SELF-CONSISTENT DEVELOPMENT OF FAST MAGNETIC RECONNECTION WITH AN ANOMALOUS RESISTIVITY MODEL

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Abstract: Computer simulation demonstrates the development of fast magnetic reconnection by a self-consistent anomalous resistivity model which causes an explosive magnetic energy conversion. In the earlier stage of the fast reconnection development anomalous resistivity grows locally near an X-type neutral point forming a large-scale X-type field configuration. When the anomalous resistivity fully develops, magnetic island is suddenly formed and a pair of X points move in the directions opposite to each other. The self-consistent development of fast reconnection is generally consistent with satellite observations and may hence be considered as a basic energy converter of magnetospheric substorms.

1. Introduction

Magnetic field reconnection has been recognized to play an important role in the large-scale conversion of magnetic energy observed in geomagnetic substorms (NISHIDA, 1978). In a plasma of very large electrical conductivity, magnetohydrodynamic (MHD) waves should be much more effective in releasing the stored magnetic energy than Ohmic heating. Steady configuration of magnetic reconnection involving standing slow shocks was first proposed by Petschek and has been extensively studied (VASYLIUNAS, 1975). The reconnection process that gives rise to a rapid magnetic energy conversion under significant influence of MHD waves may hence be called the fast magnetic reconnection. UGAI and TSUDA (1977) recognized the importance of local onset of anomalous resistivity for the development of fast reconnection and first demonstrated numerically the evolution and the establishment of fast reconnection. It must be very fundamental to demonstrate a self-consistent development of fast reconnection, which is the theme of the present simulation study.

As an initial static configuration, an isolated current-sheet system is assumed (UGAI, 1982). The associated antiparallel magnetic field $\boldsymbol{B}=B(y)\boldsymbol{e}_x$ is given: $B(y)=y$ for $|y|\leq 1$ (in the current-sheet region), $=1$ for $1<|y|\leq 2.4$ (in the antiparallel-field region); also, $B(y)$ is linearly reduced to zero in the return-current region ($2.4<|y|\leq 2.7$). The plasma pressure $P(y)$ is initially assumed so that the pressure balance condition is satisfied and that the ratio of the plasma pressure to the magnetic pressure is 0.1 in the antiparallel-field region. The plasma density $\rho=1$ and the fluid velocity $\boldsymbol{u}=0$ are initially assumed. All the quantities have been normalized as follows: Distances are normalized by a, the half-width of the current-sheet region, fluid velocity $\boldsymbol{u}$ by V_A [$=B_0/(\mu_0\rho_0)^{1/2}$], the Alfvén speed in the antiparallel-field region, time t by a/V_A, and so forth. Solutions will be shown in a rectangular box, $|x|\leq 2$ and $|y|\leq 3$. All the plane boundaries enclosing the region are free boundaries with the conventional symmetry conditions on the x and y axes. A full set of compressible MHD equations are solved with use of the two-step Lax-Wendroff MHD code.

In order to disturb the initial static equilibrium, we impose a finite electrical resistivity locally near the origin at time $t=0$ which disappears within a few normalized times as the current density J becomes reduced near the origin (UGAI, 1982). After the initial finite resistivity decays and, hence, the resistivity is almost zero everywhere, we may assume a resistivity model. Here, we adopt an anomalous resistivity η, consistent with current-driven instabilities (SMITH and PRIEST, 1972), in the form: $\eta(\boldsymbol{r}, t)=\eta_a \exp\{-[(|V_D|-V_0)/V_C]^2\}$ for $|V_D|\leq V_0$, and $=\eta_a$ for $V_D>V_0$, where $V_D(\boldsymbol{r}, t)=J(\boldsymbol{r}, t)/\rho(\boldsymbol{r}, t)$ is proportional to the relative electron-ion drift velocity. The anomalous resistivity is notably enhanced for $|V_D|>V_0-V_C$ and is assumed, for simplification, to become constant for $|V_D|>V_0$. The magnetic Reynolds number may be defined by $R_m(\boldsymbol{r}, t)=\mu_0 a V_A/\eta(\boldsymbol{r}, t)$, so that R_m lies in the range $R_{m0}\leq R_m<\infty$ where $R_{m0}=\mu_0 a V_A/\eta_a$. For different resistivity models and different parameter values, we have obtained quite similar results. The simulation results will thus be shown only for the typical parameter values $V_0=11$, $V_C=4$, and $R_{m0}=20$ (note that $V_D=-1$ in $|y|<1$ at time $t=0$).

