

Magnetic Trapping Acceleration in Interplanetary Plasmas

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Abstract: Magnetic trapping acceleration is a new type of particle trapping and acceleration in which, in principle, test particles are accelerated indefinitely. One model of magnetized plasma clouds is used to simulate a shock-type wave. The energies attainable by particles trapped by the moving magnetic neutral sheets are investigated by analytical and numerical methods. To account for the high energy of cosmic rays, this mechanism could play an important role in magnetic field reconnections and shock surfing accelerations in interplanetary plasmas.

1. Introduction

Many attractive events exist in the universe. One of these events is the original production of cosmic rays with ultra high energy. The universe is filled with plasmas. This ultra high energy seems to be generated somewhere in interplanetary plasmas. However, the mechanism to accelerate charged particles up to ultrahigh energy has remained a mystery. In interplanetary plasmas, interactions between electromagnetic waves and charged particles in magnetic field reconnections or in the plasma shock waves are promising candidates for ultrahigh energy particle acceleration. Leading researchers have carried out calculations with respect to plasma shock waves by both theoretical and numerical methods [1,2]. Two types of models are presented here as plasma shocks; one is the two colliding magnetized plasmas and the other is the simultaneous acceleration of an electron and positron. In both models, the magnetic trapping acceleration (MTA) [3,4] plays an important role.

2. Analogy of the Magnetic Trapping Acceleration

The new acceleration mechanism that has been discovered by the author is analogous to the elementary physics principle of electromagnetic

induction as shown in Fig.1. Suppose that a linear metallic rod moves with a velocity \mathbf{v} across a uniform magnetic field \mathbf{B} . Free electrons within the rod experience the Lorentz force $(q/c)\mathbf{v} \times \mathbf{B}$ and are accelerated along the rod. If the length of the rod is infinitely long and there is no electrical resistance, then the electrons will be continuously accelerated and consequently continue to obtain energy indefinitely. The metallic rod plays a significant role in electron trapping. Consider the use of magnetic neutral sheet (MNS) in place of the linear rod. Many electrons will be accelerated in the same way, because MNS also traps charged particles.

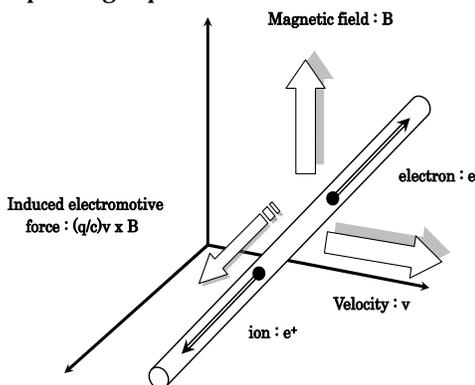


Figure 1: Schematic diagram of electromagnetic induction.

The motion of charged particles moving along the MNS is well known as a meandering motion[5]. This mechanism is the MTA which is viewed as a new mechanism of particle acceleration. Furthermore, even if we replace the linear rod with an electrostatic potential, the electrons still will be accelerated because they will be trapped by the potential well. This acceleration mechanism is explained by Surfatron[6] extending to the Shock Surfing Acceleration[7].

3. Particle Acceleration in Two Colliding Magnetized Plasmas

Suppose that two magnetized plasmas having anti-parallel magnetic fields approach and collide with each other. The cartoon depiction of this situation is shown in Fig.2 and the schematic configuration of the fields is shown in Fig.3.

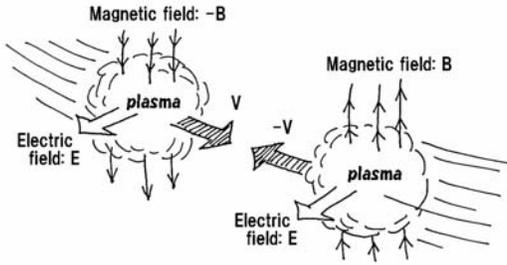


Figure 2: Cartoon of two colliding magnetized plasmas.

