Forced Reconnection by Nonlineal Magnetohydrodynamic Waves

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ABSTRACT

Forced magnetic reconnection induced by magnetohydrodynamic (MHD) waves may account for the triggering of explosive solar activities such as flares. Reconnection in a neutral sheet plasma can be driven by the ponderomotive force associated with nonlinear MHD waves accompanying plasma vortex motion. The nonlinear stage of forced reconnection by MHD waves is simulated with a MHD particle-code: Some conditions for fast reconnection are discussed with applications to solar flares.

1. INTRODUCTION

Magnetic field reconnection processes (Vasyliunas, 1975; Sonnerup, 1979; Syrovatskii, 1981; White, 1983) may play a significant role in the fast release of magnetic field energy stored in current-carrying plasma such as in a magnetic neutral sheet. They may be important also in the acceleration process of high energy particles. It becomes clear, however, that both the old steady reconnection models by Sweet (1958), Parker(1963) and Petshek(1963) and non-steady reconnection models of tearing modes (Furth, Killeen and Rosenbluth, 1963) are insufficient to expalin the impulsive phase of solar flares (Svestka, 1976; Sturrock, 1981) or the sequential triggering phase (Vorpahl, 1976).

The observation (Vorpahl, 1976) hints a mechanism of triggering of solar flares by fast magnetosonic waves. In order to explain the triggering phase of flares, Sakai and Washimi (1982) and Sakai(1983) proposed a theoretieal model of forced reconnection caused by fast magnetosonic waves. They showed that the ponderomotive force of fast magnetosonic waves enhances the plasma vortex motion in turn to a rapid growth of forced tearing modes.

Brunel, Tajima and Dawson (1982) showed that the effect of plasma compressibility leads to fast reconnection following Parker's slower reconnection phase. They demonstrated this by computer simulation making use of MHD particle-code(Brunel et al., 1981). Furthermore, in the nonlinear stage of forced tearing instability when magnetic islands are formed, the coalescence instability of magnetic islands may play a most effective role (Leboeuf, Tajima and Dawson, 1982) in the magnetic energy conversion.

About 10% of the magnetic energy stored in the current filaments can be converted into the plasma thermal energy as well as into high energy particles (Tajima, Brunel and Sakai, 1982; Tajima et al., 1983). The quasi-periodic acceleration mechanism (Tajima et al. 1982and 1983) through relaxation oscillations of two merging current filaments may explain the amplitude oscillations of X-ray, γ-ray and microwave emissions (Forrest et al., 1981 ; Nakajima et al., 1983).

In the present paper we theoretically discuss the triggering phase in terms of forced reconnection caused by external nonlinear MHD waves, and, moreover, examine and visualize this process by means of a MHD particle simulation. In Section 2, we discuss the nonlinear effect of MHD waves, the ponderomotive force. The threshold condition for external MHD waves to drive the forced reconnection is estimated. In Section 3, we present some simulation results of forced reconnection by nonlinear MHD waves and discuss conditions for fast reconnection. In Section 4, we discuss a situation where the present forced reconnection mechanism by waves may play a significant role to trigger a flare.

2. INITIAL PHASE OF FORCED RECONNECTION BY WAVES

In this section we discuss how fast reconnection is triggered by external MHD waves (fast magnetosonic waves and Alfvén waves). In the initial phase of reconnection forced by nonlinear MHD waves, the magnetic perturbation associated with the reconnection should be small. It is possible then to treat the perturbation associated with reconnection as a linear one. On the other hand, we must take into account nonlinear effects of external MHD waves and also coupling between MHD waves and reconnecting magnetic perturbation. An important nonlinear effect of MHD waves for the neutral sheet can be characterized by a slowly varying ponderomotive force, since the period of the MHD waves is much shorter than the growth time of reconnection. Both fast magnetosonic waves propagating perpendicular to the magnetic field (Sakai and Washimi, 1982; Sakai, 1983) and shear Alfvén waves propagating parallel to the magnetic field (Washimi, 1980) drive plasma vortex motion through their ponderomotive force, as depicted in Figure 1.