2. Results

Figure 1 shows the temporal variation of the magnetic flux content $\phi(t)$ defined by a line integral of $B_x(x=0, y, t)$ from $y=0$ to $y=3$, that of the magnetic energy content $U_M(t)$ residing in the first quadrant, and that of the electric field $E(\boldsymbol{r}=0, t)$ (normalized by $V_A B_0$) right at the origin. Note that $E(\boldsymbol{r}=0)$ indicates the flux transfer rate, $d\phi/dt$, at the origin. The finite resistivity initially assumed causes local tearing at the origin which leads to a decrease in ϕ at time $t=0$, and the global plasma flow grows so as to thin the current-sheet region. The anomalous resistivity model has been introduced since $t=5$. The following can be observed from the figure: $E(\boldsymbol{r}=0)$ begins to grow at $t\approx 16$, and accordingly ϕ and U_M remarkably decrease for $t\gtrsim 16$.

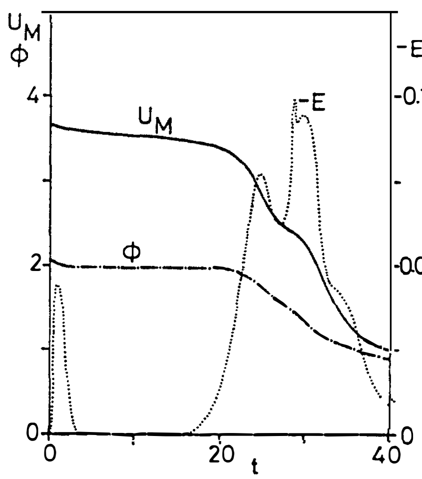

Fig. 1. Temporal behaviors of the magnetic flux content $\phi(t)$, the total magnetic energy content $U_M(t)$, and the electric field $E(\boldsymbol{r}=0, t)$ at the origin.

Note that $E(\boldsymbol{r}=0)$ should grow as a result of an onset of anomalous resistivity. But, at $t \approx 30$, $E(\boldsymbol{r}=0)$ is suddenly reduced, so that the flux transfer rate becomes smaller for $t \gtrsim 30$; nevertheless, the magnetic energy is still released explosively. Finally, for $t \geq 36$ the rate of magnetic energy release is reduced, which may indicate the termination of the fast reconnection. Obviously, there are two distinct stages characterizing the developement of fast reconnection in the time ranges $16 \lesssim t \lesssim 30$ and $30 \lesssim t \lesssim 36$, which will be examined and interpreted in what follows.

In general, a large-scale X-type field configuration is important for the proceeding of fast reconnection, so that a sufficiently large B_y field should be retained in the overall configuration. The B_y field on the x axis can be produced only through magnetic reconnection at an X-type neutral point at the rate given by $\partial B_y/\partial t \approx \partial(\eta J)/\partial x$. In the present model there is no *ad hoc* mechanism causing a local increase in J, so that a local resistivity enhancement should be important. We in fact find that at time $t \approx 16$ the drift velocity V_D becomes so large to give rise to a finite resistivity and that in the time range $16 \leq t \lesssim 30$ magnetic reconnection grows so as to enhance an anomalous resistivity locally near the origin. Figure 2a shows the resulting configuration of fast reconnection at time $t=25.1$, when the outflow velocity u_x has just attained an Alfvén speed. A large-scale X-type field configuration is set up, and the anomalous resistivity is in fact enhanced locally near the origin where an X point is formed. Apparently, in the time range $16 \lesssim t \lesssim 30$ fast magnetic reconnection develops in such a self-consistent way that the fast reconnection proceeds so as to enhance the anomalous resistivity locally near an X point and that the locally enhanced resistivity results in a large-scale X-type field configuration where the plasma outflow is effectively accelerated by the motor force.

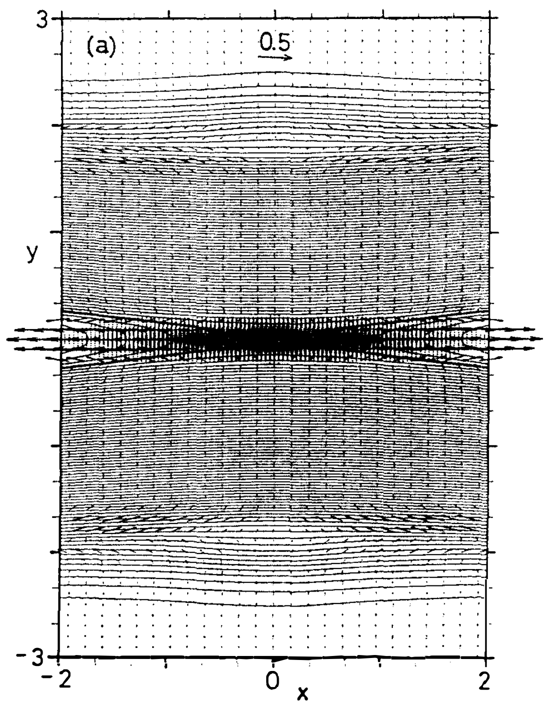

Fig. 2a.

