Physics Letters A 380 (2016) 211–214

Contents lists available at ScienceDirect

Physics Letters A

www.elsevier.com/locate/pla

# Particle accelerations in two colliding plasma shock waves

Satoshi Takeuchi

*Department of Life and Environmental Sciences, University of Yamanashi, 4-4-37, Takeda, Kofu, Yamanashi 400-8510, Japan*

A R T I C L E I N F O

*Article history:*
Received 1 December 2014
Received in revised form 24 August 2015
Accepted 28 September 2015
Available online 3 October 2015
Communicated by F. Porcelli

*Keywords:*
Plasma shock wave
Particle acceleration
Magnetic reconnection

A B S T R A C T

A kinetic model of the head-on collision of two magnetized plasma shocks is analyzed theoretically and with numerical calculations. Three-dimensional electromagnetic fields can be modeled as two magnetic fields that intersect at an arbitrary angle; such interaction plays an important role as the asymmetric collision of two shocks. The rate of increase of the attainable energy gain and the aspect ratio of an accelerating test particle are derived from theoretical analysis of the relativistic equations of motion. If the magnetic field has any curvature, a transverse magnetic field is generated that crosses the magnetic reconnection layer. The trajectory of the accelerating particle is bent by this magnetic field, producing the reduction of energy gain as a result.



The acceleration mechanism of high-energy cosmic rays is still shrouded in a veil of mystery. A plausible candidate for this mechanism is magnetic reconnection, which effectively converts magnetic energy to the internal energy of a plasma. It has been observed that high-energy particles are generated by the magnetic reconnections in many interplanetary events (e.g. solar flares, bow shocks, and supernova remnants) as well as in laboratory plasmas [1,2].

From a macroscopic point of view, the magnetohydrodynamics (MHD) model is extremely useful in understanding the steady flows of energy and the electromagnetic fields. Many studies employing magnetic reconnection have been published based on the two conventional MHD models, namely the Petschek type and the Sweet–Parker type [1,3–6]. However, since the magnetized plasmas are expressed as electromagnetic fluids in MHD models, it is difficult to explain the trapping and selective acceleration of individual particles, which are essential for the generation of high energy particles.

This paper presents a mechanism for particle trapping and acceleration in a three dimensional head-on collision of two magnetized plasma shocks, as shown in Fig. 1. The asymmetric magnetic fields whose configurations are handled theoretically can be represented by a simple model of two magnetic fields that intersect at arbitrary angle. The angle $\theta$ formed between the magnetic fields $B_1$ and $B_2$ is defined as the crossing angle, which plays a key role in this model. This system is examined in the present study from a kinetic point of view, in which theoretical and numerical analyses of the interaction between a test particle and the electromagnetic fields are carried out in the relativistic regime.

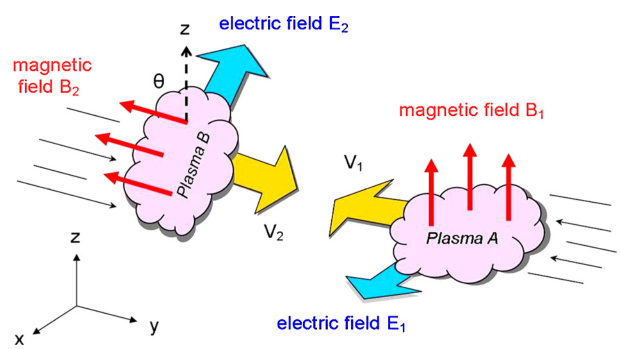


**Fig. 1.** Schematic diagram of the head-on collision of two magnetized plasma shocks. Since the two magnetic fields $B_1$ and $B_2$ may intersect at any angle $\theta$, the model presents the case of asymmetric configuration in three dimensional space.

