Preheating of the Universe by cosmic rays from primordial supernovae at the beginning of cosmic reionization

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ABSTRACT

The 21-cm signal from the cosmic reionization epoch can shed light on the history of heating of the primordial intergalactic medium (IGM) at z ∼ 30–10. It has been suggested that X-rays from the first accreting black holes could significantly heat the Universe at these early epochs. Here we propose another IGM heating mechanism associated with the first stars. As known from previous work, the remnants of powerful supernovae (SNe) ending the lives of massive Population III stars could readily expand out of their host dark matter minihaloes into the surrounding IGM, aided by the preceding photo-evaporation of the halo’s gas by the UV radiation from the progenitor star. We argue that during the evolution of such a remnant, a significant fraction of the SN kinetic energy can be put into low-energy (E ≲ 30 MeV) cosmic rays that will eventually escape into the IGM. These subrelativistic cosmic rays could propagate through the Universe and heat the IGM by ∼10–100 K by z ∼ 15, before more powerful reionization/heating mechanisms associated with the first galaxies and quasars came into play. Future 21-cm observations could thus constrain the energetics of the first SNe and provide information on the magnetic fields in the primordial IGM.

Key words: supernovae: general – cosmic rays – dark ages, reionization, first stars.

1 INTRODUCTION

Although it is clear that the reionization of hydrogen in the Universe was essentially complete by z ∼ 6, the history of cosmic reionization remains poorly known (see Barkana & Loeb 2001; Fan, Carilli & Keating 2006 for reviews). The spin–flip transition of H i, at an observed wavelength of 21(1 + z) cm, provides a potentially powerful and unique tool for studying the corresponding early epochs observationally (e.g. Morales & Wyithe 2010). The properties of the 21-cm signal crucially depend on the deviation of the H i spin temperature from that of the cosmic microwave background (CMB) as a function of redshift. The spin temperature in turn is sensitive to the kinetic temperature of the (nearly neutral) medium (hereafter referred to as the intergalactic medium, IGM) filling the early Universe and thus depends on the efficiency of any gas heating mechanisms that might have been at play (see Furlanetto, Oh & Briggs 2006; Pritchard & Loeb 2012 for detailed discussions of the physics involved).

It is widely accepted that cosmic reionization was mostly driven by stellar UV radiation from the first galaxies. Reionization by stars operates through seeding, growing and merging of H ii bubbles in the IGM, with the medium outside the ionized regions remaining cold and neutral. However, it has been suggested (Venkatesan, Girou & Shull 2001; Madau et al. 2004; Ricotti & Ostriker 2004; Mirabel et al. 2011; Tanaka, Perna & Haiman 2012) that during the early epoch of star formation there possibly existed X-ray sources, such as microquasars and high-mass X-ray binaries, which could significantly heat the gas throughout the Universe by their radiation thanks to the low opacity of the IGM to X-rays compared to UV radiation. As a result of such X-ray preheating, the spin temperature of the H i gas could become coupled to its kinetic temperature already by z ∼ 15. This would make the 21-cm signal from the early phases of cosmic reionization quite different from what it would be in the absence of such heating (Pritchard & Furlanetto 2007; Pritchard & Loeb 2010; Mesinger, Ferrara & Spiegel 2013; Fialkov, Barkana & Vishal 2014). However, current estimates of the X-ray heating of the IGM are very uncertain because of the poor knowledge of the abundance and spectral properties¹ of X-ray sources in the early Universe (see McQuinn 2012 for a discussion of current observational constraints).

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¹ Note that the mean free path of X-rays in primordial H–He gas is roughly proportional to the cube of the photon energy, so that the Universe at z ∼ 10 is transparent to X-rays with E ≥ 1 keV, which diminishes the efficiency of ionization and heating.
The first X-ray sources could appear in the Universe only with the beginning of star formation. In particular, the scenario where high-mass X-ray binaries or microquasars are responsible for early IGM heating rests on the assumption that a significant fraction of Population III (Pop III) stars end their lives with a supernova (SN) explosion, leaving behind a black hole which subsequently acquires gas from a companion star or ambient medium and produces X-ray emission. Alternatively, X-rays suitable for IGM heating could be provided by primordial supernovae (SNe) themselves, namely by thermal emission from the SN remnant (SNR) and by inverse Compton scattering of the CMB photons on relativistic electrons accelerated by the SN (Oh 2001; Kitayama & Yoshida 2005). However, the efficiency of these mechanisms (the fraction of the total SN explosion energy that goes into X-rays) is likely to be low.

We argue that primordial SNe can nevertheless cause a significant preheating of the early Universe, through low-energy cosmic rays (LECRs) generated by them. A number of studies (Bromm, Yoshida & Hernquist 2003; Kitayama & Yoshida 2005; Greif et al. 2007; Whalen et al. 2008) have demonstrated that powerful SNe associated with massive Pop III stars could readily escape from their host minihaloes into the surrounding IGM. In this situation, a significant fraction of the SN kinetic energy will be put into low-energy CRs escaping into the IGM. These CRs could then propagate through the Universe and gradually lose their energy by ionizing and exciting H and He atoms, thus heating the ambient gas. Below we demonstrate that low-energy CRs from the first SNe could cause a significant global preheating of the primordial IGM. The heating is expected to be somewhat (depending on the topology and strength of IGM magnetic fields) concentrated around the Pop III star-forming minihaloes, more so than in the case of X-ray heating, since typical distances travelled by low-energy CRs from their sources are larger than typical distances between minihaloes but much smaller than the Hubble horizon, whereas the mean free paths of X-rays with \( E \sim 1 \text{ keV} \) are comparable to the horizon.

Before proceeding, we note that the general possibility of ionization and heating of the IGM by CRs from young galaxies was discussed already by Ginzburg & Özeren (1965) and later by Nath & Biermann (1993). More recently, Stacy & Bromm (2007) discussed a possible impact of a uniform cosmic ray (CR) background on star formation within haloes in the early Universe, considering the energy density of this background a free parameter. Also, Tueros, del Valle & Romero (2014) recently suggested that CRs produced by the first generations of microquasars could contribute to cosmic reionization.