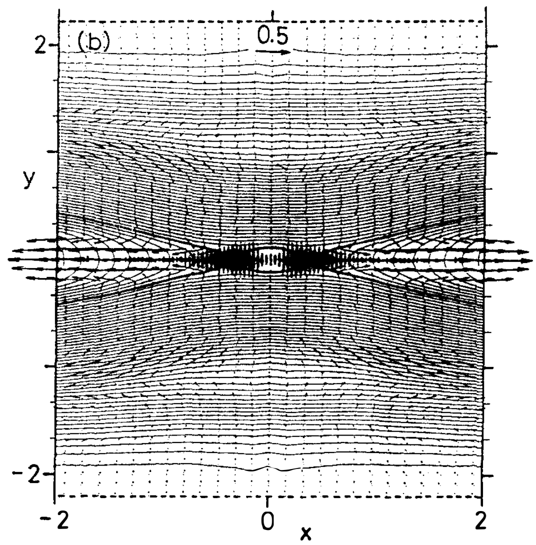

Fig. 2b.

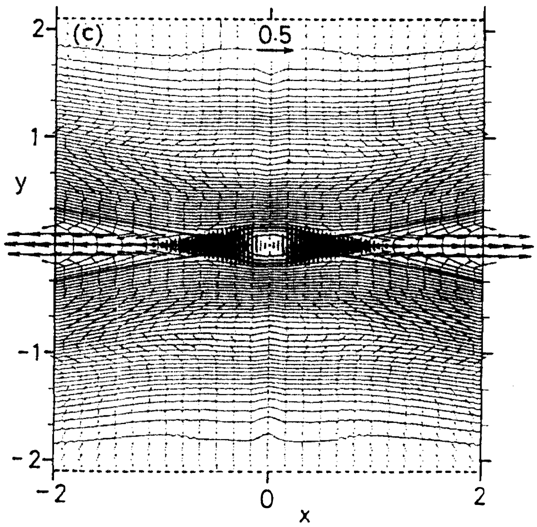

Fig. 2c.

Fig. 2. Magnetic-field and plasma-flow configurations at times (a) t=25.1, (b) t=32.8, and (c) t=34.8. The separatrixes are shown by bold lines and the magnitude of anomalous resistivity is indicated by (*) at each mesh point.

After the anomalous resistivity fully develops near the origin (at $t \approx 29$), we find that magnetic field lines become flattened in the immediate vicinity of the origin and then that the flattened field lines suddenly tear to form a pair of X points (at $t \approx 30$). Figure 2b thus shows that an O-type neutral point is formed at the origin, leading to formation of magnetic island. As magnetic reconnection proceeds at a pair of X points where resistivity is locally enhanced, plasma is largely confined in the magnetic island and the drift velocity V_D becomes suddenly reduced, so that anomalous resistivity decays near the O point (Fig. 2b). Figure 2c apparently indicates that, as magnetic island evolves, a pair of X points move in the positive and negative x directions and that the regions of enhanced resistivity simultaneously move with the X points. Remark the vital hydromagnetic properties of the system at large which, together with the anomalous resistivity, strongly promote the effective proceeding of fast reconnection. We also find in the large-scale X-type field configuration shown in Fig. 2c that slow shocks are standing where magnetic field lines distinctly change their directions, which enables the explosive magnetic energy conversion (Fig. 1).

3. Conclusion

The simulation model has clearly shown, in good agreement with Ugai and Tsuda (1977), that localized enhancement of resistivity near an X point, which has been realized self-consistently with the anomalous resistivity model, is crucial for the development of fast reconnection. We have found that magnetic island is formed and grows during the proceeding of fast reconnection. This is consistent with Hones *et al.* (1984) who reported an evidence of plasmoid formation in the tail that resulted from the buildup of substorm. In summary, the proceeding of fast reconnection and the occurrence of anomalous resistivity due to current-driven instabilities are found to be quite favorable to each other. Since the drift velocity near an X point tends to become larger for a plasma of larger magnetic Reynolds number (Ugai, 1983), we expect that the ion-acoustic or Buneman instability, as well as the lower-hybrid-drift instability, would also be important for the buildup of fast reconnection even in the geomagnetic tail where the ion-acoustic instability is usually unlikely to take place.

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