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# Acceleration of secondary electrons by cosmic-ray discharge in the universe

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We recently proposed a new discharge process caused by streaming cosmic rays (CRs) in the universe. The CRs current drives a return current of thermal electrons to compensate for the CR current. Then, a resistive electric field is induced by the resistivity of the return current. In this work, we show that the resistive electric field can accelerate secondary electrons which is generated by the CRs. We investigate the evolution of the energy spectrum of secondary electrons by solving the Boltzmann equation numerically. The discharge accelerates high-energy secondary electrons, resulting in enhancements of ionization and heating. The return current of thermal electrons is not fully replaced by the electric current of secondary electrons after the discharge. In a quasi-steady state, although the resistive electric field is weaker than one before the discharge, the weak resistive electric field accelerates the secondary electrons weakly. The quasi-steady state spectrum of secondary electrons is formed by a balance of the weak acceleration and the energy loss due to excitation and ionization of hydrogen atoms or molecules.

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## 1. Introduction

The energy of CRs is much larger than the energy scale of any astrophysical objects, so that CRs play various roles in the universe. One of the CR's roles is ionization in dense molecular clouds in the universe [1]. In addition, CRs generate high-energy secondary electrons in Earth's atmosphere. In thunderclouds of Earth's atmosphere, an electric field is generated by the charge separation due to friction [2]. The high-energy secondary electrons are accelerated by the electric field in thunderclouds and generate further secondary electrons. This discharge in thunderclouds is expected to be the origin of some types of gamma-ray flares from thunderclouds [3].

Streaming CRs in the universe induce a resistive electric field by the Coulomb interaction of the return current of thermal electrons [4, 5]. We recently found that secondary electrons generated by CRs can be accelerated by the resistive electric field induced by streaming CRs themselves [6]. In addition, we provided the self-discharge condition and runaway-acceleration condition. In this work, we investigate the evolution of energy spectrum of secondary electrons during the CR self discharge. To investigate the spatial evolution of discharge processes, we numerically solve a steady-state Boltzmann equation.

## 2. Self-discharge condition

We review the self-discharge condition [6] in this section. Once streaming CRs enter a region, the system drives a return current to satisfy the charge and current neutrality conditions. Then, thermal electrons have a drift velocity, $V_{\rm e} = (n_{\rm CR}/n_{\rm e})V_{\rm CR}$ in the thermal proton rest frame. $n_{\rm CR}, n_{\rm e}$, and $V_{\rm CR}$ are the CR density, electron density, and the streaming velocity of CRs. For simplicity, the CR charge is assumed to be the positive elementary charge, $e$, and the thermal plasma is assumed to be composed of protons and electrons. If the electron temperature is on the order of $T_{\rm e} = 10$ K, the Coulomb interaction between thermal electrons and protons is the main source of the resistivity as long as the electron fraction is larger than $\sim 5 \times 10^{-8}$. The time scale for the Coulomb scattering is given by

$$t_{\rm C} = 1.9 \times 10^{-1}~{\rm sec} \left(\frac{n_{\rm e}}{1~{\rm cm}^{-3}}\right)^{-1} \left(\frac{T_{\rm e}}{10~{\rm K}}\right)^{\frac{3}{2}} . \tag{1}$$

From Ohm's law, the resistive electric field before discharge is given

$$\begin{aligned} E_0 &= -\frac{m_{\rm e} n_{\rm CR} V_{\rm CR}}{e n_{\rm e} t_{\rm C}} \\ &= -9.5 \times 10^{-14}~{\rm V~cm}^{-1} \left(\frac{V_{\rm CR}}{c}\right) \left(\frac{n_{\rm CR}}{10^{-9}~{\rm cm}^{-3}}\right) \left(\frac{T_{\rm e}}{10~{\rm K}}\right)^{-\frac{3}{2}} , \end{aligned} \tag{2}$$

where $m_{\rm e}$ is the electron mass. It should be noted that the above electric field depends only on the CR current and the electron temperature.

