Vlasov Simulation of Plasma Processes in Collisionless Shocks

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Abstract

Results of a simulation of the wakefield acceleration, which is a plasma process thought to operate in the upstream region of a relativistic collisionless shock, are presented. A power-law energy spectrum with index -2 is reproduced as previous works claim.

Key words: radiation mechanisms: non-thermal

1. Introduction

Shock waves are ubiquitous structure seen in high-energy astrophysical phenomena and play important roles in generation of non-thermal particles. Especially, shock waves forming in collisionless plasmas, in which the mean free path of particles is larger than the scale length of the plasmas, are called collisionless shocks. Such shocks are thought to form in SNRs, GRBs, flare in AGNs, microquasars, and so on.

Various acceleration processes are proposed in order to reproduce power-law energy spectrum of particles that is implied by radio or X-ray observations of high-energy phenomena. Wakefield acceleration (Tajima & Dawson 1979; see Esarey et al. 1996 for review) is one of the processes. The mechanism of the process is as follows: 1) an intense light pulse propagates in a stationary plasma composed of ions and electrons, 2) radiation pressure of the pulse modifies the spatial distribution of electrons, 3) the displacement of the spatial distribution of electrons excites a longitudinal electric field, 4) the thus excited electric field accelerates electrons.

Astrophysical applications of the wakefield process have been proposed recently. Chen et al. (2002) claimed that the wakefield excited by some magnetowaves could procudes ultra high-energy cosmic rays(UHECRs). Lyubarsky (2006) argued that the wakefield acceleration can occur in the upstream of a relativistic collisionless shocks. Hoshino (2008) showed that the wakefield acceleration actually occur in the upstream of a relativistic collisionless shock by using a particle simulation.

2. Method

2.1. Vlasov-Maxwell system

Behaviors of a relativistic collisionless plasma are governed by the relativistic Vlasov-Maxwell system. In this study, we use the system with one dimensional in the physical space and two dimensional in the momentum space. The complete set of the Vlasov-Maxwell system that describes time evolutions of a plasma with the distribution $f^s(x,p,q,t)$ for species s in the phase space (x,p,q) at time t, the longitudinal electric field $E^{\parallel}(x,t)$, the transverse electric field $E^{\perp}(x,t)$, and the transverse magnetic field $B^{\perp}(x,t)$ is as follows,

$$\frac{\partial f^s}{\partial t} + \frac{p}{m_s\Gamma^s}\frac{\partial f^s}{\partial x} + Q_s\left(E^{\parallel} + \frac{q}{m_s c\Gamma^s}B^{\perp}\right)\frac{\partial f^s}{\partial p} + Q_s\left(E^{\perp} - \frac{p}{m_s c\Gamma^s}B^{\perp}\right)\frac{\partial f^s}{\partial q} = 0, \quad (1)$$

where

$$\Gamma^s = \sqrt{1 + \left(\frac{p}{m_s c}\right)^2 + \left(\frac{q}{m_s c}\right)^2}, \quad (2)$$

and

$$\frac{\partial E^{\parallel}}{\partial t} = -4\pi J^{\parallel}, \quad (3)$$

$$\frac{1}{c}\frac{\partial E^{\perp}}{\partial t} + \frac{\partial B^{\perp}}{\partial x} = -4\pi J^{\perp}, \quad (4)$$

$$\frac{1}{c}\frac{\partial B^{\perp}}{\partial t} + \frac{\partial E^{\perp}}{\partial x} = 0, \quad (5)$$

where the electric current densities $J^{\parallel}$ and $J^{\perp}$ are expressed in terms of $f^s(x,p,q,t)$ as

$$J^{\parallel} = \sum_s Q_s \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \frac{p}{m_s c\Gamma^s} f^s(x,p,q,t)dpdq, \quad (6)$$

$$J^{\perp} = \sum_s Q_s \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} \frac{q}{m_s c\Gamma^s} f^s(x,p,q,t)dpdq. \quad (7)$$

Here m_s and Q_s represent the mass and the charge of species s and c represents the speed of light. We have developed a simulation code that solves the above equations numerically (Suzuki & Shigeyama 2009). Using the code, we calculated the wakefield process.

