Three-Dimensional Dynamics of Spontaneous Fast Reconnection Evolution

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Three-dimensional fast reconnection development is studied by computer simulations on the basis of the spontaneous fast reconnection model. In this model, once a current-driven anomalous resistivity is ignited, fast reconnection grows explosively as a nonlinear instability. In understanding the fast reconnection mechanism in actual systems, it is important to investigate the temporal dynamics of the fast reconnection mechanism in general three dimensions. Hence, the physical mechanism of fast reconnection evolution and the resulting steady fast reconnection configuration in three dimensions are shown and argued.

1. Introduction

Magnetic reconnection is recognized to play a crucial role in explosive phenomena observed in space plasmas, such as solar flares and geomagnetic substorms. In the spontaneous fast reconnection model, once a current-driven anomalous resistivity is ignited, fast reconnection grows explosively as a nonlinear instability (Ugai et al., 2004). Here, the spontaneous fast reconnection model is studied in three-dimensional conditions, and we argue that it may be responsible for flare phenomena.

2. Simulation Model

2.1 Basic equations and initial-boundary condition

MHD equations are as follows:

\[
\frac{D\rho}{Dt} = -\rho \nabla \cdot \mathbf{u}, \quad \frac{Du}{Dt} = -\nabla P + \mathbf{J} \times \mathbf{B},
\]

\[
\frac{DB}{Dt} = \nabla \times (\mathbf{u} \nabla \mathbf{B}) = -\nabla \times (\eta \mathbf{J},)
\]

\[
\mathbf{J} = \frac{1}{\mu_0} \nabla \times \mathbf{B}, \quad \nabla \cdot \mathbf{B} = 0,
\]

\[
\frac{D\rho_e}{Dt} = -P \nabla \cdot \mathbf{u} + \eta \mathbf{J}^2,
\]

\[
P = (\gamma - 1)\rho e, \quad \mathbf{E} + \mathbf{u} \times \mathbf{B} = \eta \mathbf{J},
\]

where \(e\) is the internal energy per unit mass and \(\gamma\) is the specific heat ratio with \(\gamma = 5/3\); \(\eta\) is a resistivity. For the numerical computation, these basic equations (1) are transformed to a conservation form, and the modified 2 Step Lax-Wendroff method is used.

As an initial configuration, an antiparallel magnetic field \(\mathbf{B} = (B_x, 0, 0)\) is assumed: \(B_x = \sin(\pi y/2)\) for \(0 \leq y \leq 1\), \(B_x = 1.0\) for \(1 \leq y \leq 3.5\), \(B_x = \cos \pi(y - 3.5)\) for \(0 \leq y \leq 3.8\), \(B_x = 0.0\) for \(3.8 \leq y\). Fluid velocity \(\mathbf{u} = (0, 0, 0)\), and the plasma pressure \(P\) satisfies the pressure balance condition

\[
P = 1 + \beta_0 - B_x^2,
\]

where \(\beta_0\) is the ratio of plasma pressure to magnetic pressure with \(\beta_0 = 0.3\). Temperature \(T = P/\rho\) is assumed to be constant everywhere.

In this paper, we assume the number of mesh points \(N_x = 505, N_y = 405\) and \(N_z = 103\); mesh size \(\Delta x = 0.04, \Delta y = 0.015\) and \(\Delta z = 0.10\). Symmetry boundary conditions are assumed on the X-Y, Y-Z and Z-X planes, so that the computational region can be restricted to the first quadrant only and has a rectangular box, \(0 < x < L_x, 0 < y < L_y\), and \(0 < z < L_z\); here, \(L_x = 20, L_y = 6,\) and \(L_z = 10\) is assumed.

2.2 Anomalous Resistivity Model

The anomalous resistivity is assumed as follows for \(t > 4\):

\[
\eta = \begin{cases} 
0.002 \times (|V_D| - |V_C|) & (|V_D| \geq |V_C|), \\
0 & (|V_D| < |V_C|),
\end{cases}
\]

where \(V_D = J/\rho\) is the relative electron-ion drift velocity, and \(V_C\) is a threshold of current-driven instability. Also, initial disturbance is given at the origin for \(0 < t < 4\) in the form

\[
\eta = \eta_0 \exp\left\{-(\frac{x}{k_x})^2 - (\frac{y}{k_y})^3 - (\frac{z}{k_z})^3\right\}.
\]

3. Results

Figure 1 shows the three-dimensional structure of the magnetic field line and the isosurface of the plasma pressure \(P=1.42\). The strong fast reconnection jet is produced by the magnetic reconnection, and compresses plasmas at the tip of the jet. Hence, the plasmoid swells and propagates as time progresses. Then, the secondary tearing suddenly occurs at time \(t=48.2\). Figure 2 shows the contour lines of plasma pressure inside the plasmoid at different time.

Figure 3 shows the isosurface of the anomalous resistivity \(\eta = 0.011\), which is identified with the diffusion region, and magnetic field lines in the X-Y plane. The X reconnection point is bifurcated in the positive and negative x directions before \(t=48.2\), and the domain of high resistivity simultaneously moves with the X point in the positive x direction after the secondary tearing.

Figure 4 shows the plasma flow vectors for \(|\mathbf{u}| > 0.5\), where the contour lines of plasma pressure are also shown. The reconnection flow becomes faster, as it is closer to the X axis. The fast reconnection flow is observed along the boundary of the plasmoid, and the plasmoid propagates in the positive x direction and remains to be confined in the z direction. After the secondary tearing occurs, the flow near the X point changes its direction.
4. Conclusions

The spontaneous fast reconnection model is studied by precise computer simulations in three dimensions for different plasma parameters. As magnetic reconnection proceeds, the fast reconnection jet grows explosively. Ahead of the jet, the plasma is significantly compressed, and a large-scale plasmoid is produced. The central diffusion region is unstable against resistive tearing, and is bifurcated into a pair of diffusion regions.

After the tearing occurs in the diffusion region, the flow velocity changes near the X point, and the anomalous resistivity moves with the diffusion region in the x direction. Also, the fast reconnection jet grows and extend along the boundary of the plasmoid.

In summary, we have demonstrated that the fast reconnection mechanism can be realized as an eventual solution in the general three-dimensional situations, which may be applied to flare phenomena in actual systems.

Acknowledgments. This work was partially supported by Grant-in-Aids from the Ministry of Education in Japan, Mitsubishi Foundation, Radio Science Center for Space and Atmosphere of Kyoto University, and the Solar-Terrestrial Environment Laboratory of Nagoya University. The computer program was tested and run at the Computational Center of Nagoya and Kyoto Universities.

References