The typical energy of secondary electrons generated by the CR interaction with hydrogen atoms or molecules corresponds to the first ionization potential, that is, $\varepsilon \sim 10$ eV. The excitation and ionization of neutral hydrogens are main energy loss process of the secondary electrons as long as an electron fraction of $n_{\rm e}/n_{\rm H}$ is smaller than $8.3 \times 10^{-4}$. The CR discharge happens if the energy gain from the electric field, $E$, is larger than the energy loss of the secondary electrons. Therefore, the discharge condition is given by

$$\frac{\mathrm{d}\varepsilon}{\mathrm{d}t} = -eEv + \dot{\varepsilon}_{\mathrm{loss}} > 0, \tag{3}$$

where $v$ is the velocity of secondary electrons and $\dot{\varepsilon}_{\mathrm{loss}}$ is the energy loss rate. For a atomic gas, the energy loss rates at $\varepsilon = 10$ eV is given by $\dot{\varepsilon}_{\mathrm{loss}} = -6 \times 10^{-8}$ eV s$^{-1}(n_{\mathrm{H}}/1\ \mathrm{cm}^{-3})$. Then, the self-discharge condition (3) is reduced to

$$n_{\mathrm{CR}} V_{\mathrm{CR}} > 3.2 \times 10^{-1}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1} \left(\frac{T_{\mathrm{e}}}{10\ \mathrm{K}}\right)^{\frac{3}{2}} \left(\frac{n_{\mathrm{H}}}{1\ \mathrm{cm}^{-3}}\right). \tag{4}$$

The self-discharge condition is satisfied more easily in gases with lower temperatures and lower densities because the lower temperature makes the resistive electric field larger and the lower density makes the energy loss of the secondary electrons smaller.

## 3. Spectral evolution of secondary electrons

In our previous work [6], we analytically solved the evolution of the resistive electric field by using a fluid approximation for the secondary electrons. Furthermore, we did not consider ionization by secondary electrons, that is, we did not consider the avalanche process during discharge. To improve these points, in this work, we numerically solve the one-dimensional spatial evolution of energy spectrum of secondary electrons in the direction of the CR streaming, where ionization by primary CRs and secondary electrons is considered. We consider only the one dimensional velocity space, $v_{\mathrm{x}} > 0$, in the direction of CR streaming. Then, the kinetic energy is given by $\varepsilon = m_{\mathrm{e}} v_{\mathrm{x}}^2/2$.

In this work, we do not solve the evolution of primary CR spectrum, but assume a spatially uniform distribution, that is, we simply assume a constant CR current. This approximation is valid as long as the energy loss of primary CRs is negligible and the dynamical timescale of the CR source is longer than the timescale that we consider here.

We set the left boundary at $x = 0$ and solve the spatial development of secondary electrons spectrum in $x > 0$, where the directions of CR streaming and development of discharge is the positive x direction. The region in $x < 0$ is assumed to be warm or hot medium, where the resistivity and the resistive electric field are negligible because of the high temperature ($T \gtrsim 10^4$ K). The region in $x \geq 0$ is assumed to be cold medium (atomic or molecular clouds), where the temperature is cold and $T \sim 10^1 - 10^2$ K. Then, discharge processes start to happen at $x = 0$ and a quasi-steady state is expected to be realized at a sufficient distance from $x = 0$.

The Boltzmann equation for secondary electrons in the steady state is given by

$$v_{\mathrm{x}} \frac{\partial f_{\mathrm{2nd}}}{\partial x} + \frac{\partial}{\partial \varepsilon}(\dot{\varepsilon} f_{\mathrm{2nd}}) = Q_{\mathrm{ion,CR}} + Q_{\mathrm{ion,2nd}} + Q_{\mathrm{ex,2nd}}, \tag{5}$$

where $\dot{\varepsilon}$ in the second term on the left hand side is given by

$$\dot{\varepsilon} = -eE_{\mathrm{x}} v_{\mathrm{x}} - \dot{\varepsilon}_{\mathrm{C,loss}}(\varepsilon) \tag{6}$$

The first and second terms describe acceleration by the resistive electric field and the the Coulomb loss, respectively. In this work, we use the continuous slowing-down approximation for the Coulomb loss, but exactly solve energy loss processes for ionization and excitation as discrete processes. The energy loss rate due to the Coulomb loss is [7]

$$\dot{\varepsilon}_{\rm C,loss}(\varepsilon) = -2\times 10^{-4}~{\rm eV~s^{-1}}\left(\frac{n_{\rm e}}{1~{\rm cm^{-3}}}\right)\left(\frac{\varepsilon}{1~{\rm eV}}\right)^{-0.44}. \tag{7}$$

