3D SIMULATION OF EXTERNALLY DRIVEN RECONNECTION

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A 3D magnetohydrodynamic simulation is presented. The essential conclusions obtained by the previous 2D model, such as the slow shock formation and the strong plasma jet generation, are reconfirmed. In addition, several new findings pertinent to three dimensionality are obtained. Among them, particularly interesting and important is the generation of field aligned currents at the slow shock associated with a local interruption of the neutral sheet current. It is also interesting to observe the generation of super-magnetosonic flows with the Mach number of 2.

1. INTRODUCTION

The solar flare and the magnetospheric substorm are the most familiar, naturally occuring energy release phenomena. Among others, magnetic reconnection is the most efficient and explosive energy conversion mechanism in plasmas.

In the earth's magnetosphere, there are two places where reconnection is likely to occur; they are the dayside magnetopause and the magnetotail neutral sheet. On the dayside no such a violent energy release as we observe on the nightside is observed. Provided reconnection actually takes place on both sides, therefore, the energy conversion rate of reconnection must be largely dependent upon circumstantial conditions.

In the past we studied extensively the reconnection process for several different conditions and compared their results in detail by using 2D simulation codes (1-5). The conclusion obtained by these studies is that the energy conversion rate is certainly largely dependent on the external conditions. More specifically, energy conversion occurs most efficiently and rapidly in such a situation that an open-ended Harris type high β neutral sheet is locally compressed by an external force. The conversion rate is rather independent of resistivity but largely dependent on the strength of the driving force (1).

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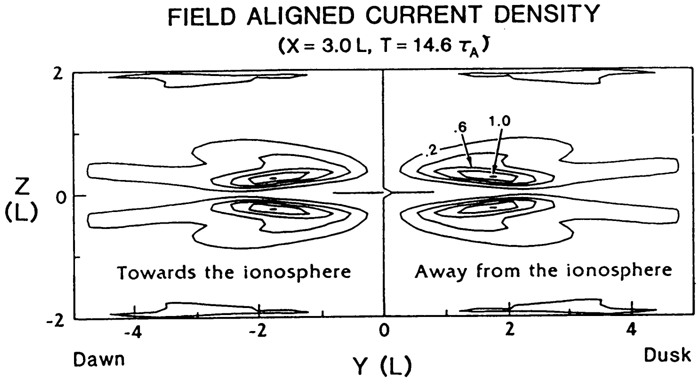

Fig. 1 Contour map of the field aligned current generated by 3D driven reconnection.

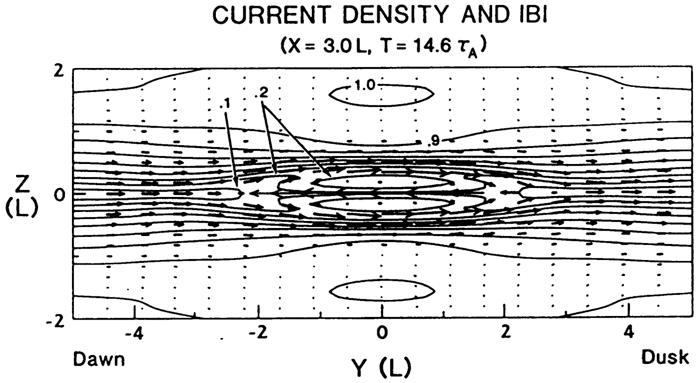

Fig. 2 Neutral sheet current vectors on the same cross section as that of Fig. 1. The solid lines represent the contours of the magnetic field strength.

2D models were sufficient to reveal the slow shock structure and the plasma acceleration. Actual magnetospheric substorms, however, are associated with other complicated features that can never be explained by a 2D model. As such, we know the existence of localized field aligned currents which are presumably connected to strong westward ionospheric currents called "westward auroral electrojets" (6), and the three-dimensional deformation of the magnetic field.

These facts provide us with a sufficient motive force to study the externally driven reconnection in 3D dimensions (7).

2. SIMULATION MODEL AND RESULTS

A rectangular box nested by equally spaced grid points in three directions (x,y,z) is provided wherein a Harris type equilibrium is set up; the neutral sheet is placed at z=0, and the anti-parallel magnetic field is parallel to the x axis. A plasma with a certain amount of magnetic energy density is continuously injected through the two boundary planes parallel to the neutral sheet ("input" boundaries, $z = \pm L_z$). On the two output boundaries ($x = \pm L_x$) and on the side boundaries ($y = \pm L_y$), we impose a free boundary condition that the normal derivative of any variable vanishes. The plasma injection pattern on the input boundaries is assigned in such a way that the neutral sheet is most strongly compressed at the origin (x=y=z=0) of the simulation box.

