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THREE-DIMENSIONAL COMPUTER STUDY OF THE GENERATION OF FIELD-ALIGNED CURRENTS FROM A LONG CURRENT SHEET SYSTEM (EXTENDED ABSTRACT)

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It has been believed that the generation of field-aligned currents is fundamental for the coupling between the magnetosphere and the ionosphere (IIJIMA and POTEMRA, 1976). When a substorm occurs, the geomagnetic tail current in the plasma sheet region is expected to be deflected partly towards the earth along the magnetic field lines. In this respect, a fundamental question is: what 3-D plasma processes drastically lead to a large-scale field-aligned current from the initial tail (sheet-like) current? Such a large-scale plasma process may take place, in principle, in magnetohydrodynamic (MHD) time scales. Hence, a number of theoretical models of the generation of field-aligned currents have been constructed on the basis of low-frequency modes (LYSAK and DUM, 1983; NAKAMURA and TAMAO, 1989). However, the temporal dynamical processes that cause large-scale field-aligned currents in a long current-sheet system, where the fast reconnection may play a significant role, have not yet been clarified convincingly, with 3-D numerical computations (BIRN and HONES, 1981; SCHOLER and OTTO, 1991; SATO *et al.*, 1984). In the driven model by SATO *et al.*, the reconnection region is compressed by a plasma injection, which readily leads to FAC, whereas in the present spontaneous model the reconnection region is distinctly rarefied.

Recently, UGAI (1991) extended his 2-D simulation model and studied numerically some basic physical processes of the so-called spontaneous fast reconnection in a 3-D computation, which may be applicable to some distinct aspects of a substorm phenomenon. The purpose of the present paper is to apply the 3-D fast reconnection model (UGAI, 1991) to a question of the field-aligned current generation. In the present compressible 3-D MHD simulation, a one-dimensional (1-D) current sheet system is assumed initially to be in an equilibrium state. By assuming such a simple initial profile, we may easily see how the global 3-D configurations of magnetic field and current flow change in accordance with the proceeding of fast reconnection. Unlike the model of UGAI (1991), the present model assumes the system length to be sufficiently long so that a compressed plasma sheet region (or plasmoid) ahead of the (Alfvénic) fast reconnection jet can be taken into account. Magnetic reconnection occurs in a finite extent of the system, and the fast reconnection mechanism develops spontaneously without external driving forces. Here, we are interested, in particular, in the basic physical processes that cause drastic changes of the (initially sheet-like) current profile and bring about a current along the (zero-order) magnetic field lines. The present model is not designed for a precise simulation of an actual complicated phenomenon, but it is simplified so that the underlying physical principles can be easily visualized.

In the present model, all the variables depend on x, y and z. As an initial current sheet system, the magnetic field $\boldsymbol{B}=[B_x(y), 0, 0]$ is assumed as: $B_x(y)=\sin(y\pi/2)$ for $0<y<1$; $B_x=1$ for $1<y$; also, $B_x(y)=-B_x(-y)$ for $y<0$. The plasma pressure $P(y)$ satisfies the pressure-balance condition initially, $P+B_x^2=1+\beta_0$ ($\beta_0=0.1$ is taken here). Fluid velocity $\boldsymbol{u}=(u_x, u_y, u_z)=(0, 0, 0)$, and plasma density $\rho=1$ are initially assumed. Normalization of variables are self-evident: distances are normalized by L, $\boldsymbol{B}$ by B_0, fluid velocity $\boldsymbol{u}$ by V_A $[=B_0/(\mu_0\rho_0)^{1/2}]$, time t by L/V_A, current density $\boldsymbol{J}$ by $B_0/(\mu_0 L)$, and so forth. The computational region is taken to be a rectangular box, $0\leqslant x\leqslant L_x=9$, $0\leqslant y\leqslant 2.4$, and $0\leqslant z\leqslant 16$, enclosed by six planes (Fig. 1). The conventional symmetric 2-D fast reconnection flow being taken into account, the relevant symmetry boundary conditions are imposed on the planes, $x=0$ (y–z plane), $y=0$ (z–x plane), and $z=0$ (x–y plane); also, on the outflow boundary plane $x=L_x$ the same symmetry boundary conditions as the plane $x=0$ are imposed, so that there is no plasma flow nor current flow across the boundary of $x=L_x$. On the other boundary planes, free boundary conditions are