In our calculations, we adopt the cosmological parameters determined by Planck Collaboration (2015).

2 COSMIC RAY PRODUCTION BY PRIMORDIAL supernovae

According to the modern paradigm (see Bromm & Larson 2004 for a review), the first stars appeared in significant numbers at \( z \sim 20 \) in dark matter minihaloes of mass \( M_\text{bh} \sim \text{a few } 10^5 - 10^7 \text{ M}_\odot \), as a result of molecular cooling of primordial gas heated to the halo’s virial temperature \( T_\text{vir} \sim 10^4 \text{ K} \). Although there have been no observations of this early epoch of star formation yet and there remain many theoretical uncertainties and computational difficulties, the prevailing view is that PopIII was dominated by massive and very massive, \( \sim 10^{-7} - 10^{-5} \text{ M}_\odot \), stars (e.g. Hirano et al. 2014). These stars lived for several million years and a significant fraction or perhaps most of them eventually exploded as powerful SNe, with kinetic energies reaching \( \sim 10^{51} \text{ erg} \) (Heger & Woosley 2002; Tominaga, Umeda & Nomoto 2007; Heger & Woosley 2010). This energy exceeds by orders of magnitude the binding energy of the minihalo’s gas, \( E_\text{b} \sim 10^{49} - 10^{51} \text{ erg} \) (assuming that the gas contributes a fraction \( f_\text{gas} \sim 0.19 \) of the mass of the halo), so a single SN is potentially capable of driving most of the gas from its halo and stalling subsequent star formation in it.

The above energy argument is, however, oversimplified, since if an SN explodes in a sufficiently dense environment it can quickly lose a significant fraction of its initial energy through radiation. Nevertheless, as has been demonstrated by many authors (Kitayama et al. 2004; Whalen, Abel & Norman 2004; Abel, Wise & Bryan 2007; Johnson, Greif & Bromm 2007; Yoshida et al. 2007), the strong UV radiation of the Pop III progenitor star of an SN exploding in a minihalo is expected to ionize the IGM within several kpc and almost completely photo-evaporate gas within the virial radius of the halo, \( R_\text{vir} \sim 100 \text{ pc} \), lowering the hydrogen number density there to \( n_\text{H} \sim 0.1 - 1 \text{ cm}^{-3} \). As a result, the ensuing SN explodes in an environment almost devoid of gas, so that the SNR experiences very little radiative losses for the first \( \sim 10^5 \text{ yr} \) as it expands out to \( r \sim R_\text{vir} \). At about this distance, the SNR shock encounters increased gas density due to the preceding shock driven by the photonization and, as a result, starts to suffer significant radiation losses. Nevertheless, the SNR retains significant energy to expand further into the \( H_\text{II} \) region created by the progenitor star and eventually disperses at \( r \sim 10^5 \text{ kpc} \) (Kitayama & Yoshida 2005; Greif et al. 2007; Whalen et al. 2008).

The scenario described above is only applicable to primordial SNe exploding in minihaloes, whereas the situation was likely completely different in more massive haloes, with \( M_\text{bh} \gtrsim 10^7 \text{ M}_\odot \). In this case (Kitayama & Yoshida 2005; Whalen et al. 2008), the progenitor Pop III star is unable to photoevaporate the gas from the halo and the SN explodes in a dense environment with \( n_\text{H} \gtrsim 10^4 \text{ cm}^{-3} \). As a result, the thermal energy of the SNR is radiated away before the beginning of the Sedov–Taylor (ST) phase and the SNR fades away within a few pc of its origin. This is why we only consider the case of primordial SNe exploding in minihaloes in this work.

Apart from the (presumably) larger explosion energy, the case of a primordial SN in a minihalo at \( z \sim 20 \) closely resembles the more familiar case of SNRs in the Milky Way at the present epoch. Indeed, the gas densities encountered by a primordial SNR, \( n_\text{H} \sim 0.1 - 1 \text{ cm}^{-3} \) at \( r \lesssim R_\text{vir} \), are similar to the densities of the medium through which SNRs propagate in the Galaxy (e.g. \( n_\text{H} \sim 0.1 \text{ cm}^{-3} \) for Type Ia SNRs in the interstellar medium (ISM) and \( n_\text{H} \sim 10^{-2} \text{ cm}^{-3} \) for Type Ib/c and Type IIf SNRs in a rarefied bubble formed by the progenitor star, see, e.g. Ptuskin, Zirakashvili & Seo 2010). Based on this similarity (although there is a potentially important difference between the strengths of magnetic fields in the primordial ISM and IGM and in the present-day ISM, see a discussion in Section 2.1 below), it is reasonable to expect that primordial SNRs were as efficient CR producers as Galactic SNRs are known to be. Moreover, we can rely on the well-developed theory of CR production in the Galaxy in making our estimates.

We consider a simplistic scenario in which a single massive Pop III star forms and then explodes in a minihalo, stalling further star formation. In reality, it is possible that more than one massive star will be formed within the same halo (especially if it is rather large, \( M_\text{bh} \sim 10^7 \text{ M}_\odot \)), so that several SNe will explode nearly simultaneously. These multiple explosions can then drive a ‘supernwind’ that is more powerful than a single SN (see e.g. Schwarz, Ostriker & Yahil 1975; Tegmark, Silk & Evrard 1993). On the other hand, it is possible that a significant fraction of minihaloes did not produce...
Pop III stars, and hence SNe, at all, in particular due to suppression of H$_2$ formation by a Lyman–Werner (LW) background from previous generations of Pop III stars (Haiman, Abel & Rees 2000). This effect should be especially strong in overdense regions of the early Universe, as has recently been demonstrated by Xu, Wise & Norman (2013) who simulated formation of thousands of minihaloes and Pop III stars at $z = 30–15$ taking into account kinetic, thermal, chemical and radiative feedback. In addition, there is significant uncertainty in the initial mass function of Pop III stars and consequently in the fraction of such stars that exploded as SNe (rather than collapsed to black holes) and in the energy of typical primordial SNe.