The most striking feature observed is the local interruption of the neutral sheet current and associated generation of field aligned currents. Fig. 1 shows a contour map of the field aligned current density on a cross section close to the output boundary. It is clearly seen that two pairs of field aligned currents are generated in a narrow band at the slow shock front, namely, at the sharp edge of the plasma sheet: The upper pair closes in the northern hemisphere and the lower one in the southern hemisphere in the earth's case The numbers attached to the contour lines represent the current density normalized by the initial maximum neutral sheet current. It turns out that the maximum field aligned current density becomes comparable to the neutral sheet current density, this indicating a complete interruption of the neutral sheet current at the edge of the plasma sheet. In fact, the neutral sheet current is locally interrupted. The neutral sheet current density vectors are shown in Fig. 2 for the same plane as that in Fig. 1. Along the second row from the midplane (the neutral sheet plane) the vectors are seen to disappear in the range $-2 \leq Y \leq 2$, this being coincident with the location of the field aligned current divergence and convergence. Incidentally, the solid lines represent the equi-contours of the magnetic field strength. In this respect, it is interesting to remark that the field aligned current generation is associated with $\underline{j}_{NS} \cdot \underline{\nabla} B$ where $\underline{j}_{NS}$ is the neutral sheet current. This is in good agreement with the previous prediction (8) based on the theory of field aligned current generation (9).

An important implication of such a strong field aligned current generation by 3D externally driven reconnection is that electrons could be accelerated along the field lines as a result of some current driven instability, possibly by a double layer.

Another interesting feature observed is the generation of a super-magnetosonic flow. The distributions of the outflow speed and the magnetosonic speed along the x axis are shown in Fig. 3. Beyond a certain distance from the x point the outflow becomes super-magnetosonic and the Mach number reaches roughly 2. We also wish to remark that the outflow has a strong parallel component near the edge of the plasma sheet. As predicted in the earlier literature (8), a super-magnetosonic flow along the mirror field

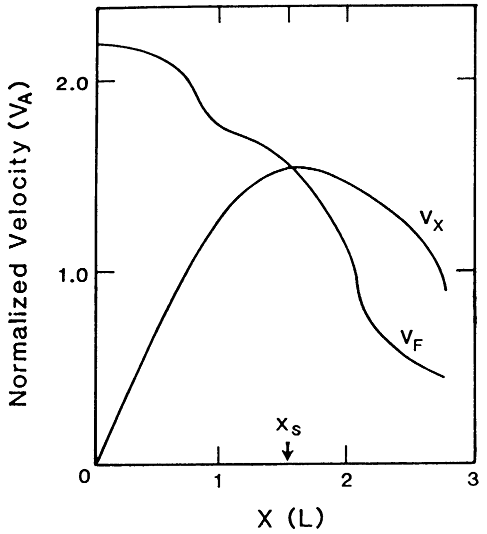

Fig. 3 The distributions of the generated outflow speed (v_x) and the fast magnetosonic speed (v_F) along the line passing the x point on the neutral sheet.

would also be a potential energy source of field aligned acceleration of electrons. We have recently developed a theory that can adequately accelerate electrons up to the directed energy of proton flows.

In conclusion, externally driven reconnection can generate localized strong field aligned currents as well as the super-magnetosonic plasma flows in a reasonably fast time scale, say, 10 τ_A (Alfvén transit time). These macroscopic energies would be potential energy sources of parallel acceleration of electrons.

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DISCUSSION

Vasyliunas: What boundary conditions were imposed at the x = const. boundaries, especially the earthward ones?

Sato: Free boundary conitions are imposed. So field-aligned currents can flow out. I suppose that driven reconnection can be a current-generator, in other words, the impedance of the reconnection region would be much larger than the ionospheric resistance. Therefore, I don't think that the inclusion of the ionosphere would alter the conclusion so much. However, certainly it is an interesting thing to develop a model that can include the finiteness of the field line and the terminating ionosphere.

Krishan: While calculating the jets, have you included gravity? This must be done before you can apply your work to double ribbons on the Sun.

Sato: No. Explicitly the earth's magnetosphere is considered. Inclusion of gravity may somewhat destroy the symmetry. But I do not think that gravity would make any essential difference.

Birn: What were the boundary conditions of your 3-D model in the y direction?

Sato: A free boundary condition is imposed; that is, the normal derivative vanishes.

Steinolfson: Is there an asymmetry along the tail in your initial state?

Sato: No. A symmetric configuration is taken, since I am interested in a rather general feature.

Bratenahl: Your last two figures refer to structures as "fast shocks", but actually these are fast mode expansion fronts because they go from sub-Alfvenic to super-Alfvenic, is it not so?

Sato: I have not checked quantitatively the Rankine-Hugoniot shock relation, but the observed feature that the outflow decreases after it passes the super-magnetosonic point seems to indicate it to be a fast shock. The fact that the tail current direction reversed in the super-magnetosonic region indicates that the outflow is self-blocked, thus leading to shocks.