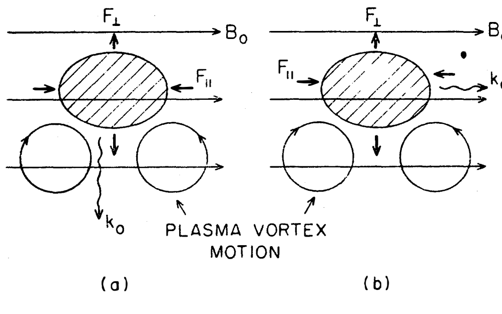

Fig. 1 Shematic plasma vortex motion by ponderomotive forces associated with a wave packet (shaded region) of fast magnetosonic waves (a) and shear Alfvén waves (b).

In a uniform plasma, the ponderomotive force : $\vec{F}$ associated with fast magnetosonic waves and Alfvén waves is described by

$$F_{\parallel} = \rho_0 V_A^2 \nabla_{\parallel} I,$$
$$F_{\perp} = -\rho_0 V_A^2 \nabla_{\perp} I, \qquad (1)$$

where F_{11} is the component parallel to the static magnetic field, $F_{\perp}$ the perpendicular component, ρ_0 the background density, V_A the Alfvén velocity and I the normalized wave intensity of MHD waves; $I = |\phi|^2$, where ϕ is the normalized wave amplitude $\delta B / B_\infty$ and B_∞ is the value of B_y at $x = \infty$. This expression shows that curl $\vec{F} \neq 0$. This suggests that the plasma vortex motion is created by the ponderomotive force (see Figure 2).

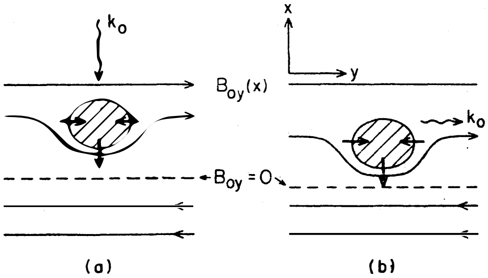

Fig. 2 Finite-amplitude MHD waves propagate (a) across or (b) along the neutral sheet, causing plasma vortex motion, which in turn causes reconnection.

In inhomogeneous plasma (e.g. a neutral sheet plasma and plasma configuration with magnetic shear (sakai, 1982)), the ponderomotive force has additional terms due to the plasma inhomogeneity. This becomes important for forced excitation of the tearing mede and ballooning mode.

This fast magnetosonic wave-forced reconnection process in its initial phase may be described by the following coupled equations (Sakai and Washimi, 1982):

$$\frac{\partial}{\partial t} \nabla^2 \Pi + \frac{\rho_0'}{\rho_0} \frac{\partial^2 \Pi}{\partial x \partial t} - \frac{B_{0y}}{4\pi\rho_0} \frac{\partial}{\partial y} (\nabla^2 A - \frac{B_{0y}''}{B_{0y}} A) + \frac{\partial}{\partial y} \{ 2(V_A^2 + \frac{V_g^4}{C_s^2}) \frac{\partial I}{\partial x} + 2 \frac{V_g^3}{C_s^2} \frac{\partial I}{\partial t} \} = 0, \quad (2)$$

$$\frac{\partial A}{\partial t} = B_{0y} \frac{\partial \Pi}{\partial y} + \frac{C^2}{4\pi\sigma} \nabla^2 A + 2\frac{\omega}{k} B_{0y} I, \quad (3)$$

where the velocity ($v = \mathrm{rot}\, \Pi \vec{e_z}$) and magnetic perturbations ($B = \mathrm{rot}\, A \vec{e_z}$) are linearized. Here $\nabla^2 = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2}$ and the prime denotes the derivative with respect to x. B_{0y} is the magnetic field produced by the neutral sheet current. Equation (2) describes the time evolution of plasma vorticity; the last term drives plasma vorticity through the ponderomotive effect. Equation (3) is the magnetic induction equation.

