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Magnetic field generation by the first cosmic rays

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It was recently proposed that cosmic rays are first accelerated at the redshift of $z \approx 20$ by supernova remnants of first stars without the large scale magnetic field. In this study, we investigate the large scale magnetic field generation by the first cosmic rays. We show that even though the current and charge neutralities are initially satisfied, the current neutrality is eventually violated if there is an inhomogeneity, so that the magnetic field is generated. In addition, we propose a new driving mechanism for the Biermann battery in an inhomogeneous plasma with streaming cosmic rays. We demonstrate the new generation mechanisms of the magnetic field by conducting three-fluid plasma simulations and particle in cell simulation. We propose that the first cosmic rays generate the magnetic field with a large scale at the redshift of $z \approx 20$.

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1. Introduction

The magnetic field and nonthermal high energy particles are ubiquitous at various scales from planets to clusters of galaxies in the current universe. They play various roles in different environments. Nevertheless, it has not been well understood when, where, and how the magnetic field and cosmic rays (CRs) were first generated in the universe. CRs are naively thought to be accelerated after a large-scale magnetic field is generated and amplified. Recently, it was shown that CRs are first accelerated at the redshift of $z \approx 20$ by supernova remnants of first stars without the large-scale magnetic field [1]. Ohira & Murase (2019)[1] proposed a new paradigm that a small-scale magnetic field is generated by the Weibel instability in the first supernova remnants at $z \approx 20$; the small-scale magnetic field and the supernova remnant shock accelerate the first CRs by the diffusive shock acceleration; the first CRs generate a large-scale magnetic field while propagating to the intergalactic space. In this study, we provide new generation mechanisms of the large-scale magnetic field by the propagating CRs.

2. Generalized Ohm's law

We firstly derive the generalized Ohm's law in a fully ionized multi-component plasma. For a partially ionized plasma, the derivation of the generalized Ohm's law is given in Kashiwamura & Ohira [2]. Electrons, protons, and beam protons are considered as particles in this study. Equations of motion for each plasma component are given by

$$\frac{\partial}{\partial t}(m_s n_s \boldsymbol{V}_s) + \boldsymbol{\nabla} \cdot (m_s n_s \boldsymbol{V}_s \boldsymbol{V}_s) = -\boldsymbol{\nabla} p_s + q_s n_s \left(\boldsymbol{E} + \frac{\boldsymbol{V}_s \times \boldsymbol{B}}{c} \right) - n_s m_s \sum_{s' \neq s} \frac{(\boldsymbol{V}_s - \boldsymbol{V}_{s'})}{\tau_{ss'}}, \quad (1)$$

where $m_s, n_s, \boldsymbol{V}_s, p_s, q_s, \boldsymbol{E}, \boldsymbol{B}$, and c are the mass, number density, velocity, pressure, charge, electric field, magnetic field, and speed of light, respectively. The subscripts s and $s'(= \mathrm{e, p, b})$ denote the particle species, where e, p, and b mean electrons, protons, and beam protons, respectively. The terms including $\tau_{ss'}$ represent the momentum transfer between particle s and particle s' by collision, where $\tau_{ss'}$ is the timescale of momentum transfer due to collision. Multiplying Equation (1) by q_s/m_s and summing these equations for charged particles, we obtain

$$\frac{\partial \boldsymbol{J}}{\partial t} + \boldsymbol{\nabla} \cdot \left(\sum_s q_s n_s \boldsymbol{V}_s \boldsymbol{V}_s \right) = -\sum_s \frac{q_s}{m_s} \boldsymbol{\nabla} p_s + \sum_s \frac{q_s^2 n_s}{m_s} \left(\boldsymbol{E} + \frac{\boldsymbol{V}_s \times \boldsymbol{B}}{c} \right) - \sum_s \sum_{s' \neq s} \frac{q_s n_s (\boldsymbol{V}_s - \boldsymbol{V}_{s'})}{\tau_{ss'}} \quad (2)$$

where $\boldsymbol{J} \equiv \sum_s q_s n_s \boldsymbol{V}_s$ is the electric current. One can derive the generalized Ohm's law by solving this equation for the electric field. For large scale phenomena compared with the electron inertial lengthscale, the first term on the left-hand side is negligible. The second term on the left-hand side has an important role in the magnetic field generation if the plasma consists of more than two components [3]. In the first and second terms on the right-hand side, the contribution from electrons dominates the others because the electron mass is much smaller than others, $m_\mathrm{p}/m_\mathrm{e} \gg 1$. The third term on the right-hand side becomes negligible as long as the magnetic field is zero or very small. Then, the generalized Ohm's law is

$$\boldsymbol{E} = -\frac{\boldsymbol{\nabla} p_\mathrm{e}}{e n_\mathrm{e}} + \frac{m_\mathrm{e}}{e^2 n_\mathrm{e}} \boldsymbol{\nabla} \cdot \left(\sum_s q_s n_s \boldsymbol{V}_s \boldsymbol{V}_s \right) + \frac{m_\mathrm{e}}{e^2 n_\mathrm{e}} \sum_s \sum_{s' \neq s} \frac{q_s n_s (\boldsymbol{V}_s - \boldsymbol{V}_{s'})}{\tau_{ss'}} \quad . \quad (3)$$

The first and second terms on the right-hand side describe the Biermann battery by the thermal and ram pressures, respectively [3–5]. The third term originates from the momentum transfer between two components. It describes the resistive term that usually dissipates the magnetic field, but there are some interesting cases where the magnetic field is generated by the resistive term [6–9].