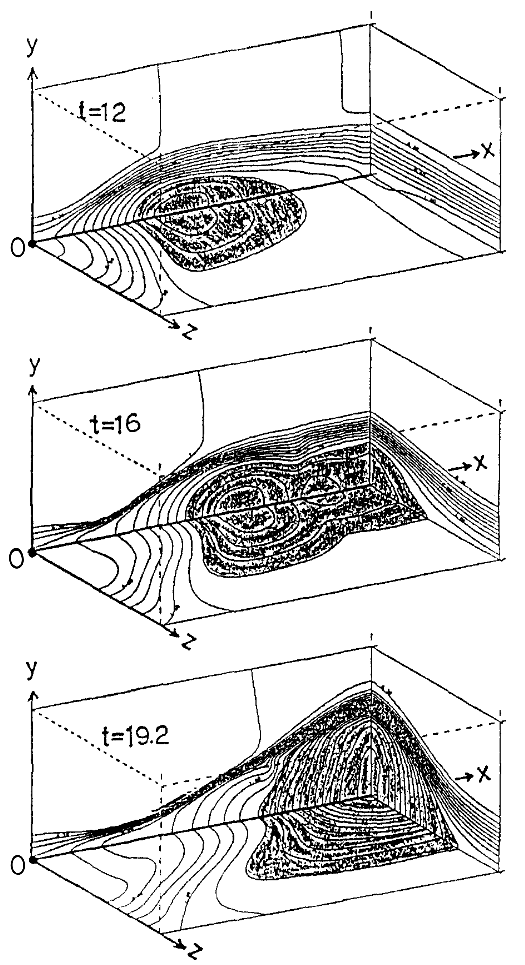

Fig. 1. 3-D display of the plasma pressure distributions, where shaded region indicates the plasmoid where pressure P is greater than 1.2.

assumed (UGAI, 1991). Also, an anomalous resistivity is simply assumed to be present locally near the origin ($\boldsymbol{r}=0$): $\eta(\boldsymbol{r}) = \eta_0 \exp[-(x/k_x)^2 - (y/k_y)^2 - (z/k_z)^2]$. The localized resistivity is imposed on the initial configuration, and all the phenomena are initiated by the resulting magnetic diffusion. In the present simulations, the grid numbers (including boundaries) $N_x=185$, $N_y=65$, and $N_z=45$, and the mesh sizes $\Delta x=\Delta y=0.04$, $\Delta z=0.4$ are taken to be constant throughout all the computations; also, the resistivity parameters $k_x=k_y=0.8$, $k_z=8$, and $\eta_0=0.05$ are fixed.

The simulation results may be summarized as follows:

(1) Initiated by a localized resistivity, fast reconnection develops spontaneously in a finite region of the current sheet, giving rise to an Alfvénic plasma jet. Ahead of the strong plasma jet plasma is notably compressed, and a plasmoid swells and propagates in the x-direction. Figure 1 shows plasma pressures at different times and indicates the plasmoid by shaded region. For the longer system length the plasmoid can freely propagate in a long-axis direction, so that the plasma compression in the plasmoid becomes greater; when the plasmoid collides with the boundary $x=L_x$ a distinct plasma compression is caused near the boundary.

(2) In the fast reconnection region plasma is distinctly rarefied and the plasma flow tends to converge, whereas in the plasmoid plasma is notably compressed and the plasma flow tends to diverge, leading to a flow velocity shear. The velocity shear between the fast reconnection region and the plasmoid gives rise to a magnetic shear along the plasmoid boundary. The increased plasma compression in the plasmoid should enhance the velocity shear and thus the magnetic shear. Figure 2 shows the magnetic field configurations at times $t=12$ and 19.2, indicating that a

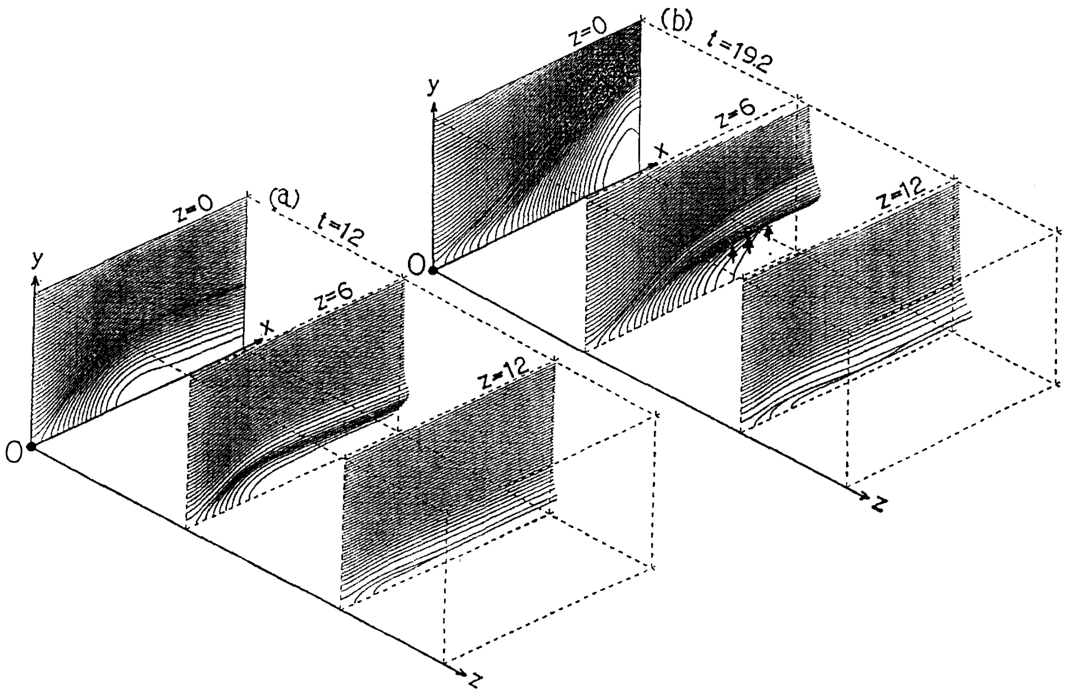

Fig. 2. 3-D display of the magnetic field configurations. Black arrows in the diagram of z=6 in (b) indicate the region of distinct magnetic shear.