This set of equations along with the wave kinetic equation for MHD waves self-consistently describes the linear stage of forced reconnection. Forced excitation of tearing modes by magnetosonic waves has been studied (Sakai and Washimi, 1982; Sakai, 1983). The instability grows with a time scale τ given by

$$\tau \simeq 0.2 \tau_A (ka)^{-2} (v_A/v_g)^{4/3} S^{1/3} I_0^{-4/3} , \quad (4)$$

where τ_A is the Alfvén transit time across the current sheet, defined as $\tau_A = a/v_A$ ($v_A = B_\infty / \sqrt{4\pi\rho(0)}$), a thickness of the current sheet, $\rho(0)$ the density at x=0, k the wavenumber of the mode, v_g the group velocity of fast waves, $S = \tau_r / \tau_A$ the magnetic Reynolds number,

τ_r the resistive time and I_0 is the wave intensity of fast waves at $x=0$.

This forced tearing mode can be excited if the wave intensity I_0 of the fast waves exceeds a critical value I_C given by

$$I_C = (v_A/v_g)(ka)^{-9/5} S^{-1/5} \quad . \qquad (5)$$

From Eq. (4), we find two conditions for rapid growth of forced tearing modes:

(1) when wave intensity is large;

(2) when ka is large.

Note that $v_A \simeq v_g$ and S is fixed. The second condition indicates that if the external driven fast wave amplitude is modulated locally, we obtain a more rapid grewth. The threshold (Eq. (5)) was drived from the condition that the width, $x_s \simeq a(2I_0 v_g/v_A S)^{1/3}$, within which the ponderomotive force is dominant, exceeds the usual reststive thickness layer, $x_r \simeq a(kaS)^{-1/2}(\gamma\tau_r)^{1/4}$.

3. FORCED RECONNECTION OBSERVED IN A COMPUTER SIMULATION

It is difficult to study the nonlinear stage of forced reconnection analytically. Therefore, we present instead the result of a MHD simulation. The purposes in this section are two-fold. The first is to demonstrate the two factors for fast reconnection that were pointed out in the previous section: (1) that the wave amplitude of the external MHD waves exceeds a threshold value ; (2) that a local enhancement of the wave amplitude along the y-direction significantly accelerates reconnection. The second purpose is to explore any hidden condition that escapes the analytical approach, predicted in the previous section, playing a vital role in controlling the process of wave-triggered reconnection. In particular we study the effect of the toroidal magnetic field on wave-triggered fast reconnection.

The study of nonlinear development of forced reconnection by simulation is carried out using a MHD particle-code (Brunel et al., 1981). In the MHD particle-code, the equation of motion is solved in Lagrangian coordinates, while the Maxwell equations are solved in Eulerian coordinates, by means of Lax-Wendroff algorithm. The conservation of fluid and momentum is exact,.

The density and the magnetic field of the neutral sheet plasma at $t=0$ should satisfy the static pressure balance and the following choice was made:

$$\rho_0 = \rho(x=34\Delta)\ \mathrm{sech}^2[(x-34\Delta)/a] \qquad (6)$$

$$B = B_\infty \tanh[(x-34\Delta)/a]\vec{e}_y + B_t\ \vec{e}_z, \qquad (7)$$

where a is the thickness of the current sheet, B_t the toroidal component of the magnetic field and Δ is the grid length. A periodic boundary codition is imposed in the y-direction, while in the x-driection the metallic boundary condition is taken (i. e. $\sigma=\infty$ and $\vec{v}=0$ on $x=0$ and 64Δ). The physical parameters used in the simulation are as follows: the magnetic Reynolds number $S=300-2020$, $a=5\Delta$, the resistivity $\eta=0.06$ in appropriate normalization of space by Δ and velocity by c_s. In order to excite nonlinear MHD waves far from the neutral sheet, an oscillating external current with frequency $\omega_0=2.1,\ 3.1,\ 6.2(\Delta c_s^{-1})$ is imposed at $x=50\Delta$. This option was due to the metallic boundary condition employed in the code where the incoming wave solution is not allowed.

In order to observe the rate of reconnection, we have computed the destruction of magnetic flux at the X-point as a function of time as shown in Figure 3. Figure 3(a) shows time evolution of the destruction of maguetic flux when the wave amplitude is above a threshold.

