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# Intergalactic Heating Induced by Streaming Cosmic Rays in the Early Universe

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Our Universe has undergone a transition from a cold and neutral state to a hot and ionized state. In the standard picture, this transition is caused by UV and X-ray photons emitted by stars and galaxies. However, cosmic rays (CRs) can also contribute to the heating and ionization of the cosmic gas. It is suggested that CRs are accelerated in the early Universe in the supernova remnants of the first stars, just as they are in the current Universe. Although it has been pointed out that ionization by CRs raises the global temperature of the intergalactic medium by 10 to 200 K, in our previous work, we found that the heating rate of resistive heating induced by streaming CRs can exceed that of ionization heating. The resistive heating is caused by the electron return current induced by streaming CRs. In this work, we study the heating around a galaxy, which is the source of photons and CRs, including the photo-heating, CR ionization heating, and CR resistive heating. It is shown that the gas in the vicinity of the galaxy is rapidly heated up to $\sim 10^4$ K by CR resistive heating.

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## 1. Introduction

In the current Universe, cosmic rays (CRs) play a vital role in determining the plasma environment of galaxies [e.g. 1]. In the same way, it is natural to suppose that CRs accelerated in the early Universe affects the evolution of galaxies and intergalactic medium (IGM). However, investigating the influence of CRs in high-$z$ environment is a challenging work, because of complex interplay between CRs and galaxies and IGM (Figure 1). Although in the current Universe, CRs are thought to be accelerated in the supernova remnants (SNRs) [e.g. 2], it is not trivial whether CRs are accelerated in the early Universe in the same way, since the strength of the magnetic field, which is necessary to confine the CRs, may be weaker. However, it is shown that, even if the initial magnetic field is small, CR acceleration up to $\sim$ GeV energy is possible in the SNRs of the first stars, because turbulent magnetic fields are generated by plasma instabilities [3]. Because acceleration and propagation of CRs depend on the nature of galactic magnetic field, we have to understand the evolution of the magnetic field in high-$z$ galaxies. Here, in this work, we will investigate the influence of CRs on IGM environment simply assuming that CRs freely escape from a galaxy.

Because of the streaming velocity of CRs, they can generate the intergalactic magnetic fields. It was shown that the magnetic field with $B \sim 10^{-16}$, G, which is sufficient as the seed of the galactic magnetic field, can be generated by steaming CRs [4–6]. In addition, CRs can also induce the heating of the IGM by ionization, by Coulomb interactions, and by inducing resistive electric field [e.g. 7, 8]. In this work, we investigate this resistive process in detail.

## 2. Heating mechanisms

We consider that CRs freely escape from a galaxy into the thermal intergalactic plasma. Because the CRs are mainly composed of protons, streaming CRs drive electric current ($\boldsymbol{J}_{\rm CR}$). In order to cancel out the CR current, return current is induced by thermal electron flow. However, because the collisions between thermal electrons and thermal protons are negligible, resistive electric field is induced in order to maintain the return current, and this causes the resistive Joule heating. The temperature evolution of the intergalactic gas heated by the Joule heating induced by the resistive