Bearing all these uncertainties in mind, we introduce two free parameters: the average number of SNe per minihalo, $f_{\text{SN}}$, and the average SN explosion energy, $E_{\text{SN}}$. In making our estimates, we consider the range $E_{\text{SN}} = 10^{51}–10^{53}$ erg, where the upper boundary is intended to represent the case of a single pair-instability SN.

2.1 Cosmic ray spectrum and energy budget

The modern paradigm of the origin of Galactic CRs builds on the non-linear theory of diffusive shock acceleration (DSA, see Bell 2013; Bykov et al. 2013 for recent reviews) and a detailed treatment of the problem of CR escape from SNRs (e.g. Berezhko, Elshin & Ksenofontov 1996; Berezhko & Volk 2000; Puskin & Zirakashvili 2005; Caprioli, Amato & Blasi 2010; Puskin et al. 2010). According to this theory, the time-integrated energy spectrum of CRs injected into the ambient medium is the sum of two components: (i) CRs steadily escaping from the upstream region of the shock, and (ii) CRs gradually accumulated within the remnant and released into the surrounding medium at the end of the SNR evolution. At any given time, the instantaneous spectrum of the CRs escaping upstream from the shock is peaked around a maximum momentum $p_{\text{max}}(t)$, which decreases with time over most of the evolution due to the decreasing shock velocity and hence weakening magnetic field amplification, except for the short initial free-expansion phase when the shock velocity, $V_{\text{sh}}$, is constant. Particles with $p(t) < p_{\text{max}}(t)$ cannot escape and remain within the remnant, suffering adiabatic losses, until some later moment when their momentum becomes larger than the current $p_{\text{max}}$ at the shock. Importantly, as emphasized by Drury (2011), the energy adiabatically lost by particles within the remnant goes to driving the shock and is thus constantly recycled into the acceleration of new particles.

In the time-integrated CR spectrum (see e.g. fig. 3 in Caprioli et al. 2010), the contribution of particles leaking from the upstream region is only important at the highest energies (near the “knee”), whereas the rest of the spectrum is composed of particles escaping at the end of the SNR evolution, when the remnant disperses in the ambient medium. Interestingly, except for the knee region, the resulting spectrum seems to be almost insensitive to the type and environment of a Galactic SN, with the slope of the momentum distribution ($dN/dp \propto p^{-\alpha}$) changing from $\alpha \approx 3$ at $p < mc$ (here $m$ is the mass of the particle) to $\alpha \approx 2$ at $p \gg mc$ (see fig. 1 in Puskin et al. 2010). In terms of particle kinetic energy, this implies that $dN/dE \propto E^{-\beta}$ with $\beta \approx 2$ across the entire spectrum including both the non-relativistic and relativistic parts, i.e. the energy carried away by CRs is distributed approximately uniformly on a logarithmic energy scale.

Recently, the Voyager 1 spacecraft has apparently left the heliosphere modulation region and for the first time measured the local CR spectrum down to $\approx 3$ MeV per nucleon (Stone et al. 2013). This observed spectrum represents the result of very strong transformation (suppression) of the CR source spectrum due to energy losses during the diffusion of CRs through the interstellar medium. Schlickeiser, Webber & Kempf (2014) have demonstrated that the Voyager 1 data are consistent with a simple model where the Solar system resides within a spatially homogeneous layer of distributed CR sources injecting the same momentum power-law spectrum $dN/dp \propto p^{-s}$, with $s = 2.24 \pm 0.12$. This corresponds to $dN/dE \propto E^{-1.62}$ and $dN/dE \propto E^{-2.24}$ at non-relativistic and relativistic energies, respectively. However, as noted by the authors, this result should currently be taken with caution and requires further verification. It should be emphasized that the local CR spectrum measured by Voyager 1 has little relation to the Galactic CR source spectrum at $E \lesssim 100$ MeV, since such subrelativistic particles essentially cannot leave their production sites in the Galaxy, given the ISM density and magnetic fields (in contrast to the situation with the primordial IGM discussed below).

The overall efficiency of CR production by SNe is not well known. Theoretical studies of the DSA mechanism usually demonstrate the possibility of putting up to $\approx 50$ per cent of the shock kinetic energy into acceleration of CRs. In recent state-of-the-art simulations of DSA of ions in non-relativistic astrophysical shocks by Caprioli & Spitkovsky (2014a), this efficiency was found to be $\approx 10–20$ per cent. On the other hand, an average CR production efficiency of 10–30 per cent in SNe is required to maintain the observed CR energy against losses from the Galaxy (e.g. Drury, Markiewicz & Voelk 1989; Berezhnskii et al. 1990).

As noted above, the case of a primordial SN exploding in a minihalo is similar to that of SNe in the Milky Way. In particular, the evolution of the remnant in the former case is not very different from that in the latter, as has been demonstrated by Greif et al. (2007) using three-dimensional hydrodynamical simulations in a cosmological setup (their results are in good agreement with those obtained by Kitayama & Yoshida 2005 and Whalen et al. 2008). Specifically, these calculations show that the evolution begins with a free-expansion phase, which continues for $\lesssim 10^3$ years and ends when the SNR has expanded to $\approx 20$ pc. After that, a ST adiabatic phase begins, which continues for $\approx 10^4$ yr and terminates when the shock front approaches the virial radius $R_{\text{vir}} \approx 100$ pc and catches up with the previously formed photo-heating shock associated with the progenitor. This accelerates radiative losses and triggers a so-called snowplow phase,$^2$ which continues for $10^3–10^4$ yr and finishes by the dispersal of the SNR at a distance of a few $10^2$ pc, i.e. already outside the virial radius of the minihalo. Once the remnant has faded away, the bulk of the CRs accelerated during its evolution get injected into the IGM. Continuing the analogy with Galactic SNRs, most of the energy contained in the CRs was probably generated in the ST and early snowplow phases, with lower energy particles produced later than higher energy ones.

