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A New Thermodynamic Plasma Acceleration Mechanism in the Spontaneous Fast Magnetic Reconnection

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Abstract

The Petschek reconnection model suggests that the plasma jets cannot steadily exceed the Alfven velocity measured in the magnetic field region. In contrast, in the spontaneous fast reconnection model, plasma jets can steadily exceed the Alfven velocity. Actually, in our 2D MHD studies, the final steady velocity of the plasma jets reaches 1.4 times of the Alfven velocity. We found that this acceleration mechanism is established by a combination of slow shocks associated with the reconnection process and a superfast (supersonic) adiabatic expansion fan. This expansion fan is similar to the Parker's solar wind acceleration with an exception of the gravity force. Eventually, the superfast plasma jets terminate at a fast shock in the magnetic loop, giving rise to a strong plasma heating.

Keywords:
magnetic reconnection, supersonic, fast shock, adiabatic expansion

1. Introduction

Petschek [1] predicted that slow shocks in a magnetic reconnection process can efficiently generate plasma jets. Especially, when the slow shock is a switch off shock, the plasma jet can reach the maximum velocity, which is the Alfven velocity measured in the magnetic field region. Actually, slow shocks are reported in many numerical studies related with the magnetic reconnection, and frequently observed in recent observations of space plasma. Also, the spontaneous fast magnetic reconnection, which is proposed by Ugai [2], generates slow shocks and the Alfvenic plasma jets. In addition, our recent precise MHD simulations reveals that the plasma jets can steadily exceed the Alfven velocity. The strong acceleration process cannot be explained by the Petschek model. In section 2, the MHD simulation results are demonstrated. In section 3, the acceleration mechanism is explained by the thermodynamic adiabatic expansion theory. Section 4 is devoted to conclusions.

2. 2D MHD Simulation

This simulation starts from an anti parallel magnetic field configuration enclosed by the upper and lower open (free) boundaries, where has no magnetic field. A current driven anomalous resistivity [3,4] is selfconsistently set. Then, the fast magnetic reconnection spontaneously is built up by the resistivity enhanced naturally at the origin [4]. Figure 1(a) demonstrates magnetic field lines in a quasi-steady state reconnection process, which has a pair of slow shocks extended from the origin and a growing plasmoid (magnetic loop). The plasmoid is swelling and propagating toward the right side (open) boundary. Figure 1(b) demonstrates profiles of plasma pressure P, velocity U_x and the local fast wave velocity C_f on the x-axis. From x = 13 to 17, a rapid increase of U_x (a dash

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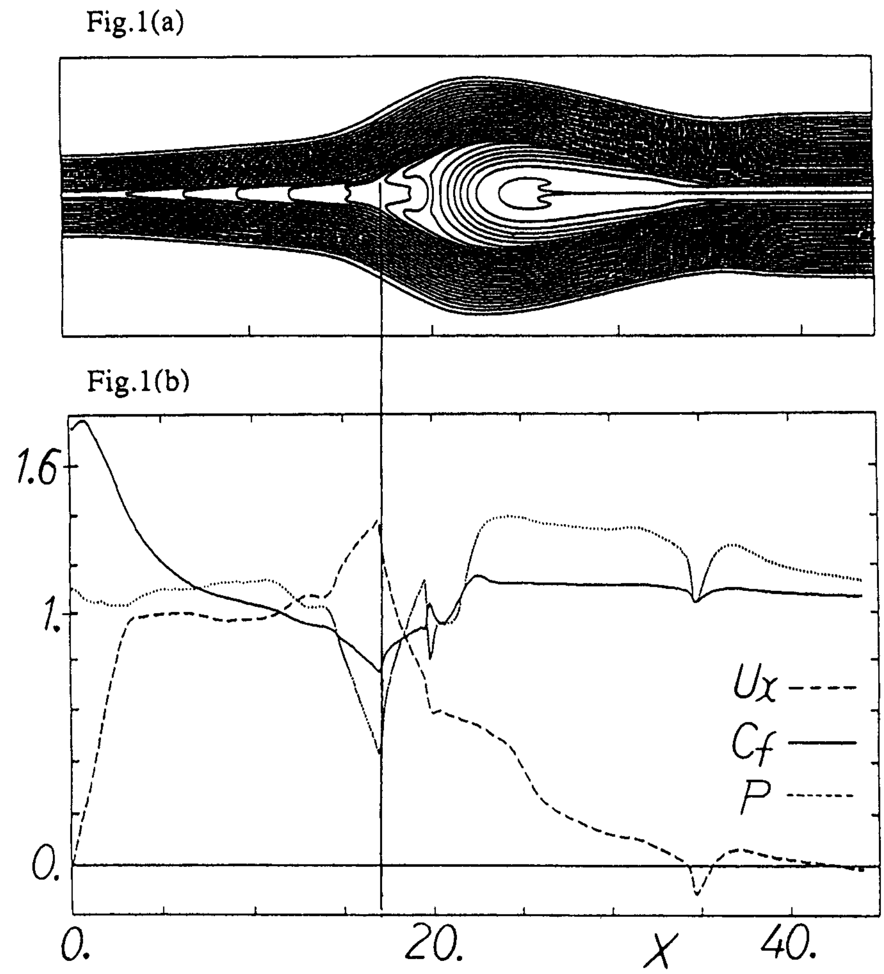