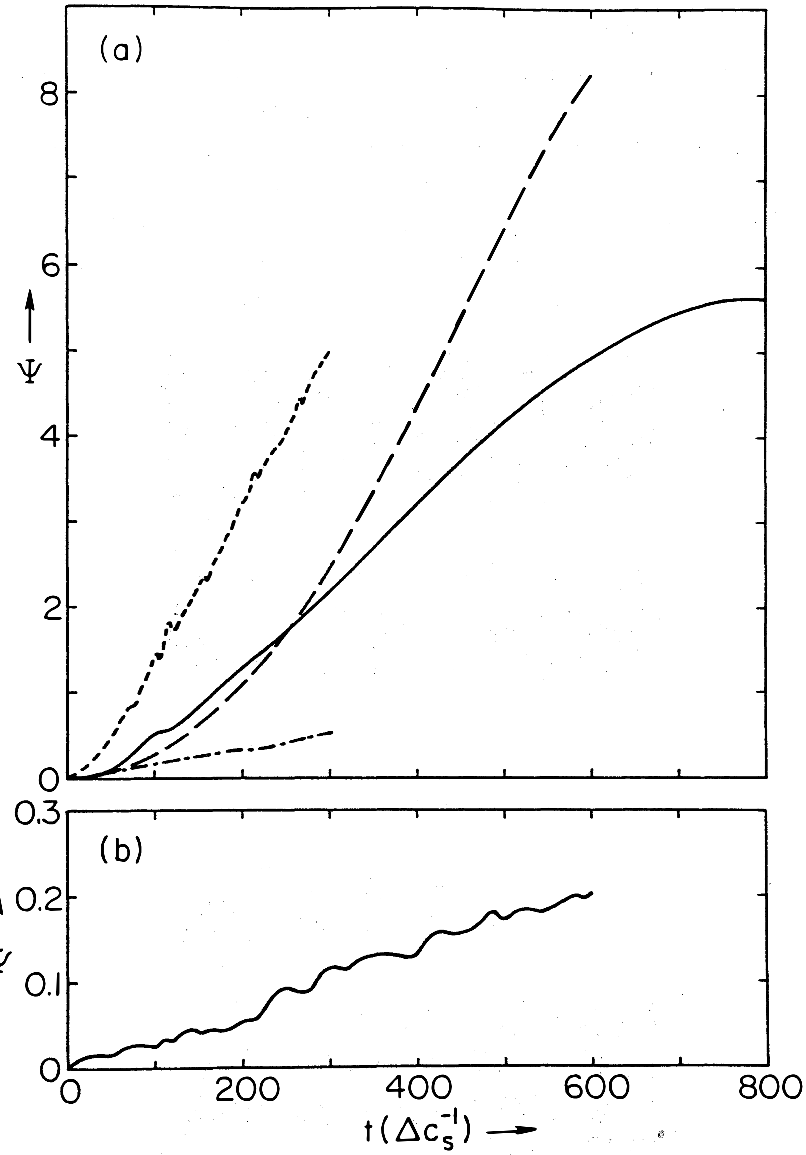

Fig. 3 Reconnecting magnetic flux (ψ) as a function of time
(a) Dash-dotted curve: B_t/B_∞ = 3, S = 2020.
Solid curve: B_t/B_∞ = 1.25, S = 700.
Dashed curve: B_t/B_∞ = 0.625, S = 300.
Dotted curve: B_t/B_∞ = 1.25, wave intensity 10 times larger then above thtee cases. S = 700.
(b) No wave : B_t/B_∞ = 1.25, S = 700, .

While Figure 3(b) shows the case when the wave is absent. When the wave amplitude is below a threshold, no fast reconnection is observed as seen in Fig. 3(b). We could not find the threshold of wave amplitude, numerically. We, therfore, discuss only cases above the threshold in the following.

In order to confirm the second condition, i.e. a local enhancement of the wave amplitude along the y-direction, we tried two different cases; (case 1) the external current intensity is constant along the y-direction and (case 2) the current intensity is modulated in the y-direction by superposing two Fourier modes with different wave numbers; $k_1 = 2\pi/128$ and $k_2 = 2\pi/64$, whose amplitudes are 0.0625. In both cases we maintained the intensity of the external waves. In the case(1), we hardly saw reconnection within the length of computer run. Figure 4 shows magnetic field lines in the x-y plane at $t = 300\ \Delta\ c_s^{-1}$ in the case of unlocalized wave simulation. When a local enhancement of the wave amplitude is added with the total wave amplitude kept constant, however, a dramatic acceleration of reconnection took place [case(2)].