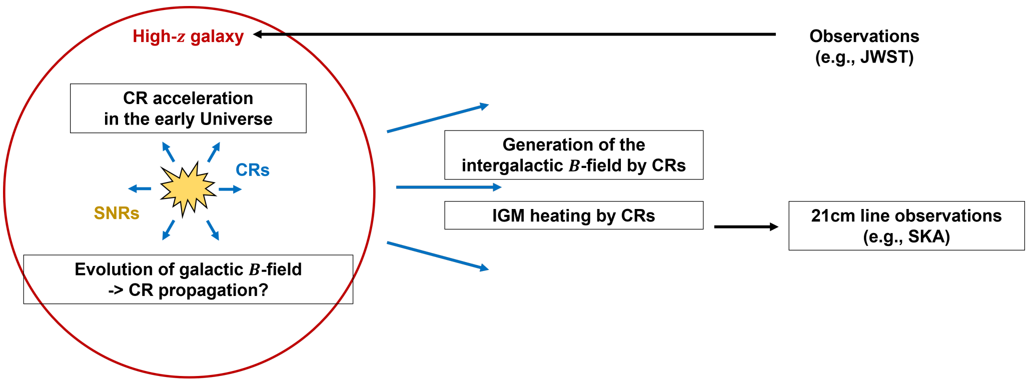


**Figure 1:** Conceptual figure of CR effects in the early Universe.

electric field is described by

$$\frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{3}{2}(1+\chi_{\mathrm{e}})n_{\mathrm{H}}k_{\mathrm{B}}T\right) = \eta \boldsymbol{J}_{\mathrm{CR}}^2, \tag{1}$$

where $\chi_{\mathrm{e}}$ is the ionization degree. The resistivity by Coulomb collisions between thermal particles is given by the so-called Spitzer resistivity $\eta \simeq 1.4 \times 10^{-7}(T/1\,\mathrm{K})^{-3/2}\,\mathrm{s}^{-1}$. We will numerically solve this equation with other heating mechanisms, that is, X-ray heating and CR direct heating, in the next section.

## 3. Model calculation

In this section, we calculate the temperature evolution of the IGM around a galaxy by assuming a simplified model. First, we assume that UV photons from stars in the galaxy are consumed to produce a $\mathrm{H_{II}}$ region around the galaxy. The radius of the $\mathrm{H_{II}}$ is estimated to be $\lesssim 10\,\mathrm{kpc}$ [e.g. 9]. Because we consider the heating outside this radius, we ignore the heating by UV photons. Then, the IGM heating is caused by X-rays and CRs from the galaxy, and we assume that X-rays and CRs freely escape from the galaxy.

Although the X-ray and CR luminosity of the high-$z$ galaxies are largely uncertain, here we estimate them as a function of star formation rate (SFR) utilizing the relation in the current Universe [10]:

$$L_{\mathrm{X}} = 3.4 \times 10^{40}\,\mathrm{erg\,s^{-1}}\left(\frac{f_{\mathrm{X}}}{1}\right)\left(\frac{\mathrm{SFR}}{1\,\mathrm{M_{\odot}yr^{-1}}}\right), \tag{2}$$

$$L_{\mathrm{CR}} = 3.2 \times 10^{40}\,\mathrm{erg\,s^{-1}}\left(\frac{\varepsilon_{\mathrm{CR}}}{0.1}\right)\left(\frac{\mathrm{SFR}}{1\,\mathrm{M_{\odot}yr^{-1}}}\right)\left(\frac{E_{\mathrm{SN}}\nu_{\mathrm{SN}}}{10^{49}\,\mathrm{erg\,M_{\odot}^{-1}}}\right), \tag{3}$$

where $f_{\mathrm{X}}$ is a correction factor which compensate the large uncertainty about the nature of X-ray emitters in the early Universe. In Equation (3), we have assumed that a supernova liberates energy of $E_{\mathrm{SN}} = 10^{51}$ erg at a rate $\nu_{\mathrm{SN}} = 10^{-2}\,\mathrm{M_{\odot}\,yr^{-1}}$ and 10 % ($\varepsilon_{\mathrm{CR}} = 0.1$) of the explosion energy is converted to the CR energy. In addition, we assume that both X-rays and CRs have power-law energy distribution $L_\nu \propto \nu^{-\alpha}$ and $\mathrm{d}n/\mathrm{d}p \propto p^{-s}$, respectively, with $\alpha = 1.5$ and $s = 2.0$. The minimum and maximum energy of X-rays are set as $h\nu_{\mathrm{min}} = 0.2\,\mathrm{keV}$ and $h\nu_{\mathrm{max}} = 10\,\mathrm{keV}$, and those of CRs are chosen as $E_{\mathrm{min}} = 3\,\mathrm{MeV}$ and $E_{\mathrm{max}} = 3\,\mathrm{GeV}$ [3, 10].