An important difference between Galactic and primordial SNRs is that the former propagate through a substantially magnetized ($B_0 \sim 1 \mu$G) ISM, whereas the latter through a medium with likely much weaker magnetic fields. For example, Xu et al. (2008) simulated Pop III star formation including seed field generation by the Biermann battery mechanism. They found magnetic field strengths declining from $B \sim 10^{-9}$ G in the dense protostellar core to $\sim 10^{-15}$ G at the virial radius of the minihalo. Seed magnetic fields might also be spewed out by stellar winds and SN explosions $^2$ By the end of this stage additional energy losses due to inverse Compton scattering of the CMB become important (Kitayama & Yoshida 2005; Greif et al. 2007).
of Pop III stars (see e.g. Bisnovatyi-Kogan, Ruzmaikin & Sunyaev 1973). Once generated, seed fields of ~1 nG can be further amplified by several orders of magnitude via small-scale dynamo in the cores of primordial haloes during their collapse (e.g. Sur et al. 2010).

According to the modern paradigm, the ambient magnetic field is strongly amplified at an SNR shock during DSA of CRs. Indeed, observations indicate that magnetic fields in young Galactic SNRs are up to ~100 times stronger than in the ISM (see e.g. Bell 2013). Recent simulations of DSA in strong non-relativistic shocks confirm that various instabilities can greatly amplify the ambient field. In particular, Caprioli & Spitkovsky (2014b) find that the amplification factor, $B_{sh}/B$, is proportional to the square root of the Alfvénic Mach number of the shock, $M_A$ (which in their work is nearly equal to the sonic Mach number, $M_s$), for $M_s < 100$. Bykov et al. (2014) performed calculations reaching larger Mach numbers, $M_A \sim 2500$, and found that magnetic field amplification can be much stronger, $B_{sh}/B \propto M_A^{1/2}$. In fact, in their simulations the magnetic pressure saturates at ~10 per cent of the shock ram pressure. Naively this suggests that despite the presumably much weaker ambient field in the case of a primordial SNR, it can be amplified to the same intensity as in the case of a Galactic SNR. However, this is based on a bold extrapolation of our current knowledge by perhaps several orders of magnitude in $M_A$. Indeed, taking fiducial values for the ambient number density and temperature $n_0 = 10^{-2} \text{ cm}^{-3}$ and $T = 100$ K (taking into account that the gas upstream of the SNR is likely to be preheated by the photoionizing radiation from the progenitor star and the SNR itself, we find the sound speed may be $c_s = \sqrt{(5/3)kT/m_p} \sim 1$ km s$^{-1}$ and the Alfvénic speed $v_{sh} = B/\sqrt{4\pi n_0 m_p} \approx 0.02 (B/10^{-9} \text{ G}) \text{ km s}^{-1}$. Hence, for shock velocities of $10^{-1} - 10^{9}$ km s$^{-1}$ (corresponding to late and early stages of SNR evolution), the sonic Mach number is likely to be $\sim 10^{-1} - 10^{3}$, similar to Galactic conditions, while the Alfvénic Mach number is likely to exceed $10^{5}$. Regardless of the actual magnitude of magnetic field amplification in primordial SNRs, it is unlikely to significantly affect the overall efficiency of CR production. However, the actual strength of the magnetic field should determine the maximum energies of CRs accelerated in such shocks, as is further discussed below.

As explained in Section 3 below, we are primarily interested in CR protons with energies $E \lesssim 30$ MeV. The spectrum of CRs generated by a primordial SNR probably begins at $E_{min} \sim 1$ keV$^3$ and cuts off at $E_{max} \sim 10^5$ GeV or maybe at a much lower energy if magnetic fields at the shocks of primordial SNRs are not amplified to the same strength as in Galactic SNRs (since $E_{max} \propto V_{sh} R_{sh} B_{sh}$ for DSA, where $R_{sh}$ is the characteristic size of the shock). Therefore, subrelativistic CRs with 1keV $\lesssim E \lesssim 30$MeV, which are hereafter referred to as LECRs, may provide a significant contribution, $\sim 5$–50 per cent to the total CR energy budget. Here, the lower value corresponds to the Galactic CR source spectrum inferred by Schlickeiser et al. 2014 from Voyager 1 measurements and $E_{max} \sim 10^5$ GeV, and the higher one to the d$N$/d$E \propto E^{-2}$ spectrum suggested by detailed calculations of CR production in SNRs and $E_{max} \sim 10^9$ GeV (see the preceding discussion). Taken into account that the total CR energy output is $\sim 10$–50 per cent of the SN explosion energy (see again the preceding discussion), we conclude that LECRs will carry away a fraction $\eta \sim (0.05 – 0.5) \times (0.1 – 0.5) \sim 0.005$–0.25 of the total SN explosion energy. We may then estimate the total energy of LECRs per minihalo as

$$E_{LECR} = \eta E_{SN} = 5 \times 10^{50} \frac{\eta}{0.05} \frac{f_{SN}}{1} \frac{E_{SN}}{10^{52} \text{ erg}}. \quad (1)$$

We note that the same primordial SNRs are also expected to produce bremsstrahlung X-ray radiation. The results of the aforementioned simulations by Whalen et al. (2008) indicate that of the order of 1 per cent of the total explosion energy can be released in the form of X-rays at the late stages of the evolution of the remnant of a primordial SN exploding in a minihalo. The energy efficiency of X-ray production is thus likely an order of magnitude lower than it is for LECRs. Therefore, the X-rays from primordial SNe probably played a less important role in heating the early Universe compared to the CRs produced by the same SNe.