distinct magnetic shear is generated along the plasmoid boundary. Also, Fig. 3 the plasmoid. We find that the positive field-aligned current $J_{\parallel}$ ($=\boldsymbol{J}\cdot\boldsymbol{B}/|\boldsymbol{B}|>0$) shows distributions of the field-aligned current $J_{\parallel}$ in the planes vertically crossing (consistent with region -1 current) is formed along the plasmoid boundary like a tube stretching in the x direction.

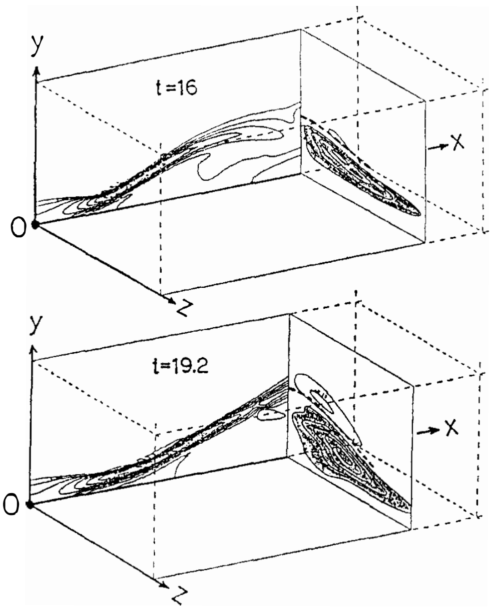

Fig. 3. Distributions of the field-aligned current $J_{\parallel}$ *in the planes* $x=7.4$ *(upper diagram) and* $x=7.2$ *(lower diagram), where broken lines indicate the plasmoid boundary and in the shaded region* $J_{\parallel}>0$. *Also, in the xy* ($z=0$) *plane distributions of* $J_{\perp}$ is indicated.

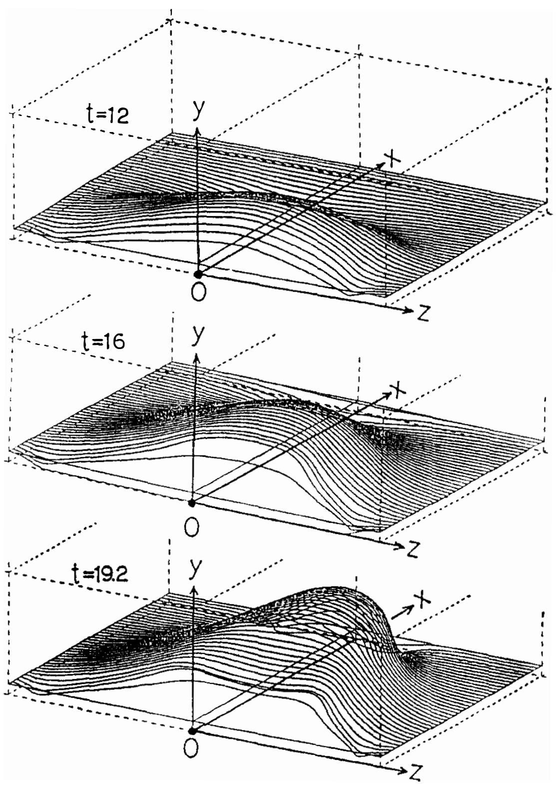

Fig. 4. 3-D display of electric current lines starting from $y=0.2$ and $z=L_z$ at successive times for the case of $L_x=9$.

(3) The magnetic shear results from the generation of the magnetic field component B_z. The positive field-aligned current $J_{\parallel}$ (>0) consists mainly of the current component J_x (>0), and J_x is given by $\partial B_z/\partial y$ in the field-aligned current tube. Hence, $J_{\parallel}$ (>0) is generated along the magnetic shear (along the plasmoid boundary), and it becomes stronger with increasing plasma compression in the plasmoid. In the terminology of MHD waves, the magnetic shear should result from the rotation of magnetic field, so that intermediate waves play a crucial role in generating the field-aligned current.

One of the most significant aspects of the 3-D fast reconnection dynamics may be a drastic change of the overall electric current topology. In order to see this clearly, we may introduce electric current flow lines since $\nabla \cdot \boldsymbol{J}=0$ in the MHD treatments, which are defined to be drawn along the direction of current density $\boldsymbol{J}$ (UGAI, 1991). Figure 4 thus shows the temporal changes of the current flow profile for the case of $L_x=9$. Note that initially (at $t=0$) all the current flow lines are in the negative z direction; also, on the boundary $x=L_x$ there is no field-aligned current, so that any current flow line cannot pass through the boundary. We can readily see from this figure that, as the fast reconnection grows, the electric current at relatively low latitude ($y=0.2$) drastically changes its profile to result in a new electric circuit along the plasmoid boundary.

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