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Particle-in-Cell simulations of a relativistic shock propagating in an eletron-proton-Helium plasma

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Chemical abundances in cosmic rays are a crucial information about their origin and acceleration mechanisms. The observed chemical composition of the cosmic rays shows enhancements than the solar abundances. The cause of the chemical enhancements of some ions has not been understood. It is not clear, in relativistic collisionless shocks propagating in multispecies-ion plasmas, how each ion and electrons are accelerated. We perform the first Particle-In-Cell simulation of a relativistic collisionless shock propagating in an electron-proton-helium plasma. We found that helium ions are accelerated efficiently compared with protons.

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1. Introduction

Cosmic rays (CRs) observed at the earth have a power-law distribution ranging from 10^9 eV to 10^{20} eV. According to a transport model and an arrival direction distribution of high-energy CRs, the origins of the cosmic ray less (more) than $\sim 10^{17}$ eV are thought to be in (out of) our galaxy [1]. However, the origins and the acceleration mechanisms of the CRs have not yet been understood. Chemical abundances in CRs have a crucial information to understand such issues. Around 10^{18} eV, protons are the dominant component of CRs, and and above $\sim 10^{18.5}$ eV, the ions which is heavier than protons and lighter than irons is the dominant composition of CRs [2]. On the other hand, we have not yet understood these observational data theoretically.

The candidates for the origin of ultra high-energy CRs are thought to be relativistic high-energy astrophysical phenomena such as active galactic nuclei jets, gamma-ray bursts, and pulsar wind nebulae. CRs are believed to be accelerated by diffusive-shock acceleration (DSA) mechanisms [3, 4] in relativistic collisionless shock formed in the above astrophysical phenomena. This means that the particles inject into the DSA in the same fraction, and they are accelerated in diffusive motion. Because the DSA cannot predict the number of accelerated particles, we need an injection theory that predicts the observed flux of CRs.

In order to investigate the particle acceleration in the relativistic collisionless shock, *ab-initio* particle-in-cell (PIC) simulation of a relativistic shock propagating in electron-proton plasmas have been performed so far. Some early studies [5–7] showed that the acceleration fraction of protons is a few percent. The injection efficiency of protons has not yet understood theoretically. In reality, there are not only protons but also helium ions in the upstream region of the shock propagating in the interstellar medium. We do not know the acceleration efficiency of helium ions and helium's effect on the proton injection efficiency. Since previous studies have performed the PIC simulations of the relativistic shock in the electron-positron or electron-proton plasma, the acceleration efficiency of helium ions has not been investigated so far.

We perform the first two-dimensional PIC simulations of an unmagnetized relativistic collisionless shock propagating in electron-proton-helium plasma. We found that the injection efficiency of helium ions is 10 times larger than that of protons for the case where the upstream plasma is the solar abundance. Furthermore, we propose a theoretical model of injection to the DSA, which can explain results of PIC simulations.

2. Simulation Setup

We perform *ab-initio* two-dimensional simulations of a relativistic Weibel-mediated shock propagating in an electron-proton-helium plasma using electromagnetic PIC code [8, 9]. The simulation box is the $x - y$ plane. A periodic boundary is set in the y-direction, and particles are continuously injected with a drift velocity in the $-x$-direction from one side of the simulation boundary, and reflected at the opposite side. The Weibel instability [10] is excited between the injected and reflected particles. Then a collisionless shock is formed and propagates to the $+x$-direction. The simulation frame is set in the downstream rest frame. The bulk Lorentz factor of the upstream flow and thermal velocity are 10 and 0.18 c, respectively. The plasma composition is set in the solar abundance. The mass ratios of electrons, protons, and heliums are set to be

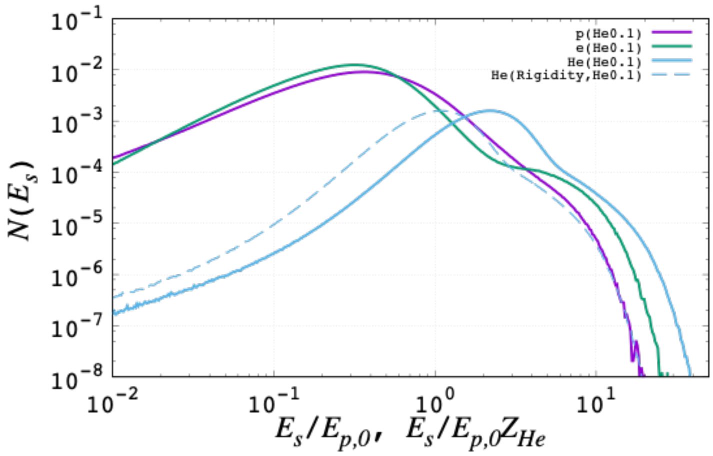

Figure 1: Downstream ($1300\ c/\omega_{pp} < x < 1320\ c/\omega_{pp}$) spectra for each species at $t = 3400\ \omega_{pp}^{-1}$. The solid and dashed lines are the energy spectra and rigidity spectra, respectively. The purple, green, and light blue lines are spectra for protons, electrons, and helium ions, respectively.