In collision-less and fully ionized plasmas in a quasi-neutral state, if the magnetized plasma moves, then the motional electric field generated by this magnetic field also moves with the plasma. The relationship between the electromagnetic fields and the plasma is recognized as the "frozen-in" state. In transition phenomena such as magnetic reconnections, the electromagnetic fields in the frozen-in state play a significant role [6,8]. Since the electric and magnetic fields of two shocks are derived from Maxwell's equations, the principle of superposition can be applied for these fields. In order to understand some basic concepts of the asymmetric model, let us first focus on a simple model. Let the profile of the magnetic fields be a soliton shape [9,10], as shown in Fig. 1, defined as

*E-mail address:* take@yamanashi.ac.jp.

http://dx.doi.org/10.1016/j.physleta.2015.09.049

$$B_i = (b_i/2)[\tanh(\eta_i) + (-1)^{i+1}], \tag{1}$$

$$\eta_i \equiv k_i(y + v_i t + f_i) + \phi_i, \tag{2}$$

$$E_i = (v_i/c)B_i, \tag{3}$$

where $b_i$, $v_i$ and $\phi_i$ are the magnitudes of the magnetic field, the propagation velocity and the initial phase, respectively. The subscript $i = 1$ stands for backward propagation and $i = 2$ for forward propagation. The function $f_i$ describes the shape of the shock front, with $f_i = 0$ defining a plane wave uniform in the $xz$ plane. Further, $w_i \equiv 2\pi/k_i$ corresponds to the width of the shock front and $w_1 = w_2 \equiv w_s$. Therefore, the components of the electric and magnetic fields of two plasmas crossing at an angle $\theta$ can be written as

$$E_{x1} = (v_1/c)B_1, \qquad B_{z1} = B_1, \tag{4}$$

$$B_{x2} = B_2 \sin\theta, \qquad B_{z2} = B_2 \cos\theta, \tag{5}$$

$$E_{x2} = -(v_2/c)B_{z2}, \; E_{z2} = (v_2/c)B_{x2}. \tag{6}$$

Let us investigate the motion of a test particle under the influence of these electric and magnetic fields. The relativistic equations of motion [10] of a particle with mass $m$ and charge $q$ are given in the form

$$m\frac{d\gamma v_x}{dt} = q(E_{x1} + E_{x2}) + \frac{q}{c}(B_{z1} + B_{z2})v_y, \tag{7}$$

$$m\frac{d\gamma v_y}{dt} = \frac{q}{c}(B_{x2})v_z - \frac{q}{c}(B_{z1} + B_{z2})v_x, \tag{8}$$

$$m\frac{d\gamma v_z}{dt} = q(E_{z2}) - \frac{q}{c}(B_{x2})v_y, \tag{9}$$

where $\gamma \equiv [1 - (v_x^2 + v_y^2 + v_z^2)/c^2]^{-1/2}$ is the Lorentz factor and $c$ is the velocity of light. The energy equation is derived from the above equations as

$$mc^2\frac{d\gamma}{dt} = q(E_{x1} + E_{x2})v_x + q(E_{z2})v_z. \tag{10}$$

The test particle interacting with two plasma shocks experiences electric and magnetic fields that vary with the crossing angle. Therefore, visualizing these fields provides us with much information relating to an asymmetric three-dimensional model of magnetic reconnection. Let us qualitatively investigate the behaviors of the test particle interacting with these fields.

The relative velocity of the two plasma shocks is given by $v_1 + v_2$. This corresponds to the propagation velocity of the front created by the head-on collision. To provide the essence of this model, suppose that the relative velocity is nearly equal to zero, i.e. $v_2 \approx -v_1$, and magnitudes of the two magnetic fields are roughly equal, $B_1 \approx B_2$. Two distinct cases of the crossing angle are investigated in the following.

First, we consider the case where $0 < \theta \le \pi/2$. As shown in Fig. 2(a), the particle initially located at the center of the collision region is sandwiched by the two shocks. The flat, delta-shaped plateau of the magnetic field is created by the collision as time passes. The particle experiences this amplified magnetic field, and the radius of the particle's cyclotron motion becomes small. Thus, the particle is trapped inside this region and cannot move freely anywhere. On the other hand, the motional electric fields are given by $E_{x1} + E_{x2} \approx 0$. Therefore, as indicated in eq. (10), the particle experiences the field $E_{z2}$ and is accelerated in nearly parallel to the $z$ direction.

Next let us examine the case of $\pi/2 < \theta \le \pi$. As shown in Fig. 2(b), the magnetic neutral sheet is created in the center of the collision region. This sheet has a distinctive feature: once the particle is trapped by the magnetic neutral sheet, it can never escape. This mechanism has been pointed out in previous reports [11,12].

