Development of the Fast Reconnection Mechanism in a Sheared Field

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Abstract

The development of the fast reconnection mechanism is studied in a sheared field geometry. Initially, there are antiparallel fields (of component B_{x0}) as well as a uniform sheared field component (B_{z0}). On the basis of the spontaneous fast reconnection model, the fast reconnection mechanism, initiated by a small disturbance, can fully be established. It is demonstrated that the thin (shock) transition layer standing in the quasisteady fast reconnection region is divided into the intermediate wave region, where magnetic field simply rotates without changing its magnitude, and the slow shock region, where a slow shock is coupled to an intermediate wave. In order to examine the detailed shock structure, one-dimensional MHD simulations with high numerical resolution study the temporal dynamics of MHD shocks that are placed in a noncoplanar situation. It is shown that for any case the noncoplanar shock structure can be sustained by physical dissipations involved. The resulting noncoplanar slow shock structure is, both qualitatively and quantitatively, in good agreement with the two-dimensional shock transition layer associated with the sheared fast reconnection mechanism. The reconnection (flux transfer) rate is estimated to scale as $E_0/[1+\tan^2(\Omega/2)]$, where $\Omega = 2\tan^{-1}(B_{z0}/B_{x0})$ and E_0 is the reconnection rate for the coplanar case ($B_{z0}=0$).

1. Introduction

Magnetic reconnection may play an important role in a variety of space plasma phenomena, such as solar flares and geomagnetic substorms. In actual applications to solar flares where magnetic Reynolds number is extremely large, the so-called fast reconnection mechanism should be most effective. The fast reconnection mechanism may be characterized by standing slow shocks attached to a localized (small) diffusion region, since in the presence of slow shocks most part of stored magnetic energy can be effectively released by the large-scale motor effect. The analytical treatments argued that the fundamental structure of the fast reconnection mechanism was determined by external boundary conditions without need of any special form of internal finite electrical resistivity (Petschek, 1964; Forbes and Priest, 1987). On the contrary, we have proposed that the self-consistent interaction between localized microscopic plasma (anomalous) resistivities and macroscopic reconnection flows should be fundamental for this problem (Ugai and Tsuda, 1977; Ugai, 1984); in fact, it was recently demonstrated that the fast reconnection mechanism strongly depends on the resistivity model (Ugai, 1992). According to this idea, the fast reconnection mechanism should spontaneously build up and be set up without any direct influence of specified boundary conditions. This reconnection mechanism may hence be called "the spontaneous fast reconnection model".

Most of the previous studies on the fast reconnection mechanism have been directed to coplanar situations. In understanding the complicated plasma processes involved, it may be fundamental to clarify the basic structures of fast reconnection mechanism in realistic noncoplanar plasma situations. Hence, on the basis of the spontaneous fast reconnection model, we systematically study the fast reconnection structure in a sheared field geometry by 2.5 dimensional MHD simulations (for details, see Ugai, 1993). The associated three-dimensional skewed field line structure are examined in detail, and the noncoplanar shock structure associated with the sheared fast reconnection mechanism are examined. In particular, we are interested in how magnetic reconnection proceeds even without any magnetic neutral (zero) point. Also, note that in the sheared field geometry magnetic field should rotate across the shock transition layer, so that the Rankine-Hugoniot jump relations cannot be satisfied in such a noncoplanar situation. Hence, a question is how the noncoplanar shock-like transition layer can stand quasisteadily? In order to examine this question, we further perform one-dimensional dissipative MHD simulations with high numerical resolution. In what follows, computer simulations systematically study the above fundamental questions.

2. Simulation model and results

We first perform 2.5 dimensional simulations. The phenomenon to be studied is 2.5 dimensional in the sense that variables depend on x and y but not on z, whereas both the flow velocity **u** and the magnetic field **B** may have z components. As an initial configuration, a current sheet system with antiparallel field components (B_x) as well as a uniform sheared field component (B_{z0}) is assumed. As an initial disturbance, a small electrical resistivity is imposed in a local region near the origin in the initial time range $0<t<4$. Initiated by this disturbance, all the phenomena will develop from near the local region and extend outward on Alfven time scales. The reconnection process is strongly influenced by the resistivity model (Ugai, 1992), so that in the present study, an anomalous resistivity is assumed to increase with the relative electron-ion drift velocity when a threshold value is exceeded. The resistivity model is imposed for time $t>4$ after the initial disturbance is removed.

