningen.
Figure 5.7: The density-temperature phase diagram for the Lyman alpha resonant scattering case. The figure corresponds to $N_\alpha = 10^{-16}$.

Figure 5.8: Projected brightness temperature for the Lyman alpha resonant scattering case. The figure corresponds to $N_\alpha = 10^{-16}$. The values of temperature are in mK. Comoving 100 kpc corresponds to the angular resolution of 0.04 arcsec.
Figure 5.9: Projected brightness temperature for the no heating case with box size 700 kpc. The values of temperature are in mK. Comoving 100 kpc corresponds to the angular resolution of 0.04 arcsec.
Figure 5.10: The density-temperature phase diagram for the case when a 100 $\text{M}_\odot$ star is formed inside the halo.

Figure 5.11: Projected brightness temperature for the case when a star is formed inside the halo. The values of temperature are in mK. Actual values can be found by subtracting 80 mK from the values given by the colorbar. Comoving 100 kpc corresponds to the angular resolution of 0.04 arcsec.
Figure 5.12: The density-temperature phase diagram for a stellar irradiation case with a heating rate of $5 \times 10^{-25} \text{erg/s/baryon}$.

Figure 5.13: Projected brightness temperature for a stellar irradiation case with a heating rate of $5 \times 10^{-25} \text{erg/s/baryon}$. The values of temperature are in mK. Comoving 100 kpc corresponds to the angular resolution of 0.04 arcsec.