### 3 COSMIC RAY ENERGY LOSSES IN THE IGM

By the time of the dispersal of the SNR and escape of LECRs, the ambient gas, which was previously photoionized by the progenitor star (and by the SNR itself, Johnson & Khocharf 2011), could have recombined and cooled down (the recombination time at $n_0 \sim 10^{-2} - 10^{-3} \text{ cm}^{-3}$, the density in this region, is of the order of a few million years or shorter). Therefore, the LECRs will essentially start travelling through the IGM, with the ionization fraction $x_e = n_e/(n_0 + n_{HI}) \geq 2 \times 10^{-4}$ (here the lower limit is given by the residual ionization fraction after cosmic recombination, Zel’dovich, Kurt & Sunyaev 1969, evaluated for the current concordance cosmology, e.g. Loeb & Furlanetto 2013) and lose their energy by ionizing and exciting H and He atoms.

The loss time-scale for protons in a weakly ionized medium ($x_e \lesssim 0.1$) due to ionization and excitation of hydrogen atoms is (Schlickeiser 2002)

$$t_\text{loss} \approx \frac{E}{dE/dt} \approx \begin{cases} 45 n_{HI} \text{yr}, & E < 45 \text{keV} \\ 3 \times 10^7 n_{HI}^{-1} \left(\frac{E}{1 \text{ MeV}}\right)^{3/2} \text{ yr}, & 45 \text{keV} \leq E < 550 \text{MeV}, \end{cases} \quad (2)$$

where $n_{HI}$ is in units of $\text{cm}^{-3}$. Note that at $E > 550$ MeV, proton energy losses are dominated by pion production, which is not included in equation (2).

Given the cosmic baryon fraction, $\Omega_b = 0.05$, and the contribution of He to the total baryon density, 25 per cent in mass, we obtain the following dependence of $n_{HI}$ on redshift:

$$n_{HI}(z) = 1.8 \times 10^{-3} \left(\frac{1+z}{21}\right)^3 \text{ cm}^{-3}. \quad (3)$$

Substituting this expression into equation (2), we find

$$t_\text{loss} = \begin{cases} 2.5 \times 10^4 \left(\frac{1+z}{21}\right)^{-3} \text{ yr}, & E < 45 \text{keV} \\ 1.6 \times 10^6 \left(\frac{1+z}{21}\right)^{-3} \left(\frac{E}{1 \text{ MeV}}\right)^{3/2} \text{ yr}, & 45 \text{keV} \leq E < 550 \text{MeV}. \end{cases} \quad (4)$$

This time-scale should be compared with the age of the Universe at redshift $z$,

$$t_H \approx 1.9 \times 10^8 \left(\frac{1+z}{21}\right)^{-3/2} \text{ yr}. \quad (5)$$

Therefore, at $z \sim 20$, only subrelativistic CRs with $E \lesssim 30$ MeV could deposit their energy into the IGM within a time comparable...
to the Hubble time at that epoch. Of course, more energetic CRs were also heating the IGM, but much less efficiently. For example, CRs with $E \sim 300$ MeV were able to lose only $\sim 2.5$ per cent of their energy within a Hubble time at $z \sim 20$.

At $E < 10$ MeV, one can use the following approximate formula for the delay between CR production and ensuing IGM heating:

$$
\Delta z \approx -0.75 \left(1 + \frac{1}{2z} \right)^{5/2} \frac{\tau_{\text{loss}}}{10^9 \text{ yr}},
$$

$$
\approx -0.1 \left(1 + \frac{1}{2z} \right)^{-1/2} \frac{E}{1 \text{ MeV}}^{3/2},
$$

at $E < 45$ keV, $\Delta z \approx 0$.

In reality, only some of the energy injected by LECRs into a neutral or weakly ionized IGM will go into heat, with the rest being spent on ionization and excitation of atoms. To evaluate the resulting ionization and heating rates, we should first take into account that each direct ionization of an H atom by a CR proton is accompanied on average by a loss of $\sim 60$ eV by the proton, with about half of this energy going into Ly$\alpha$ line excitation, this result being only weakly dependent of the energy of the proton (Dalgarno & Griffin 1958; Spitzer & Scott 1969). The free electron arising from ionization of an H atom by a CR proton can ionize further H atoms. Both the average number of secondary ionizations and average energy released as heat per primary ionization depend on the ionization fraction of the gas (Spitzer & Scott 1969). If the latter is very low, for instance $x_e \sim 2 \times 10^{-4}$, each free electron resulting from primary ionization of an H atom causes on average $\phi \sim 0.75$ secondary ionizations and the amount of energy that eventually goes into heating the gas (via Coulomb collisions of the secondary electrons with thermal electrons) is $E_{\text{heat}} \sim 8$ eV per primary ionization. Therefore, a CR proton will deposit as heat a fraction $f_{\text{heat}} \sim 8$eV/60eV $\sim 0.13$ of its total energy. If the ionization fraction is higher, $\phi$ decreases while $E_{\text{heat}}$ increases, so that the heating fraction also increases: for $x_e = 0.01$, $\phi = 1.57$, $E_{\text{heat}} = 16$ eV, hence $f_{\text{heat}} \sim 0.27$; for $x_e = 0.03$, $\phi = 1.41$, $E_{\text{heat}} = 22$ eV, hence $f_{\text{heat}} \sim 0.37$; for $x_e = 0.1$, $\phi = 1.25$, $E_{\text{heat}} = 26$ eV, hence $f_{\text{heat}} \sim 0.43$ (see table 1 in Spitzer & Scott 1969). Note that in the case of a strongly ionized medium, with $x_e \gtrsim 0.1$, not considered here, CR protons will release most of their energy as heat due to direct Coulomb collisions with thermal electrons. We also note that ionization and excitation of helium is neglected in our treatment, as is the contribution of non-proton CRs.