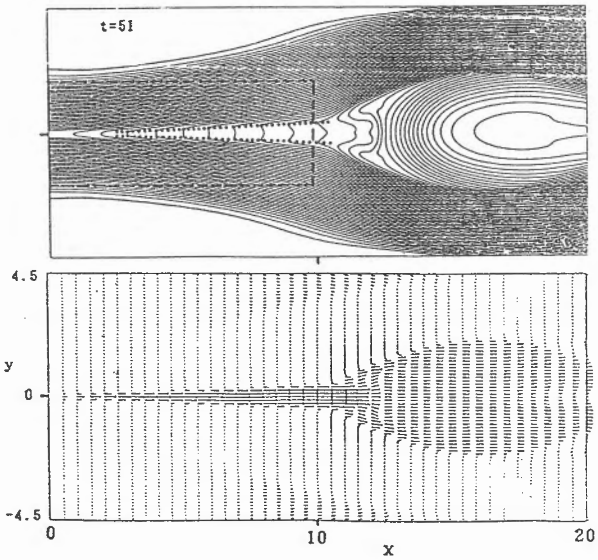

Fig. 1. Magnetic field and plasma flow configurations [projected onto the (x, y) plane], associated with the sheared fast reconnection mechanism for the case of $B_{z0}=0.25$, where a pair of quasisteady shock transition layers are shown by dotted lines.

We find that the fast reconnection mechanism can fully be established with the anomalous resistivity model. It is found that even in the noncoplanar situation a pair of thin shock-like transition layers could eventually be set up quasisteadily. Figure 1 typically illustrates the resulting magnetic field and plasma flow configurations (projected onto the (x, y)-plane) for the case of B_{z0}=0.25. We can readily see from this figure that the field lines in fact change topologically because of the reconnection process. As in the well-known coplanar situation, a pair of thin shock transition layers (denoted by dotted lines in Fig. 1) extend outward almost straightly from near the diffusion region and stand quasisteadily in the resulting fast reconnection configuration. Figure 2 also shows the changes in quantities across the transition layer shown in Fig. 1 and indicates that the transition layer can be divided into the intermediate wave region and the slow shock region; in the intermediate wave region, magnetic field simply rotates without changing its magnitude, whereas in the slow shock region a slow shock is combined with an intermediate wave. In Fig. 2, the intermediate wave region is located in $y_s<y<y_w$ and the slow shock region in $y_b<y<y_s$ (the propagation direction of the shock transition layer may be considered to be approximately the positive y direction in Fig. 1).

In order to examine the (noncoplanar) shock structure in more detail, we perform one-dimensional MHD simulations where all the variables depend only on x, but both the flow velocity **u** and the magnetic field **B** may have x, y, and z components. The simulation model is based on coplanar shock solutions which should be obtained from dissipative MHD equations. Here, every (coplanar) shock under consideration, which has only the x and y components of magnetic field, is treated in the shock frame and is designed so as to be located steadily in the middle of the computational region. At time t=0, the left, or upstream, state and the right, or downstream, state of the shock are given on the basis of the Rankine-Hugoniot jump relations in the so-called deHoffman-Tellar frame. Then, dissipative MHD equations are solved numerically with the free boundary conditions on the left and right boundaries, and we find that by the time t=40 the system relaxes to a steady shock profile that connects the initial left and right states according to the physical dissipations assumed. Note that by this time (t=40) the system has been coplanar ($B_z=u_z=0$ everywhere), and all the simulation runs will start from this situation.