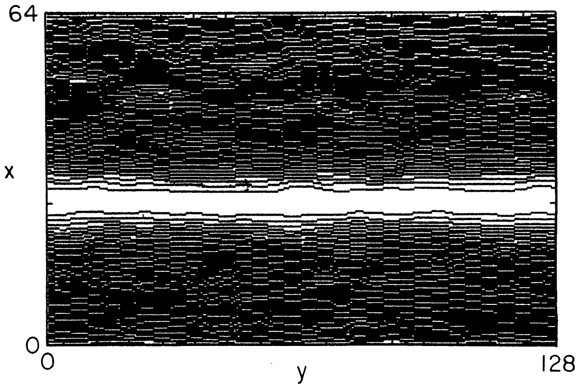

Fig. 4 Unlocalized wave-simulation result at $t=3000\Delta c_s^{-1}$. Away from the neutral sheet, the field lines are so dense that they aggregate to look like dark areas, while the neutral sheet region looks light.

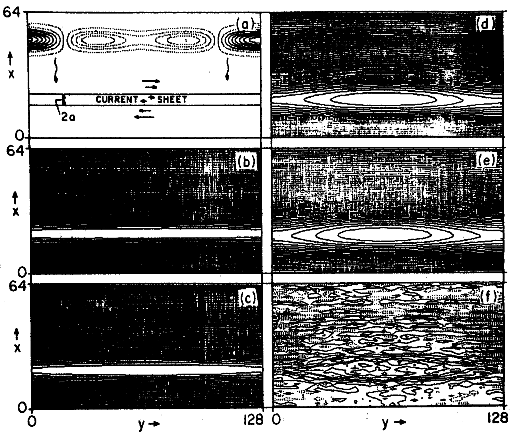

Fig. 5 Simulation results (Localized waves)

(b) The field line at $t = 120\ \Delta c_s^{-1}$.
(c) The field line at $t = 200\ \Delta c_s^{-1}$.
(d) The field line at $t = 610\ \Delta c_s^{-1}$.
(e) The field line at $t = 800\ \Delta c_s^{-1}$.
(f) The density contours at $t = 625\ \Delta c_s^{-1}$. The solid lines are high density regions and the dotted ones are lowdensity regions.

Figure 5 shows the time evolution of magnetic field lines in the x–y plane for the case (2). Reconnection started at the point in the neutral sheet where the amplitude of the external current has a maximum. Figure 5(a) shows the intensity distribution of the external current which was imposed near $x = 50\Delta$. The amplitude of the external current has a maximum near $y = 124\,\Delta$. Therefore the excited MHD waves can be considered to be generated with a maximum amplitude near $y = 124\,\Delta$. At the stage of Figure 5(b) we see some modulations in the magnetic field– lines due to the nonlinear MHD waves propagating across the neutral sheet. As shown in Figure 5(d), reconnection occurs at the point where the external MHD waves push the neutral sheet with maximum strength. As reconnection proceeds, the magnetic island grows as shown in Figure 5(e). In Figure 5(f), the density distribution is shown at $t = 625\,\Delta c_s^{-1}$. Particles are squeezed near the point where reconnection takes place. The time evolution of reconnecting magnetic flux at the X– point corresponding to Figure 5 is shown by the solid curve in Figure 3(a). The reconnection rate in this case is about 25 times faster than the case of no–wave at $t = 600\,\Delta c_s^{-1}$.

We now turn to a new effect of the toroidal magnetic field on fast reconnection. In this series of simulation, we studied wave–triggered reconnection with the toroidal magnetic field B_t (added vertically in the x–y plane) varied. It turns out that the speed of reconnection is much reduced when the toroidal field is applied. Figure 3(a) shows the rate of reconnection for three cases; $B_t/B_\infty = 3$ (dash–dotted curve), $B_t/B_\infty = 1.25$ (solid curve), and $B_t/B_\infty = 0.625$ (dashed curve). When the toroidal field (B_t) is less than the poloidal field (B_∞), fast reconnection takes place. This effect is not explained by the conventional theories including Furth et al. s' (1963) and Sakai and Washimi (1982). We therefore seem to have found an additional parameter that controls the wave–induced fast reconnection, i.e. the magnitude of the toroidal magnetic field. We attempt to focus on this effect in the following.