3. Magnetic field generation by the electron ram pressure induced by the return current

In this section, we discuss the magnetic field generation by the second term in Eq. (3). If there is initially no magnetic field in a two component (electron-proton) plasma, this term is initially zero, so that no magnetic field is generated. However, if a plasma consists of more than two components, it does not always vanish, that is, a magnetic field could be generated. When streaming CRs enter an electron-proton plasma, the charge and current neutralities are initially violated. After a time scale of the electron plasma oscillation, electrons move to neutralize the charge and current densities, so that the return current of electrons is induced. For simplicity, we consider an uniform CR streaming and an uniform proton velocity field, but electrons and protons have a nonuniform density distribution. Then, the Ohm's law in the proton rest frame is reduced to

$$\boldsymbol{E} = -\frac{1}{en_{\mathrm{e}}}\boldsymbol{\nabla}\cdot\left(m_{\mathrm{e}}n_{\mathrm{e}}\boldsymbol{V}_{\mathrm{e}}\boldsymbol{V}_{\mathrm{e}}\right). \quad (4)$$

In the proton rest frame, electrons have a drift velocity, $\boldsymbol{V}_{\mathrm{e}}$, because of the electron return current. The above expression means that the electric field is induced by the gradient of the electron ram pressure induced by the return current. If the electron density has inhomogeneity, the gradient of the electron ram pressure is nonzero, so that the electric field is induced. If the curl of the electric field is nonzero, a magnetic field is generated. This new generation mechanism of magnetic field can be interpreted as a simple extension of the Biermann battery mechanism [5] that is induced by the gradient of the electron thermal pressure. By conducting particle-in-cell simulations, we confirmed the magnetic field generation discussed in this section [3]. The simulation results are in good agreement with our theoretical estimation.

4. Magnetic field generation by the Biermann battery induced by the return current

In this section, we discuss the magnetic field generation by the first term in Eq. (3), that is, the Biermann battery [5]. The Biermann battery is one of the promising mechanisms of magnetic field generation and it has been widely investigated in many astrophysical phenomena. In the Biermann battery mechanism, the electron pressure gradient that is not parallel to the density gradient makes a vortex flow of electrons, so that the electric current and the magnetic field are generated. To generate such a pressure structure, a distorted shock front or some electron heating has been considered in two component (electrons and ions) plasmas In this study, we propose a new driving mechanism for the Biermann battery.

As mentioned in the previous section, electrons have a drift velocity to make the return current. The electron flow changes the initial distribution of the electron pressure. The time evolution of the electron pressure is described by the energy equation of fluid dynamics,

$$\frac{\partial p_{\rm e}}{\partial t} + \boldsymbol{V}_{\rm e} \cdot \boldsymbol{\nabla} p_{\rm e} = -\gamma p_{\rm e} \boldsymbol{\nabla} \cdot \boldsymbol{V}_{\rm e}, \tag{5}$$

where γ is the adiabatic index. If there is initially no pressure gradient, that is, the nonuniform density structure is organized by entropy modes, the time evolution of the electron pressure is approximately given by

$$p_{\rm e} = p_{\rm e,0} \exp\left(-\gamma t \boldsymbol{\nabla} \cdot \boldsymbol{V}_{\rm e}\right), \tag{6}$$

where $p_{\rm e,0}$ is the initial electron pressure. Then, the induced electric field is given by

$$\boldsymbol{E} = -\frac{\boldsymbol{\nabla} p_{\rm e}}{e n_{\rm e}} = \frac{p_{\rm e}}{e n_{\rm e}} \gamma t \boldsymbol{\nabla}(\boldsymbol{\nabla} \cdot \boldsymbol{V}_{\rm e}), \tag{7}$$

The initial distribution of the electron pressure is changed by the electron flow. However, the density profile of electrons does not change significantly because the electron distribution has to be almost the same as that of protons to satisfy the charge neutrality condition. Then, the electron flow associated with the return current can make a pressure structure in which the Biermann battery works ($\boldsymbol{\nabla} p_{\rm e} \times \boldsymbol{\nabla} n_{\rm e} \neq 0$). For $\gamma t \boldsymbol{\nabla} \cdot \boldsymbol{V}_{\rm e} \ll 1$, the electric field linearly increases with time. Therefore, the ram pressure of the electron flow initially generates magnetic fields, but the Biermann battery discussed in this section eventually dominates the magnetic field generation. We performed three-fluid plasma simulations and confirmed the magnetic field generation discussed in this section [4]. The simulation results are excellently in good agreement with our theoretical estimation.

5. Discussion

In this study, we provided two new mechanisms of the magnetic field generation in a plasma with streaming CRs. The streaming CRs induces the electron return current. The electron flow associated with the return current drives the two mechanisms of the magnetic field generation. The ram pressure of the electron flow initially generates magnetic fields (section 2). Then, the Biermann battery induced by the electron flow (section 3) eventually dominates the magnetic field generation.

From the Faraday's equation, the magnetic field strength can be estimated by $B \sim E(ct/L)$, where t, and L are the characteristic timescale and lengthscale, respectively. From Eq. (7), the magnetic field strength at $z \approx 20$ is

$$B \sim 5.5 \times 10^{-18}\ {\rm G} \left(\frac{V_{\rm e,0}}{10^4\ {\rm cm\ s^{-1}}}\right) \left(\frac{T_{\rm e,0}}{0.1\ {\rm eV}}\right) \left(\frac{L}{0.1\ {\rm kpc}}\right)^{-3} \left(\frac{t}{10^8\ {\rm yr}}\right)^2 , \tag{8}$$

where $T_{\rm e,0}$ is the electron temperature. This is sufficiently large as the seed of the magnetic field in the current galaxies [10]. Therefore, the first CRs can generate large scale magnetic fields by the mechanism discussed in this study.

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