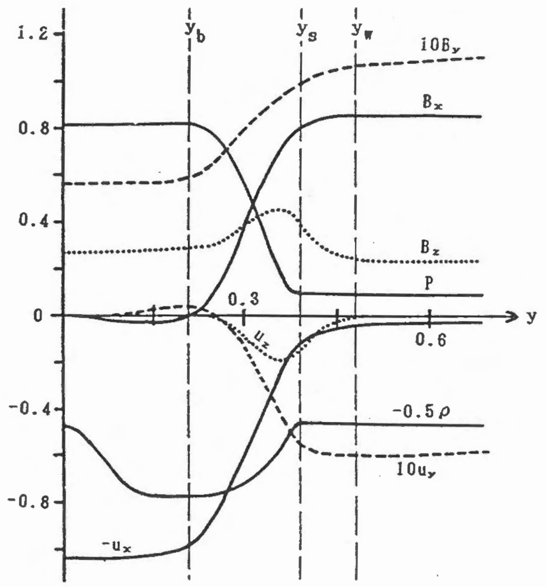

Fig. 2. Changes in quantities along the y direction at x=7.5 across the shock transition layer shown in Fig. 1, which is divided into two regions, $y_w>y>y_s$ and $y_s>y>y_b$.

In order to examine the shock behavior in a noncoplanar situation, we suddenly impose a uniform sheared field component $B_z=B_{z0}$ on the coplanar system at time t=40. Such a uniform sheared field gives rise to no effective force at any spatial point, but it effectively specifies definite noncoplanar boundary conditions ahead of and behind a shock. In a noncoplanar situation, the Rankine-Hugoniot relations can no longer be satisfied, and the shock profile should gradually change with time. Note that this simulation model is designed by considering the basic plasma situations in which the noncoplanar transition layers (Fig. 1) have been caused by the establishment of the fast reconnection mechanism in the sheared field geometry. Here, we examine the question with respect to the noncoplanar shock transition layers (Figs. 1 and 2) associated with the sheared fast reconnection mechanism. It is well known that in a coplanar fast reconnection structure, the thin transition layer should be identified with a switch-off shock (Ugai, 1992), so that we examine the case of switch-off shock in the present study.

In order to apply the present results to the noncoplanar shock transition layer (Fig. 2), we may choose the relevant case of η =0.002, which is found to be consistent with the physical (anomalous) resistivity involved in the transition layer shown in Fig. 2. Also, the plasma quantities ahead of the shock have been chosen so as to be consistent with Fig. 2 (except for the difference of the coordinate system). Figure 3 shows the resulting