Therefore, the IGM heating rate per CR proton of energy $E$ is

$$
\Gamma \approx f_{\text{heat}}(x_e) \frac{E}{\tau_{\text{loss}}(E)}. \tag{7}
$$

where $\tau_{\text{loss}}(E)$ is given by equation (4). The corresponding total ionization rate (number of free electrons produced per unit time) is

$$
\xi = [1 + \phi(x_e)] \frac{E/60 \text{ eV}}{\tau_{\text{loss}}(E)}. \tag{8}
$$

In order to use the above equations, we need to know the ionization fraction $x_e$, which affects the quantities $\phi$ and $f_{\text{heat}}$. If the CR-driven mechanism discussed here were the only reionization/heating mechanism operating at $z \sim 20–15$, we could calculate the IGBox ionization history self-consistently, by following the evolution of $x_e$ and the resulting evolution of $\Gamma$ and $\xi$. Such an integration should start from $x_e \sim 2 \times 10^{-3}$, the minimum possible ionization degree at $z \sim 20$, resulting from the preceding adiabatic expansion of the Universe. However, as mentioned above, already at such low an ionization level a significant fraction ($\sim 15$ per cent) of the energy lost by CRs goes into heating the gas, with this fraction increasing to $\sim 27$ per cent as $x_e$ increases to 0.01. As the IGM ionization fraction may increase to $\sim 1$ per cent due to the propagation of LECRs and the action of some other mechanisms (e.g. X-ray heating) in the early Universe, it is convenient to use some fiducial value for the heating fraction, e.g. $f_{\text{heat}} = 0.25$, fix the average number of secondary ionizations at $\phi = 0.5$ (since it is not strongly dependent on $x_e$), and rewrite equations (7) and (8) as follows:

$$
\Gamma = 0.25 f_{\text{heat}} \frac{E}{0.25 \tau_{\text{loss}}(E)} \tag{9}
$$

and

$$
\xi = \frac{E/40 \text{ eV}}{\tau_{\text{loss}}(E)}. \tag{10}
$$

where $\tau_{\text{loss}}(E)$ is again given by equation (4).

Therefore, only a fraction $f_{\text{heat}} \sim 0.25$ of the total energy $E_{\text{LECR}}$ released by a given minihalo in the form of LECRs (equation 1) will go into heating the IGM, while the remaining $1 – f_{\text{heat}} \sim 0.75$ goes into ionization and excitation of neutral atoms in the IGM. We note that the efficiency, $f_{\text{heat}}(x_e)$, of CR heating discussed here is close to that of X-ray photoionization heating (Shull 1979; Furlanetto & Stoever 2010).

Using equation (1), we can estimate that LECRs from a single minihalo can ionize in total $\sim 8 \times 10^6 \eta_{0.05} f_{\text{SN}}(E_{\text{SN}}/10^{52} \text{ erg}) H$ atoms in the IGM. This number can be compared with the total number of ionizing photons emitted by a Pop III star over its lifetime, which is $\sim 1.5 \times 10^{63}, \sim 7 \times 10^{63}$ and $\sim 1.8 \times 10^{64}$ for $M_{\text{SN}} = 25 M_\odot, 80 M_\odot$ and $200 M_\odot$, respectively (Schaerer 2002; Kitayama et al. 2004), i.e. 2–3 orders larger. As was discussed in Section 2, these UV photons, emitted by the progenitor star, ionize the medium within and in the vicinity of the minihalo before the SN explosion, but cannot ionize and heat the IGM far from minihaloes.

### 4 IMPACT OF PRIMORDIAL SUPERNOVAE ON THE EARLY UNIVERSE

To estimate the impact of LECRs produced by primordial SNe on the IGM, we need to know the abundance of minihaloes collapsed by a given redshift. This can be estimated e.g. using the fitting formula from Sheth, Mo & Tormen (2001). The result depends on the definition of a minihalo, i.e. on the minimum and maximum halo masses. We adopt $M_{\text{min}} = 10^5 M_\odot$ and $M_{\text{max}} = 10^7 M_\odot$ as fiducial values. In the redshift range of interest here, $z \sim 10–30$, the abundance of minihaloes is mostly sensitive to the lower boundary of the mass range; e.g. it increases by a factor of $\sim 5$ at $z \sim 15–20$ if we use $M_{\text{min}} = 3 \times 10^5 M_\odot$ instead of $M_{\text{min}} = 10^5 M_\odot$. We should also take into account that IGM heating is delayed with respect to LECR production by $\Delta z(E)$. As discussed above (in Section 3), this delay is negligible for $E < 1$ MeV but becomes large for $E > 1$ MeV. Taking into account the uncertainties in the LECR spectrum and especially in the energetics of primordial SNe, it seems reasonable to use a time lag corresponding to a fixed particle energy $E = 1$ MeV, so that $\Delta z \sim -0.1$ (see equation 6), in estimating the cumulative effect of LECRs on the IGM.

Assuming that each minihalo produces $f_{\text{SN}}$ SNe with energy $E_{\text{SN}}$, of which a fraction $\eta$ is liberated as LECRs, and then a fraction $f_{\text{heat}}$
mentioned in Section 2. In our model, there are \( \sim 180 \) haloes with \( M_0 = 10^6 - 10^7 M_\odot \) per (comoving) Mpc\(^3\) formed by \( z = 15 \), and hence nearly the same (there is a small difference due to \( \Delta z \)) number of SNe exploded by the same redshift. For comparison, in Xu et al. (2013) simulations there are \( \sim 100 \) Pop III stars and remnants per Mpc\(^3\) produced by \( z = 15 \) (see their fig. 2). Although these numbers are rather close to each other, one should take into account that Xu et al. (2013) considered an overdense (i.e. biased) region of the Universe and so the number density they find for haloes with \( M_0 \gtrsim 10^6 M_\odot \) is higher than the average over the Universe by a factor of a few. On the other hand, their simulations have a resolution of \( 10^7 M_\odot \) and so may somewhat underestimate star formation in minihaloes with \( M_0 \lesssim 10^5 M_\odot \), also because in more typical (i.e. less dense) regions of the Universe suppression of star formation may be less efficient due to the weaker LW background. Taking these considerations into account, it appears that our \( M_{\text{min}} = 10^5 M_\odot, f_{SN} = 1 \) model is not unrealistic. For comparison, the \( M_{\text{min}} = 3 \times 10^5 M_\odot, f_{SN} = 1 \) case is probably overly optimistic since it has \( \sim 5 \) times as many minihaloes by \( z = 15 \) as in the case of \( M_{\text{min}} = 10^6 M_\odot \) while only a minority of such low-mass haloes are likely to be able to produce Pop III stars and hence SNe (see again Xu et al. 2013 and references therein).