Consider that the magnetic field is described in the form:

$$B_{zi} = (B_0/2)[\tanh\eta_i + (-1)^i],$$

$$\eta_i \equiv k(y + v_{pi}t) + h_i(ky) + \phi_i, \quad (1)$$

where ϕ_i and B_0 are the phase constant and the magnitude of the magnetic field and $2/k$ corresponds to the width of the shock wave. Subscript $i=1$ denotes the plasma located at the left-hand side in the initial stage and $i=2$ denotes the right-hand one, and v_{pi} is the velocity in the y direction. Further, the function $h_i(ky)$ gives a geometry of the magnetic field line and is as-

sumed to be given by $h(\eta) = \alpha\eta^2$ with $\eta \equiv ky$ and the parameter α , normalized, is the radius of curvature of the magnetic field. In the Petschek-type magnetic field reconnection, the magnetic field line is given by a hyperbolic function and then its approximate description is used in the reconnection region.

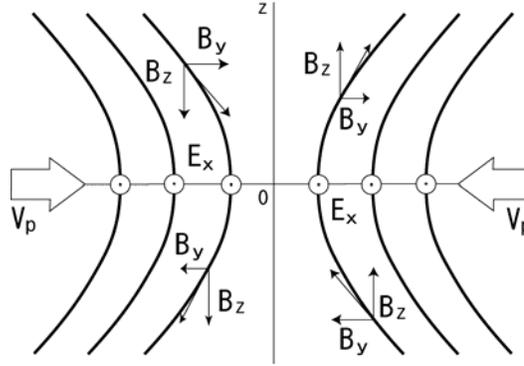


Figure 3: Fields configuration of two colliding magnetized plasmas.

The dynamics of a test particle can be investigated by the use of the electromagnetic fields as shown in Fig.3. To clearly understand certain features of particle acceleration, we suppose that both of the fields have a symmetric configuration. The relativistic equation of motion is analyzed by theoretical and numerical methods. It is found that the MNS and the stationary electric field E_x are generated near the center of the colliding region as time progresses, which has been shown in the MHD model. It is well known that particles are trapped around the stationary magnetic neutral sheet and stay there with a meandering motion. For the same reason, the particle, in the present case, is also trapped by the MNS and furthermore is accelerated by the electric field E_x in the x direction. The (energy) gain of the particle is given as

$$\gamma \approx 2(qE_x/mc)t \approx 2\Omega\beta_p t, \quad (2)$$

where $\Omega \equiv qB_0/mc$ is the cyclotron frequency. This implies that the particle will be continuously accelerated as long as it stays within the MNS.

This is explained by the MTA mechanism as shown above. Such efficient acceleration, however, can never continue indefinitely. Since the transverse magnetic field B_y exists across the MNS, the particle will be turned by the Lorentz force in the course of acceleration, and then its energy gain will sooner or later saturate. Attainable (energy) gains are described in the form:

$$\begin{aligned}\gamma_a &= C_1 \beta_p^3 / \alpha^2 \zeta_0 && \text{(theoretical),} \\ \gamma_a &= C_2 \beta_p^{2.19} / \alpha^{1.22} \zeta_0^{0.28} && \text{(numerical),}\end{aligned}$$

where C_1 and C_2 are constants and β_p is the colliding speed, α the radius of curvature of the magnetic field and ζ_0 the initial position of the test particle. The contribution of β_p to the attainable gain is small because of $0 < \beta_p < 1$. If the value α becomes smaller, then the attainable gains become larger. Many test particles located around the center of collision will also obtain remarkable gains because of $\zeta_0 \approx 0$. Such particles would form the plasmoid which is observed in the magnetic field reconnection.

4. Electron-Positron Acceleration

Recently, the particle acceleration in the electron-positron plasma (pair plasma)[1] has been shown to be in the relativistic regime by the use of electromagnetic particle code. The simultaneous acceleration of electrons and positrons in the pair plasma is an especially attractive phenomena and remains as a significant unresolved problem. We analyze this acceleration mechanism by theoretical and numerical methods and demonstrate a clear understanding of the particle trapping and acceleration by the shock waves in the pair plasma.