With these assumptions for the X-ray and CR sources, we can evaluate the heating rate of the IGM as a function of the distance $r$ from the galaxy. Here, we consider three processes: X-ray heating by photoionization, CR direct heating by ionization of neutral particles and by Coulomb interaction with free electrons, and the aforementioned CR resistive heating. X-ray heating rate density is estimated by

$$\varepsilon_{\mathrm{X}} = n_{\mathrm{H_I}}\int_{\nu_{\mathrm{min}}}^{\nu_{\mathrm{max}}} \frac{\eta_{\mathrm{X}}L_\nu}{4\pi r^2 h\nu}\sigma_\nu(h\nu - I_{\mathrm{H}})e^{-\tau_\nu}\mathrm{d}\nu, \tag{4}$$

where $\eta_{\mathrm{X}}$ is the fraction of X-ray energy converted to the thermal energy of gas, and $\tau_\nu = n_{\mathrm{H_I}}\sigma_\nu r$ describes the deficit by photo-absroption. $\sigma_\nu = \sigma_0(\nu/I_{\mathrm{H}})^{-3}$ is the frequency-dependent cross-section for photoionization, $\sigma_0 = 6.3\times 10^{-18}\,\mathrm{cm^{-3}}$, and $I_{\mathrm{H}} = 13.6\,\mathrm{eV}$ is the first ionization potential of neutral hydrogen. The heating rate density of the CR direct heating is given by the sum of the ionization heating and Coulomb heating as

$$\varepsilon_{\mathrm{CR,\,dir}} = \int_{p_{\min}}^{p_{\max}} \left[ \left( \frac{\mathrm{d}E}{\mathrm{d}t} \right)_{\mathrm{C}} + \left( \frac{\mathrm{d}E}{\mathrm{d}t} \right)_{\mathrm{I}} \right] \frac{\mathrm{d}n}{\mathrm{d}p} \mathrm{d}p, \tag{5}$$

where

$$\left( \frac{\mathrm{d}E}{\mathrm{d}t} \right)_{\mathrm{C}} = \frac{4\pi e^4 n_{\mathrm{e}}}{m_{\mathrm{e}} \beta c} \left[ \ln \left( \frac{2 m_{\mathrm{e}} c^2 \beta}{\hbar \omega_{\mathrm{pe}}} \right) - \frac{\beta^2}{2} \right], \quad \left( \frac{\mathrm{d}E}{\mathrm{d}t} \right)_{\mathrm{I}} = \frac{4\pi e^4 n_{\mathrm{H_I}}}{m_{\mathrm{e}} \beta c} \left[ \ln \left( \frac{2 m_{\mathrm{e}} c^2}{I_{\mathrm{H}}} p^2 \right) - \beta^2 \right] \tag{6}$$

are the loss rates by Coulomb interaction and by ionization, respectively [e.g. 7]. $\beta = v/c$ and $p = \gamma v/c$ are the normalized particle velocity and momentum and $\omega_{\mathrm{pe}}$ is the electron plasma frequency. The CR resistive heating rate density is given by $\varepsilon_{\mathrm{CR,\,res}} = \eta J_{\mathrm{CR}}^2$, and $J_{\mathrm{CR}}$ is obtained by the first moment of CR momentum distribution.

Figure 2 shows the results of numerical integration of Equation (1) with the above three heating mechanisms, that is, the RHS is replaced by $\varepsilon_{\mathrm{X}} + \varepsilon_{\mathrm{CR,\,dir}} + \varepsilon_{\mathrm{CR,\,res}}$). The initial conditions are $T_0 = 1$ K, $n_{\mathrm{H}} = 10^{-4}$, and $\chi_{\mathrm{e}} = 10^{-3}$, and are set to mimic the average IGM environment at $z \sim 10$ before the reionization. The density $n_{\mathrm{H}}$ and ionization degree $\chi_{\mathrm{e}}$ are fixed in this calculation, and we discuss this point in the next section. The right panel shows the instantaneous heating rate densities of X-ray heating (blue), CR direct heating (orange), CR resistive heating when the temperature varies only by CR hearing (red), and CR resistive heating when both X-rays and CRs heat the gas. The left panel is the temperature distribution when only X-rays heat the gas (blue), when only CR heat (red), and when both X-ray and CR heating work. The dotted, dashed, and solid lines show the temperature at $t = 1 \times 10^5$, $5 \times 10^6$, and $1 \times 10^8$ yr, respectively. The integration is stopped by hand at $T = 2 \times 10^4$ K, assuming that atomic cooling becomes important above this energy. This figure clearly indicates that CR resistive heating is important in the vicinity of the galaxy until the gas temperature reaches $T \sim 10^4$ K. As the temperature increases, the resistive heating becomes less efficient because of the temperature dependence of the Spitzer resistivity.