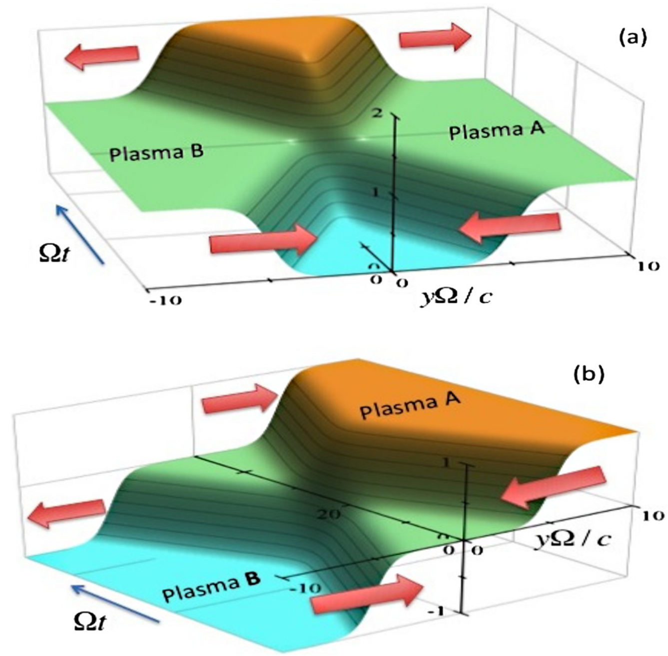


**Fig. 2.** Time development of magnetic fields formed by two colliding plasma shocks. The electromagnetic fields of *Plasma A* and *Plasma B* are superimposed on each other as time passes. The large arrows indicate the directions of the moving magnetic fields. (a) When the crossing angle $\theta = 0$ is satisfied, the two magnetic fields are parallel and enhanced near the center of the collision region. As the collision advances these magnetic fields expand uniformly in opposite directions. In contrast, the two motional electric fields cancel each other. (b) If the condition $\theta = \pi$ is satisfied, then the two magnetic fields are anti-parallel and hence a magnetic neutral sheet is created in the collision region. In addition, the motional electric fields are enhanced in the same region.

The two magnetic fields are oriented opposite to each other in the $z$ direction and thus they are offset in the collision region. Accordingly, the particle is accelerated in the $x$ direction by the field $E_{x1} + E_{x2}$ as given by eq. (10). In particular, when the crossing angle takes the value $\theta = \pi$, the collision region of this model corresponds to the magnetic reconnection of the two conventional MHD models referenced above.

As a result, it is found that even if the crossing angle takes on any value from $\theta = 0$ to $\theta = \pi$, the test particle could be trapped in the center of the collision region and continuously interacts with the electromagnetic fields.

Considering the above situations, we employ the following assumptions to solve the equations of motion: 1) $v_y \approx 0$, $y \approx 0$ are used for both the cases, and $B_{z1} + B_{z2} \approx 0$ is added to the latter case. Using these assumptions, we integrate eqs. (7) and (9) with respect to time and obtain two expressions of the form

$$\gamma\beta_x \approx \frac{q}{mc}(E_{x1} + E_{x2})t$$
$$= -(\beta_1\Omega_1 + \beta_2\Omega_2\cos\theta)t, \tag{11}$$

$$\gamma\beta_z \approx \frac{q}{mc}(E_{z2})t = (\beta_2\Omega_2\sin\theta)t, \tag{12}$$

where $\beta_i \equiv v_i/c$ and $\Omega_i \equiv qB_i/mc$ is the cyclotron frequency. By substituting eqs. (11) and (12) into eq. (10), an additional equation is derived:

$$\frac{1}{2}\frac{d\gamma^2}{dt} = \left(\frac{q}{mc}\right)^2[(E_{x1} + E_{x2})^2 + (E_{z2})^2]t. \tag{13}$$

Integration with respect to time gives

$$\gamma \approx t(\beta_1^2\Omega_1^2 + 2\beta_1\beta_2\Omega_1\Omega_2\cos\theta + \beta_2^2\Omega_2^2)^{1/2}. \tag{14}$$