The resistive electric field is given by Ohm's law ($E_{\rm x} = -m_{\rm e}V_{\rm e}/et_{\rm C}$) and the current neutrality condition ($en_{\rm e}V_{\rm e} = J_{\rm CR} + J_{\rm 2nd}$),

$$E_{\rm x} = -\frac{m_{\rm e}}{e^2 n_{\rm e} t_{\rm C}}\left(J_{\rm CR} + J_{\rm 2nd}\right), \tag{8}$$

where the current of the secondary electrons is calculated by

$$J_{\rm 2nd} = -e\int f_{\rm 2nd}(\varepsilon)v_{\rm x}d\varepsilon. \tag{9}$$

$Q_{\rm ion,CR}$, $Q_{\rm ion,2nd}$, and $Q_{\rm ex,2nd}$ are given by

$$Q_{\rm ion,CR}(\varepsilon) = n_{\rm H}\int \frac{{\rm d}\sigma_{\rm ion,p}}{{\rm d}\varepsilon}(\varepsilon,\varepsilon_0)v_{\rm CR}(\varepsilon_0)f_{\rm CR}(\varepsilon_0)d\varepsilon_0, \tag{10}$$

$$Q_{\rm ion,2nd}(\varepsilon) = n_{\rm H}\left\{\int \frac{{\rm d}\sigma_{\rm ion,e}}{{\rm d}\varepsilon}(\varepsilon,\varepsilon_0)v_{\rm x}(\varepsilon_0)f_{\rm 2nd}(\varepsilon_0)d\varepsilon_0 - v_{\rm x}(\varepsilon)\sigma_{\rm ion,e}(\varepsilon)f_{\rm 2nd}(\varepsilon)\right\}, \tag{11}$$

$$Q_{\rm ex,2nd}(\varepsilon) = n_{\rm H}\left\{\sum_k \sigma_{{\rm ex},k}(\varepsilon+\Delta_k)v_{\rm x}(\varepsilon+\Delta_k)f_{\rm 2nd}(\varepsilon+\Delta_k) - \sigma_{{\rm ex},k}(\varepsilon)v_{\rm x}(\varepsilon)f_{\rm 2nd}(\varepsilon)\right\}, \tag{12}$$

where $v_{\rm CR}$ and $f_{\rm CR}$ are the velocity and energy spectrum of CRs. ${\rm d}\sigma_{\rm ion,p}/{\rm d}\varepsilon$ and ${\rm d}\sigma_{\rm ion,e}/{\rm d}\varepsilon$ are the differential cross sections for ionization by protons and electrons, respectively. $\sigma_{\rm ion,e}$ and $\sigma_{{\rm ex},k}$ are the total cross sections for ionization and excitation, respectively. The subscript $k$ represents some excitation processes for a hydrogen atom or molecule, and $\Delta_k$ is the corresponding excitation energy. In this work, we consider thirteen processes for a hydrogen molecule, which contribute the energy loss of secondary electrons.

In this proceedings, we show simulation results for $l_{\rm ion,e}/x_0 = 1, V_{\rm CR}/c = 0.1$, and $n_{\rm e}/n_{\rm H} = 10^{-4}$, which are key parameters in this system. In particular, $l_{\rm ion,e}/x_0$ is the most important parameter that decides the development of discharge. $l_{\rm ion,e} = (4\pi a_0^2 n_{\rm H})^{-1}$ is the typical lengthscale of ionization and $a_0$ is the Bohr radius. $x_0 = I/eE_0$ is another characteristic lengthscale in which the energy gain by the initial resistive electric field is the first ionization potential, $I$. In this work, we consider a hydrogen molecular cloud as the cold medium. Then, the first ionization potential is $I = 15.4$ eV and a lot of excitation processes have to be taken into account (for detail, see [8]).

Figure 1 shows the spatial development of the resistive electric field. As secondary electrons are accelerated by the resistive electric field and generated by ionization, the return current of thermal electrons decreases, resulting in the decrease of the resistive electric field. However, the resistive electric field has a finite strength in a quasi-steady state.