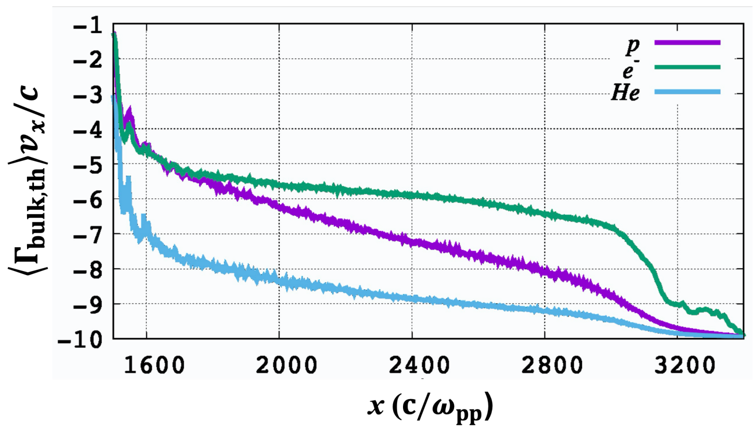

Figure 2: Spatial evolution of the transversely averaged bulk velocity of the thermal particles in the upstream at $t = 3400\ \omega_{pp}^{-1}$. The shock front is located around $x = 1500\ c/\omega_{pp}$. The purple, green, and light blue lines are bulk four velocities for protons, electron, and helium ions, respectively.

$m_e : m_p : m_{He} = 1 : 25 : 100$. The helium to proton charge ratio is 2. The number of simulation particles is 10/cell for each species, so that simulation particles have different wights for each species to make the solar abundance. The simulation box size is $170,000 \times 6,400$ cells, and the cell size $\Delta x = \Delta y = 0.02\ c/\omega_{pp}$. The total simulation time steps are 170,000, and a simulation time step is $\Delta t = 0.02\ \omega_{pp}^{-1}$.

3. Results

Fig. 1 shows particle energy spectra for each species in the local downstream region $1300\ c/\omega_{pp} < x < 1320\ c/\omega_{pp}$ at $t = 3400\ \omega_{pp}^{-1}$. The shock front is located around $x = 1500 c/\omega_{pp}$. The energy in the horizontal axis is normalized to the upstream kinetic energy of protons, $E_{p,0}$. The electrons have a non-thermal tail. Protons also have a non-thermal component although the spectral shape

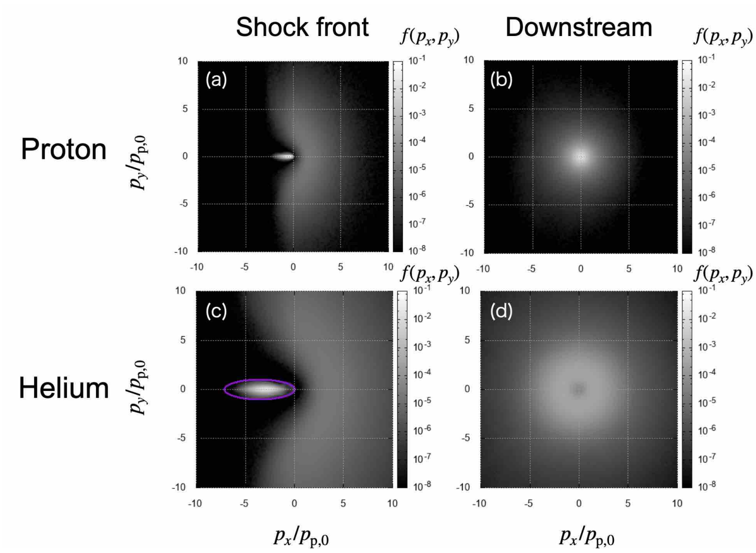

Figure 3: Particle distribution in the momentum space at the shock front ($1500c/\omega_{\rm pp} < x < 1520\ c/\omega_{\rm pp}$, panel a, c) and the downstream ($1300\ c/\omega_{\rm pp} < x < 1320\ c/\omega_{\rm pp}$) at $t = 3400\ \omega_{\rm pp}^{-1}$. The top raw (a, b) and the bottom raw (c, d) are the momentum distribution of protons and helium ions, respectively.