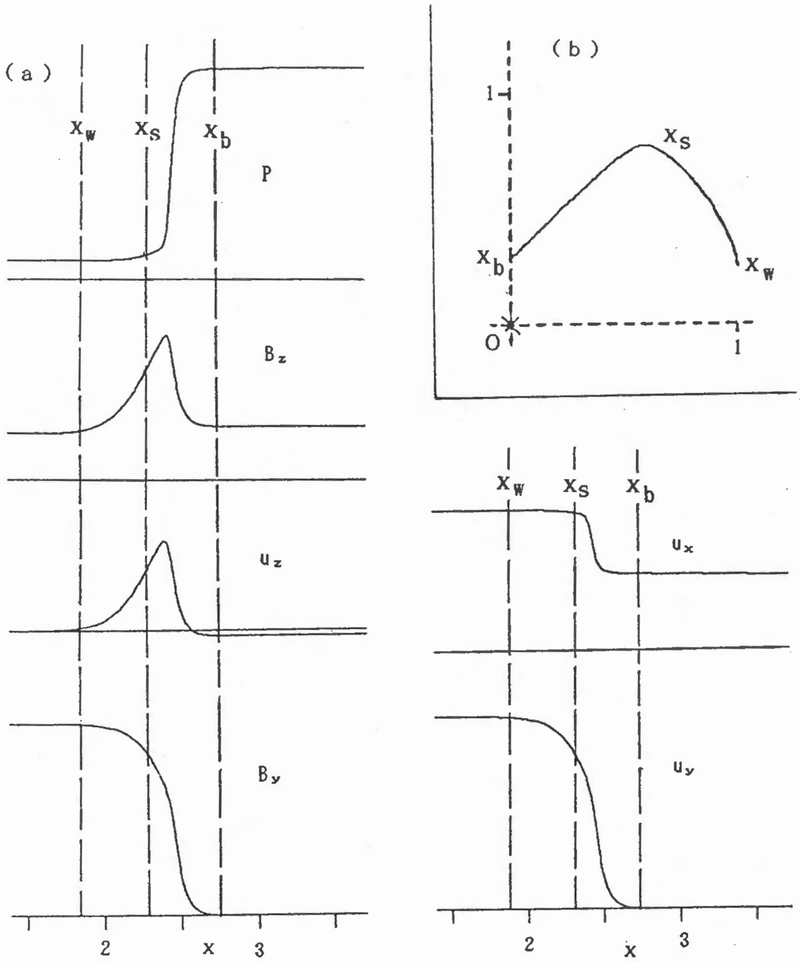

Fig. 3. (a) Profiles of quantities at time t=56 and (b) the corresponding magnetic hodograms, for the noncoplanar slow shock with B_{z0}=0.25 and η = 0.002.

noncoplanar shock structure at time t=56, which may be divided into the intermediate wave region $x_w<x<x_s$ and the noncoplanar slow shock region $x_s<x<x_b$ in the manner similar to Fig. 2 (note that in the present case the shock propagates in the negative x direction, whereas the shock transition layer in Fig. 1 propagates approximately in the positive y direction). Also, in Fig. 3(b) the corresponding magnetic hodogram is shown, in which the points corresponding to x_b, x_s, and x_w are indicated on the trajectory. Apparently, the noncoplanar shock layer (Fig. 3) is, both qualitatively and quantitatively, in good agreement with Fig. 2; in particular, in the noncoplanar slow shock region ($x_s<x<x_b$) a slow shock is combined with an intermediate wave, since magnetic field magnitude (plasma pressure) decreases (increases) [the length Ox_b is smaller than Ox_s in Fig. 7(b)], and at the same time the magnetic field notably rotates in the intermediate wave region ($x_w<x<x_s$) without changing its magnitude [$Ox_w=Ox_s$ in Fig. 7(b)]. The present numerical results may hence indicate that the 2.5 dimensional reconnection simulations by Ugai (1993) provide quite precise numerical results even in the thin shock layer.

3. Summary and Discussion

The present simulations have systematically studied the precise structure of the fast reconnection mechanism in a sheared field geometry (Ugai, 1993). In order to examine the resulting shock structure, the temporal dynamics of noncoplanar shock is further examined in the framework of one-dimensional dissipative MHD equations. This simulation model is based on coplanar shocks, on which a uniform sheared field component B_{z0} is imposed. Note that this model effectively specifies definite noncoplanar boundary conditions ahead of and behind a shock, since the magnetic field directions ahead of and behind a shock are readily specified. We then find that the noncoplanar shock structure can be sustained by physical dissipations involved, until the shock becomes coplanar as a result of magnetic field rotation in the wave plane.

The two-dimensional noncoplanar shock transition layer (Figs. 1 and 2), associated with the sheared fast reconnection mechanism, has a sufficiently long and thin structure that may be considered to be approximately one-dimensional. In fact, the present one-dimensional MHD simulations with much higher numerical resolution have obtained the noncoplanar shock structure (Fig. 3) that is, both quantitatively and qualitatively, in good agreement with Fig. 2. Since the one-dimensional noncoplanar shock structure can be sustained only in a finite time by physical dissipations involved, two-dimensional plasma processes should be important for the shock transition layer to stand quasisteadily in the (sheared) fast reconnection configuration (Fig. 1). For the fast reconnection flow, the ambient sheared magnetic field is continuously convected with the plasma inflow (Fig. 1) and is largely skewed when it enters the shock layer. In this respect, note that in the two-dimensional situation the resulting intermediate waves may propagate away from near the diffusion region along the shock layer. We may hence recognize that the noncoplanar shock transition layer (Fig. 1) could be sustained quasisteadily in a region not so far from the diffusion region, since the resulting intermediate waves may propagate away along the layer before the field rotation is not completed in the transition layer.

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