Fig. 1 (a): Magnetic field lines at the time, when the reconnection region becomes a steady state. The left side boundary is symmetry, and the others are free (open).
(b): Profiles of the pressure P, plasma velocity U_x, and the local fast wave velocity C_f. The right vertical solid line (X1) indicates a location of a fast shock around the x axis.

line) can be seen. This strong plasma acceleration is executed beyond the Alfven velocity V_A (= 1.0) measured in the upper and lower magnetic field region. In addition, since U_x is larger than C_f in $13 < x < 17$, the plasma jet is superfast. And, the rapid decrease of the pressure P means that the plasma is expanding there. Note that, in $x < 13$, the plasma velocity already reaches the Alfven velocity by slow shocks, and rapidly decreases in $X > 17$ by a fast shock in front of the plasmoid. Once this reconnection process starts, the process is almost steadily maintained [5,6], until most of the magnetic field lines are reconnected.

3. Supersonic Expansion Acceleration

In general, when plasma jets largely exceed the local fast wave velocity C_f and continues to expand in the radial direction, the superfast plasma is accelerated by the thermodynamic effect. Magnetic effects are not needed in this mechanism. The situation is drawn in Fig. 2 with a cylindrical coordinate (r, θ, z). We assume uniformity in the (θ, z) components and plasma steadily flows in the r direction. Between r_0 and r_1, the plasma expands by the rate r_1/r_0. This process is written by the following adiabatic fluid dynamics equation.

$$\partial v / \partial r \, (v^2 / C_s^2 - 1) = v / r$$

Here, C_s is the local sound velocity. According to this equation, when the velocity v exceeds C_s, $\partial v/\partial r > 0$ is established, that is an acceleration for $v > 0$. This equation can be numerically resolved and applied to the

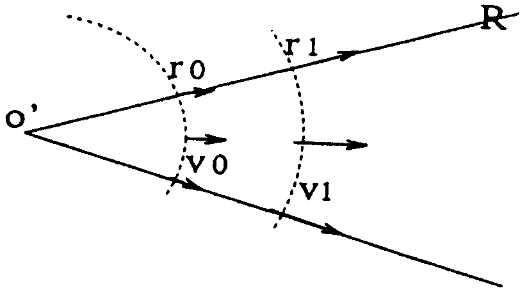

Fig. 2 Schematic superfast expansion acceleration mechanism.

present quasi steady state simulation result. Note that we may ignore the magnetic effect, since $P \gg |B^2|$ in $13 < x < 17$. In this application, $r_1 - r_0$ is the acceleration distance from $x = 13$ to 17. The expansion rate r_1/r_0 is obtained from the simulation data. As a result, r_0 and r_1 are obtained. And, v_0 and v_1 are assigned to the plasma velocity U_x at $x = 13$ and 17, respectively. We found that this equation is satisfied with the present MHD simulation data in error of 3% or less.

4. Conclusions

We found that the plasma jets generated in the reconnection process steadily exceeds the Alfven velocity measured in the magnetic field region. It is well explained, as follows. Firstly, the plasma jets must become superfast by accelerations in slow shocks associated with the reconnection process. Secondly, the superfast plasma jets experience an expansion of the plasma jet region initiated by swelling of a plasmoid (or a magnetic loop). It results in a supersonic expansion acceleration.

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