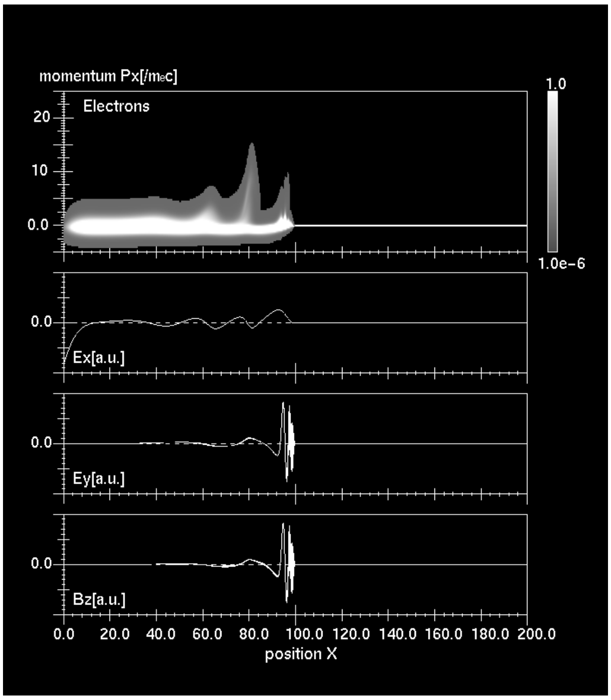

Fig. 1. The distribution of electrons in the phase space (x, p) and the profiles of electromagnetic fields at $t = 100$.

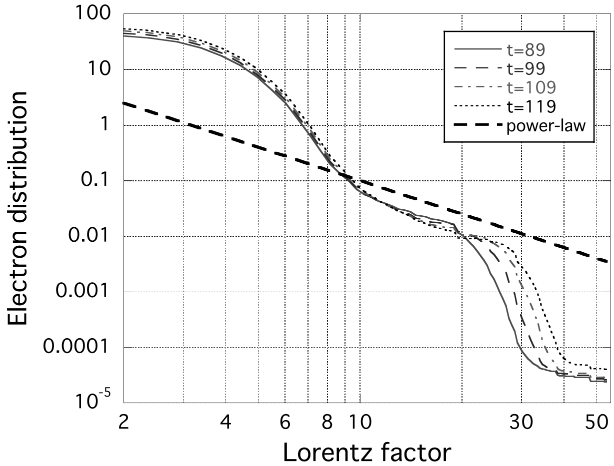

Fig. 2. Time evolutions of the energy spectrum of electrons.

2.2. setups

We calculate the response of a plasma that is uniform and stationary with no electromagnetic field initially to the passage of an intense light pulse. For the initial condition for the plasma, we assume the following distribution function for electrons,

$$f^e(x, p, q, 0) = \delta(p)\delta(q). \tag{8}$$

We treat ions as a stationary background. On the other hand, for the boundary condition for the electromagnetic fields, we assume the following condition that generates an intense light pulse propagating toward $+x$ direction,

$$G(0, t) = A_0\omega_L \exp\left[-\frac{(t-2\tau)}{\tau^2}\right]\sin(\omega_L t), \tag{9}$$

$$H(0, t) = 0, \tag{10}$$

where

$$G(x, t) = \frac{E^{\perp}(x, t) + B^{\perp}(x, t)}{2}, \tag{11}$$

$$H(x, t) = \frac{E^{\perp}(x, t) - B^{\perp}(x, t)}{2}. \tag{12}$$

Here $A_0 = 2.0$, $\omega_L = 2.0$, and $\tau = \pi/2$ represent the amplitude, the frequency, and the duration of the pulse.

3. Results

A snapshot of the distribution function of electrons and the profiles of electromagnetic fields at $t = 100$ are shown in Figure 1. Figure 2 shows the resultant energy spectrum of electrons at $t = 89, 99, 109, 119$. A power-law energy spectrum with index -2 is reproduced as previous works claim(Chen et al. 2002, Kuramitsu et al. 2008). Within our computational time, electrons accelerates up to $\gamma \sim 40$, which may provide seed particles for the diffusive acceleration or radiate some emissions.

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