## 4. Discussion

In this work, we ignored the time variation of all the parameters other than the gas temperature for simplicity. The ionization degree $\chi_{\mathrm{e}}$ must change as the temperature increases, and as the ionization degree approaches $\chi_{\mathrm{e}} = 1$, the X-ray heating becomes less efficient. X-ray and CR luminosity can also vary due to the variation in star formation activity and galaxy evolution. In addition, while we considered only the collisions between protons and electrons, collisions between electrons and neutrals will become relatively important as the temperature increases. Heating caused by kinetic plasma instabilities induced by CR beam might also be important. These heating mechanisms should be investigated in future studies.

While we assumed that CRs freely escape from a galaxy, the CR motion is well described by diffusion rather than free-streaming when the intergalactic magnetic field is strong and turbulent. Although the recent gamma-ray observations suggest that magnetic field with $B \gtrsim 10^{-16}$ G exist even in the void region [e.g. 11], the nature of the intergalactic magnetic field is highly uncertain. In addition, streaming CRs can also generate the magnetic field [4–6]. Therefore, the self-consistent

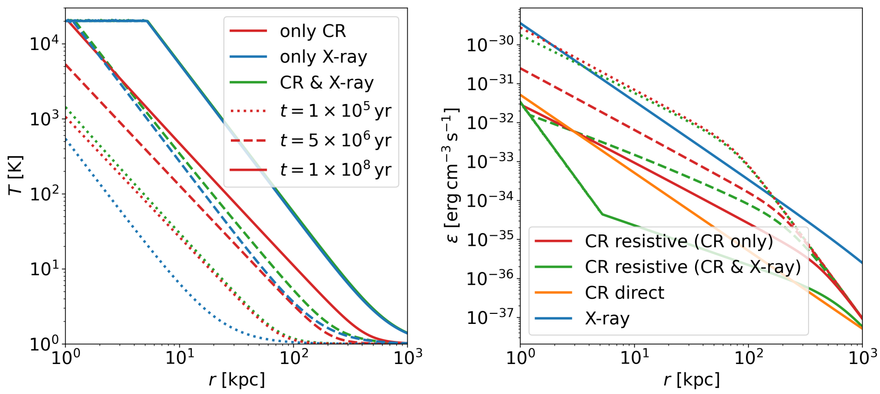


**Figure 2:** The left panel is the temperature distribution when only X-rays heat the gas (blue), when only CR heat (red), and when both X-ray and CR heating work. The dotted, dashed, and solid lines show the temperature at $t = 1 \times 10^5$, $5 \times 10^6$, and $1 \times 10^8$ yr, respectively. The right panel shows the instantaneous heating rate densities of X-ray heating (blue), CR direct heating (orange), CR resistive heating when the temperature varies only by CR hearing (red), and CR resistive heating when both X-rays and CRs heat the gas.

treatment of magnetic field generation and amplification and CR propagation is necessary to accurately determine the heating rate.

## 5. Summary

We showed that resistive heating induced by CRs can be dominant over the other mechanisms in the vicinity of a galaxy. The temperature reaches $10^4$ K at $r = 1$ kpc in $2 \times 10^6$ yr. In order to determine the CR heating rate more accurately, it is important to understand the galactic plasma environment, especially galactic magnetic field, in the early Universe. Understanding the role of CRs in the early Universe is quite important because CRs affect the evolution of the gas through heating, magnetic field generation and amplification, and metal transport, thereby affecting the subsequent galaxy evolution. The signature of IGM heating by CRs may be found by future 21-cm line observations because CR heating has a characteristic length scale different from that of X-ray heating.

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