Let us consider that the plasma shock wave with magnetic field B_1 is propagating through weakly magnetized plasmas. The test particle gyrating in the upstream region with the static magnetic field B_0 interacts with the plasma shock wave coming closer. As shown in Fig.3

particles are reflected by the wave front at the first collision and move toward the positive y direction with the gyrating motion. These behaviors strongly depend on the magnitude of B_0 as shown in Fig.3. Thus, the transverse current flow along the wave front is generated when the particle is drifting in the y direction [8]. These particles, however, fall behind the wave front in the course of time and drift to the downstream region in the positive X direction. The particles effectively escape from the wave front. It has been shown that some test particles move along the wave front with drift motion, and others are reflected by the shock front many times and obtain reasonable energy [4,9].

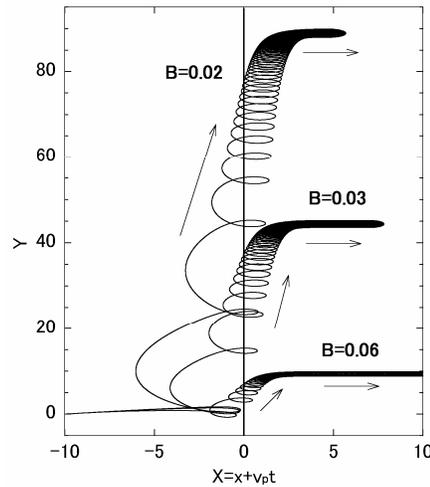


Figure 4: Typical trajectories of test particles along the wave front of the shock. The current localized along the wave front is generated by these drifting motions.

Consider the case where the test particles are electrons or positrons. The current flow localized around the wave front is generated more effectively, because the positron and electron move opposite each other. If the current J_y is described as a normal distribution, then an induced magnetic field B_i is derived from the equation $\nabla \times \mathbf{B} = (4\pi/c)\mathbf{J}$. The total magnetic field, i.e., $B_z \equiv B_0 + B_1 + B_i$, is depicted as shown in

Fig.5. Attractive features of this field show that the large amplitude of the magnetic pulse is formed in front of the shock wave and two magnetic neutral points or two MNSs along the wave front are generated behind this pulse. This is quite different from the magnetosonic soliton which is formed in the wave front [10]. Two dotted lines in the figure show the MNSs. Accordingly, the positron near the MNS is trapped by the sheet located at the left-hand side while the electron is trapped by the other. Both electrons and positrons trapped around the sheets experience a constant electric field generated by the uniform magnetic field B_0 on the wave frame. As a result, the electron and positron are accelerated in opposite directions. This acceleration mechanism is explained by the MTA and attainable energy gains of both particles are in principle unbounded as shown in Eq.(2).

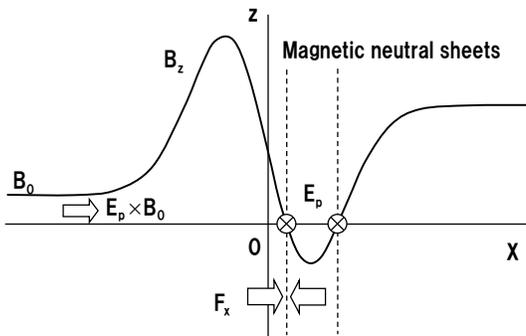


Figure 5: Schematic diagram of the MTA by the shock wave in the electron-positron plasma (on the wave frame). Two magnetic neutral sheets along the wave front are created behind the magnetic pulse.

5. Summary

Two different models of plasma shock waves are presented to analyze high energy particle acceleration. We found that common features exist in the particle acceleration, namely MTA mechanism. The MNS plays an important role in both particle trapping and acceleration. Once the particle is trapped by the MNS, it can never escape from the trapping, and so it is continuously accelerated along the MNS. The magnetic pulse generated by the current flow along the wave front

also plays a key role in forming the MNS. The attainable (energy) gain described by Eq.(2) denotes, in principle, indefinite acceleration. The new acceleration mechanism presented here is a plausible candidate to explain ultra high energy generation in interplanetary plasmas, i.e., super nova remnants [11] and pulsar winds[12], as well as the other mechanism presented by the author [13].

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