Figure 2 shows the spatial development of the secondary electron spectrum. Initially, the number of secondary electrons linearly increases with a distance from the left boundary because new secondary electrons are mainly generated by CR ionization. However, after a while, the number of secondary electrons increases exponentially because they are mainly produced by secondary

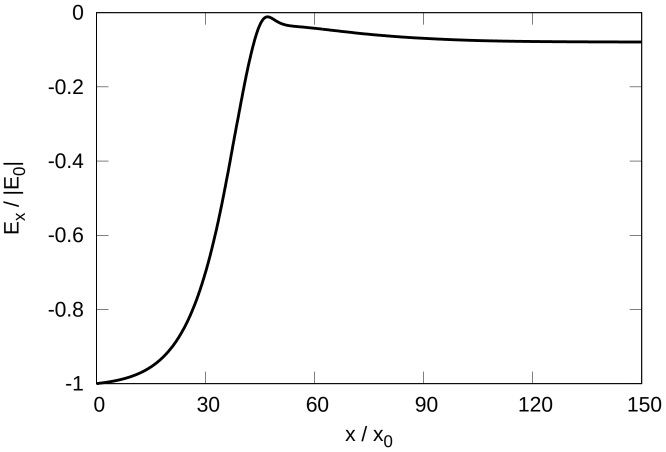

**Figure 1:** Spatial development of the resistive electric field.

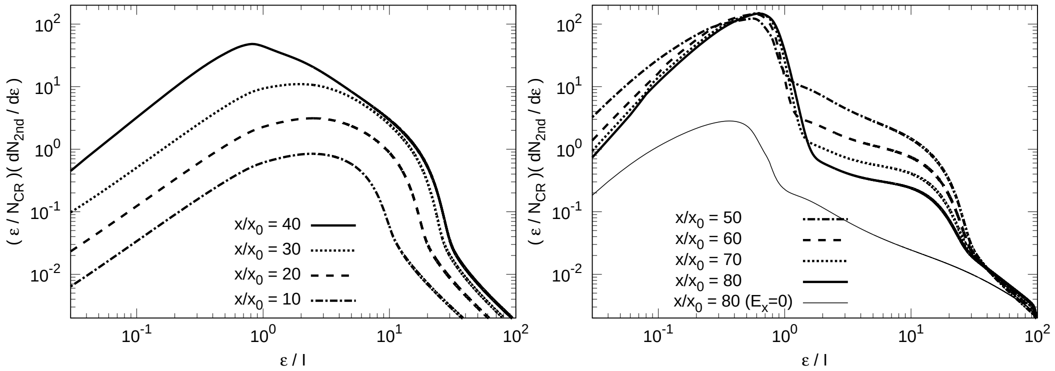

**Figure 2:** Secondary electron spectra at some points. The left panel shows spectra at $x/x_0 = 10, 20, 30, 40$. The right panel shows spectra at $x/x_0 = 50, 60, 70, 80$. The thin solid line in the right panel shows the spectrum at $x/x_0 = 80$ for no acceleration by the resistive electric field.

electrons, that is, the electron avalanche is working. In addition, the secondary electrons are accelerated by the resistive electric field until the current of secondary electrons is comparable to the CR current. After the resistive electric field becomes sufficiently small, accelerated secondary electrons lose their energy by ionization and excitation. In a quasi-steady state, the acceleration by the weakened resistive electric field is balanced by the energy loss due to ionization and excitation.

## 4. Discussion

In this work, we solve the Boltzmann equation to investigate the development of secondary electron spectrum in the discharge induced by streaming CRs. A resistive electric field is induced by streaming CRs and accelerates secondary electrons generated by CR ionization. In a quasi-steady state, most of the return current of thermal electrons is replaced by the current of secondary electrons. In the early universe, the return current of thermal electrons generate seed magnetic fields [4, 9, 10]. Therefore, the CR discharge would suppress the magnetic field generation. On the other hand, the CR discharge would heat a background gas efficiently. Then, the Biermann battery would generate seed magnetic fields [11].

In addition, the CR discharge enhances the number of secondary electrons with energy of $\varepsilon \sim I$. Therefore, ionization by secondary electrons is enhanced, which could explain the some observations that the ionization rate is larger than expected from the standard CR ionization model.

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