is different between electrons and protons. The energy spectrum of helium ions has very few low-energy particles, and in the high-energy domain, the number of helium ions is larger than that of electrons and protons. The dashed light-blue line in Fig. 1 shows the helium rigidity ($E_{\rm He}/E_{\rm p.0}Z_{\rm He}$) spectrum. The energy spectrum for protons (solid purple line) corresponds to the rigidity spectra for protons. The maximum rigidity of helium ions is almost the same as that of proton. The number of the accelerated helium ion are comparable to that of protons even though the helium ions to protons number ratio is 0.1.

Fig. 2 shows the one-dimensional structure of the upstream bulk four velocity, ($\langle\Gamma\rangle_{\rm bulk,th,s} v_x/c$), in the upstream region. The electrons are quickly decelerated by the interaction with the Weibel-generated field. Protons are slowly decelerated because of the heavier mass. This difference of deceleration between protons and electrons induces a charge separation and electrostatic field [11].

In Fig. 3, the particle distribution in the momentum space at the shock front and the downstream at $t = 3400\ \omega_{\rm pp}^{-1}$ are shown. The shock front and the downstream region are located at $1500\ c/\omega_{\rm pp} < x < 1520\ c/\omega_{\rm pp}$ and $1300\ c/\omega_{\rm pp} < x < 1320\ c/\omega_{\rm pp}$, respectively. The downstream momentum distribution of protons shows a peak at the center and is isotropic, so that protons are fully thermalized (panel (b)). On the other hand, the downstream helium ions have a ring distribution in the momentum space (panel (d)). This is because, as shown in Fig. 2, helium ions are injected into the downstream region without the strong deceleration. Therefore, the energy loss of helium ions is less than that of protons so that the number of the particles returning from the downstream to the upstream is larger than that of protons. As a result, the acceleration fraction of helium ions is larger than that of protons.

4. Discussion

We can derive the injection efficiencies to the diffusive shock acceleration theoretically by using a leakage model as below. In order for the particle to be injected to the diffusive shock acceleration, the particle velocity, v_x has to be faster than the shock velocity, $v_{\rm sh} \sim 0.45\,c$, and the particle has to penetrate the strong turbulent region around the shock front freely. Almost all helium ions satisfy the second condition in our simulation because the mean free path of helium ions is larger than the thickness of the region with strong magnetic turbulence. Then, the injection efficiency η of helium ions is written by the following.

$$\eta = \frac{\int\int_{\rm R} f_{\rm d}(p_x, p_y)(v_x - v_{\rm sh})dp_x dp_y}{n_{\rm up}(v_{\rm sh} - v_{\rm up})}, \quad (1)$$

where $n_{\rm up}, v_{\rm up}$, are the upstream number density and velocity, respectively. We assume that the downstream helium ions have a ring-like momentum distribution in the $p_x - p_y$ plane, $f_d(p_x, p_y) \propto \delta(p - \langle E_{\rm He}\rangle/c)$, where $\langle E_{\rm He}\rangle$ is the mean kinetic energy of the downstream helium ions. The upstream helium ions lose their kinetic energy by moving in the electrostatic potential produced by the charge separation, $\Delta\phi$, so that the downstream mean kinetic energy of the helium ions is given by $\langle E_{\rm He}\rangle = \Gamma m_{\rm He}c^2 + Z_{\rm He}e\Delta\phi \sim 3(\Gamma - 1)m_{\rm p}c^2$. Then η is 0.2, which is consistent with our simulation results. The injection efficiency of protons is also derived in the same way and ten times lower than that of helium ions, which is almost consistent with our simulation results.

5. Summary

We performed the first two-dimensional PIC simulations of a relativistic Weibel-mediated shock propagating in electron-proton-helium plasma. We found that the acceleration fraction of helium ions is 10 times higher than that of protons when the upstream region are composed of the solar abundance. Since helium ions have heavier mass and lower number fraction than that of protons, helium ions are not involved in the Weibel instability and do not loss their kinetic energy. As a result, the fraction of the high-energy helium ions is higher than that of the protons in the downstream region. Such high-energy helium ions easily inject to the DSA so that the acceleration fraction of helium ions is higher than that of protons.

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