Tajima (1981) found the threshold effect of the toroidal field on collisionless reconnection: when the toroidal field is less than the poloidal field, fast reconncetion takes place, while no fast reconnection is observed and instead a tearing turbulence occurs when $B_t > B_\infty$. The present simulation of reconnection triggered by impining MHD waves is consistent with the collisionless reconnection case. Figure 6 shows magnetic field–line reconnection with different toroidal fields; (a) $B_t/B_\infty = 1.25$, (b) $B_t/B_\infty = 3$ at $t = 300\Delta c_s^{-1}$. When $B_t > B_\infty$, the toroidal field tends to bar rapid reconnection from developing either due to the increased incompressibility of plasma by strong toroidal field or due to the increased magnitization of ions which changes the response of ions to the magnetic perturbation.

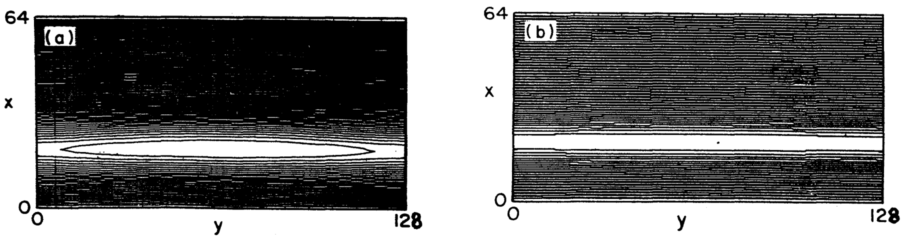

Fig. 6 Comparison of magnetic field– line reconnection with different toroidal magnetic fields ; (a) $B_t/B_\infty = 1.25$ (b) $B_t/B_\infty = 3$, at $t = 300\,\Delta c_s^{-1}$.

Summarizing the simulation, for fast reconnection induced by external nonlinear MHD waves, we find:

(1) A threshold amplitude for the external MHD waves exists.
(2) Localized wave pressure by nonlinear MHD waves can lead to fast roconnection.
(3) When there is no toroidal magnetic field, fast reconnection takes place more easily. As the toroidal field becomes stronger, the reconnection process with waves becomes slower or more difficult.

4. DISCUSSIONS

We now discuss possible mechanisms for MHD waves to localize near the neutral sheet. When a fast magnetosonic wave propagates perpendicular to the magnetic field, the wave becomes unstable against a modulation along the magnetic field, if the amplitude of the fast wave exceeds a critical value, $\phi_m = c_s / v_A$ (Sakai, 1983). This modulational instability can lead to a local enhancement of the wave amplitude.

For the Alfvén wave, local enhancement of the amplitude near the current sheet may be realized by spatial resonance. The external Alfvén waves resonate at the point where the resonance condition, $\omega = k_{11} v_A(x)$, is satisfied (Chen and Hasegawa, 1974). Amplitude enhancement takes place near the resonance when this happens.

The threshold phenomena (Tajima, 1981) for the toroidal magnetic field to control fast reconnection may be important for the magnetic energy storage in the current system of the solar atmosphere. This is because only when the magnetic field B_∞ produced by the neutral sheet current exceeds the toroidal magnetic field, fast reconnection can set in. This means that as soon as B_∞ exceeds B_t, an explosive reconnection can take place. This may account for impulsive nature of flares.

The stability of a single current loop (see Van Hoven, 1981) which feet tied to the photosphere has recently received attention. In this plasma configuration, the toroidal component of the loop magnetic field changes its sign at a certain radial position in the loop. Nevertheless, the tearing mode may not be excited due to line-tying (Mok and Van Hoven, 1982) in this configuration. Although the resistive interchange instability (Schnack and killeen, 1981) could still occur, the prowth rate is too small to explain the impulsive phase of solar flares for a single current loop. If the nonlinear MHD waves localize near the region where the magnetic field reverses, however, reconnection can occur fast enough through the present mechanism of forced excitation of resisive interchange instability. This may lead to impulsive mass ejection near the photosphere. Of course, when there are more than one loop currents, instead of a single current, the coalescence process (Tajima et al. 1982, 1983) can also play a vital role in facilitating rapid reconnection.

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