We conclude that, although LECRs from primordial SNe are unlikely to significantly contribute to the reionization of the Universe (\( \Delta x_e \) is less than \( \sim 1 \) per cent), they can cause a significant early heating of the IGM. In particular, in our tentatively favoured model with \( E_{SN} = 10^{52} \) erg, \( f_{SN} = 1 \) and \( M_{\text{min}} = 10^5 M_\odot \), the IGM gets heated above the CMB temperature, \( T_{\text{CMB}} = 2.725(1+z)K \sim 30 \) K by \( z = 12 \). In the pessimistic scenario with \( E_{SN} = 10^{51} \) erg, the resulting increment in the IGM temperature remains smaller than \( T_{\text{CMB}} \) over the whole considered redshift range of \( z = 30 - 10 \), while in the optimistic case of \( E_{SN} = 10^{53} \) erg (corresponding to an initial mass function dominated by massive Pop III stars exploding as pair-instability SNe), the IGM can be heated above the CMB temperature already by \( z \sim 18 \). These estimates, however, also depend on the \( \eta \) parameter, which characterizes the efficiency of LECR production by primordial SNe and is uncertain by roughly an order of magnitude (see the discussion prior to equation (1)), as well as on the \( M_{\text{min}} \) and \( f_{SN} \) parameters determining the efficiency of Pop III and SN production in minihaloes, which are fairly uncertain too.

### 4.1 Spatial distribution of heating

If there were no magnetic fields in the IGM, the LECRs produced by primordial SNRs would freely stream through the early Universe and lose all of their energy within a (proper) distance \( R_{\text{free}} = \int v(t)dt \), where \( v(t) = [2E(t)/m_p]^{1/2} \) is the particle velocity which decreases from the initial value of \( v_0 = (2E_0/m_p)^{1/2} \) to zero at a rate \( dv/dt = [2m_pE(t)]^{-1/2}dE/dt \), where \( dE/dt = E/\tau_{\text{los}}(E) \) and \( \tau_{\text{los}}(E) \) is given by equation (4). Performing the integration, we find

\[
R_{\text{free}}(\text{proper}) \approx \int \left( \frac{1+z}{21} \right)^{-3} \left( \frac{E}{1\text{MeV}} \right)^2 \text{kpc.}
\]

For \( E \gtrsim 1 \text{ MeV} \), this distance is larger than the average distance between minihaloes at \( z = 20 \), \( R_0 \sim 5-10 \) kpc (depending on the minimum mass of minihaloes, \( M_{\text{min}} \)). For \( E \sim 30 \text{ MeV} \), the highest CR proton energy that can be deposited into the IGM within the Hubble time at \( z \sim 20 \) (see Section 3 above), \( R_{\text{free}} \) is \( \sim 17 \) per cent of the Hubble distance in that epoch.

In the presence of magnetic fields, the LECRs will random-walk through the IGM. In the early cosmic epochs considered here, only
very weak magnetic fields, generated during inflation or early cosmological phase transitions, might have been present in the IGM (see Durrer & Neronov 2013 for a review). Unfortunately, current theoretical predictions in this respect are very uncertain. There is, however, an interesting lower limit on the magnetic fields in voids in the present-day Universe, determined from gamma-ray observations of blazars (Neronov & Vovk 2010; Tavecchio et al. 2011): $B \gtrsim 10^{-16}$ G. Taking into account that the IGM in voids might have been contaminated by magnetized outflows from galaxies by the present epoch but on the other hand magnetic fields decay as $(1+z)^2$ during the expansion of the Universe (due to magnetic flux conservation), we may adopt $B_{\text{IGM}} = 10^{-16}$ G as a fiducial value for the IGM field at $z \sim 15$. This of course assumes that LECRs are injected directly into the IGM at very late stages of SNR evolution ($\gtrsim 10^4$ yr after the SN explosion, see the preceding discussion in Section 2.1), i.e. outside the host minihalo. Nevertheless, the SN blast wave may amplify (by the dynamo mechanism) magnetic fields in its vicinity, which might affect the initial diffusion of LECRs through the IGM.

The minimum possible diffusivity is the Bohm diffusivity, given by $D_{\text{Bohm}} = v_{\text{f}} r_g / 3$, where the Larmor radius $r_g = m_e v_c/eB$. Therefore, the LECRs will move away from the source by at least

$$R_{\text{Bohm}}(\text{proper}) \sim \sqrt{-\int D_{\text{Bohm}}(t) dt} \sim 2.6 \left(\frac{1+z}{21}\right)^{-3/2} \left(\frac{B_{\text{IGM}}}{10^{-16} \text{ G}}\right)^{-1/2} \left(\frac{E}{1 \text{ MeV}}\right)^{5/4} \text{kpc},$$

before losing all of their energy. This distance is larger than the average distance between the minihaloes at $z = 20$ if $E \gtrsim 2$ MeV. In reality, IGM magnetic fields may be ordered, which would accelerate CR diffusion compared to Bohm diffusion. Hence, the true distances covered by LECRs are probably somewhere between $R_{\text{Bohm}}$ and $R_{\text{free}}$ (note that if $R_{\text{Bohm}} > R_{\text{free}}$ then one should use $R_{\text{free}}$).

Since both $R_{\text{free}}$ and $R_{\text{Bohm}}$ fairly strongly depend on proton energy and particles with $E \lesssim 1$ MeV and $1$ MeV $\lesssim E \lesssim 30$ MeV probably contain $\sim 2/3$ and $\sim 1/3$ of the total energy in LECRs, respectively (assuming an intrinsic energy distribution $dN/dE \propto E^{-3}$), the resulting IGM heating should be somewhat concentrated towards the minihaloes, especially if IGM magnetic fields are strong enough to influence the propagation of LECRs. Should the CR energy spectrum be steeper, $dN/dE \propto E^{-\beta}$ with $\beta > 2$, particles with $E \lesssim 1$ MeV will carry a larger fraction of the total energy budget, leading to stronger concentration of heating around the minihaloes. In the opposite case of a flatter CR energy distribution ($\beta < 2$) the IGM will be heated more uniformly.

For comparison, in the case of X-ray heating, the mean free path of a photon with energy $E$ is $\tau(E) = (n_{\text{H}1} r_g)^{-1}$, where the photoionization cross-section for H–He primordial gas (Verner et al. 1996) can be roughly approximated as $\sigma \approx 6 \times 10^{-20} (E/100 \text{ eV})^{-3.2}$ cm$^2$ for $E \gtrsim 100$ eV. Therefore, taking into account equation (3), an X-ray photon releases its energy within

$$R_{\text{X-ray}}(\text{proper}) \sim \tau(E) \sim 100 \left(\frac{1+z}{21}\right)^{-3} \left(\frac{E}{300 \text{ eV}}\right)^{3.2} \text{kpc},$$

of the source (taking into account that the photoelectron quickly shares its energy with the ambient IGM). Since even for soft X-rays with $E \sim 150$ eV $R_{\text{X-ray}}$ is of the order of typical distances between minihaloes at $z \sim 20$, while for $E \gtrsim 2$ keV $R_{\text{X-ray}}$ is larger than the Hubble distance at $z \sim 20$, X-ray heating is likely to affect the primordial IGM more uniformly.

In reality, similarly to the case of IGM heating by soft X-ray radiation (see e.g. Xu et al. 2014), LECR-driven heating should be concentrated around high-density regions of the early Universe since there is clustering of minihaloes due to halo biasing.

### 5 Discussion and Conclusions

We have demonstrated that subrelativistic ($E \lesssim 30$ MeV) CRs produced by primordial SNe could heat the IGM by $\sim 10–100$ K by $z \sim 15$. The expected magnitude of this effect is currently uncertain by at least an order of magnitude, mainly because of our poor knowledge of the properties (in particular, number density and initial mass function) of Pop III stars and SNe associated with them. Provided that there were no strong chaotic magnetic fields in the primordial IGM, such LECRs could deposit their energy into the IGM at distances much larger than the virial radii of their host minihaloes ($\sim 100$ pc) but of the order of or larger than (depending on the particle energy) typical (proper) distances between such haloes ($\sim 5–10$ kpc), and much smaller than the Hubble horizon.

Along with heating, LECRs from primordial SNe were also ionizing the IGM, but could not raise its ionization level by more than $\sim 1$ per cent at $z \sim 15$. Although this resulting ionization fraction is $1–2$ orders of magnitude higher than the initial free electron fraction that remained after cosmic recombination, it is still too low for recombination to start playing a significant role in the IGM at these redshifts. Interestingly, if the IGM was already ionized to more than a few per cent by some other mechanism (e.g. X-ray photoionization) by that epoch, the CR heating mechanism would be operating more efficiently, as LECRs could then release a larger fraction of their energy as heat (more than $40$ per cent instead of $25$ per cent assumed as a fiducial value in our estimates). Therefore, there might have been some synergy between CR and X-ray heating in the early Universe.

The overall heating effect associated with CRs from primordial SNe can be at least comparable to that associated with X-rays from the first generation of miniquasars and high-mass X-ray binaries. From the point of view of 21-cm observations of the early Universe, the global signatures of CR IGM heating should be similar to those of X-ray heating. In particular, depending on the cumulative power of the first SNe, the hydrogen spin temperature will couple to the (increased) IGM kinetic temperature by $z \sim 15$, which will cause the 21-cm signal to change from absorption to emission. The spatial properties of the 21-cm signal will depend on the topology and strength of the IGM magnetic fields in the early Universe. Therefore, 21-cm measurements could potentially provide information on the frequency and energetics of primordial SNe as well as on the magnetic fields in the primordial IGM.

Throughout this study, we assumed that LECRs are protons. In reality, a significant fraction of CRs with $E \lesssim 1$ MeV should turn into neutral H atoms by charge exchange with ambient hydrogen (and helium) atoms, before depositing all of their energy into the IGM. This can be understood from a comparison of the cross-sections for H$^+$–H charge exchange and ionization of H atoms by fast protons (see e.g. Fig. 1, based on data provided by the International Atomic Energy Agency, in the paper by Blasi et al. 2012 devoted to a similar phenomenon occurring during acceleration of CRs in collisionless shocks). Indeed, the ionization cross-section is $\sim 10^3$ times larger than the charge-exchange cross-section for $E \sim 500$ keV, with this ratio rapidly decreasing with decreasing energy. Therefore, since

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5 http://www-amdis.iaea.org/ALADDIN/
each H ionization is accompanied on average by a loss of $\sim 60$ eV by a CR proton (see Section 2.1). sub-MeV CRs will experience $\sim 10^8$ ionization and excitation collisions before losing their energy and will thus have a significant probability to turn into H atoms. Such neutral sub-MeV particles should be approximately as efficient in ionizing and heating the IGM as CR protons of similar energies, but, unaffected by IGM magnetic fields, will be able to propagate to larger distances from their host minihaloes. This is an interesting aspect of the problem at hand, which should be considered in more detail (in particular, taking into account helium) in future work.

Another potentially interesting implication of this study is that the global IGM preheating caused by LECRs from the first SNe may negatively affect further collapse of gas in minihaloes and star formation in the early Universe by raising the characteristic Jeans mass. According to our estimates, such feedback might be important if primordial SNe were predominantly pair-instability ones, with $E_{SN} \sim 10^{53}$ erg. A similar effect has been discussed for the case of X-ray heating (see e.g. Kuhlen & Madau 2005). On the other hand, again similarly to X-rays (see e.g. Hummel et al. 2014), LECRs from the first SNe may provide positive feedback on star formation in neighbouring and distant minihaloes by increasing the ionization fraction in their gas and hence catalyzing the formation of molecular hydrogen, which is the main coolant in the primordial gas.

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