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Multi-point observations of earthward fast flow in the plasma sheet by virtual satellites located in the MHD simulation domain

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Abstract

Time profiles of some physical values in earthward fast flows in the plasma sheet are observed at three dimensionally different positions by employing virtual satellites located in the three-dimensional magnetohydrodynamic simulation domain, and these simulations are done on the basis of the spontaneous fast reconnection model. In the spontaneous fast reconnection evolution, the width of the flow channel is narrow in the dawn-dusk direction, and it does not spread until the plasma collides with the magnetic loop. The enhancements in B_z and V_x are larger at the center of the fast flow channel than those at its dawn and dusk edges, reflecting the differences in the reconnection rate in the diffusion region. The enhancement in V_x is shorter near the plasma sheet boundary layer than that near the neutral sheet, reflecting the changes in the thickness of the flow channel.

Keywords: Magnetosphere; Fast flow; Magnetic reconnection; MHD

1. Introduction

According to sufficient evidence based on recent observations and computer simulations, fast plasma flows in the near-Earth plasma sheet are closely related with geomagnetic substorms (Nagai et al., 1998; Machida et al., 1999). These fast flows are frequently observed in both earthward and tailward directions. Therefore, they are regarded as magnetic reconnection outflows in the near-Earth plasma sheet. The typical characteristics of earthward fast flows have been investigated intensively (Angelopoulos et al., 1994; Ohtani et al., 2004). One such characteristic is the narrow channel in the y- and z-direction in the GSM coordinate system (Sergeev et al., 2000; Nakamura et al., 2004), which implies that fast flows do not spread in these directions until they enter the braking region. On the other hand, magnetic compression regions propagating in the x-direction are observed in the magnetic lobe region, and they are known as travelling compression regions (TCRs) (Slavin et al., 2005). This magnetic compression is caused by the plasma pressure of a developing and propagating plasmoid. In a previous study, fast narrow plasma jets in the plasma sheet and TCRs in the magnetic lobe region have been investigated via three-dimensional magnetohydrodynamic (MHD) simulations based on the spontaneous fast reconnection model (Kondoh and Ugai, 2008; Kondoh et al., 2009).

Recent multi-point observations have shown the importance of the observation position. In other words, observations made by satellites located at different positions differ significantly, even if the same event is observed at the same time. In this paper, we determine the relationship between observations such as time variations in physical values and three-dimensional satellite positions relative to a reconnection x-line and flow channel by employing several virtual satellites located in our simulation domain.

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2. Simulation model

As mentioned in the introduction, the purpose of this study is to determine the relationship between the satellite position in the plasma sheet and the time profiles of physical values observed by the satellite in the earthward fast flow event. The simulation model used in this study is virtually identical to that used in previous simulations (Kondoh et al., 2009). Previous magnetic loop simulations using the wall boundary have shown that fast magnetic reconnection produces a fast reconnection jet that flows in the plasma sheet; then, the reconnection jet is suddenly braked at the boundary between the dipolar and tail-like magnetic fields because of the counterward pressure force, and it decelerates (Ugai et al., 2003). This situation may be consistent with the earthward flow, and these results are in good agreement with the situation inferred from the observation results of earthward flow (Shiokawa et al., 1997).

We focus on the evolution of fast flows, and the MHD approximations are valid for these macroscopic phenomena. The compressible MHD equations are transformed to a conservation-law form, and the modified Lax–Wendroff scheme is used for numerical computation (Ugai, 2008). As an initial configuration, the anti-parallel magnetic field $\mathbf{B} = [B_x(z), 0, 0]$ is assumed as $B_x(z) = B_{x0} sin(\pi z/2)$ for $0 < z < 1$, $B_x(z) = B_{x0}$ for $1 < z < Z_1$, $B_x(z) = B_{x0} cos[(z - Z_1)\pi/1.2]$ for $Z_1 < z < Z_m (= Z_1 + 0.6)$, and $B_x(z) = 0$ for $Z_m < z$; in addition, $B_x(z) = -B_x(-z)$ for $z < 0$ (in the present study, we assume $B_{x0} = 1.0$). The plasma pressure $P(z)$ initially satisfies the pressure-balance condition

$$P + B_x^2 = 1 + \beta_0 \tag{1}$$

where β_0 is the ratio of plasma pressure to the magnetic pressure in the ambient magnetic field region $1 < z < Z_1$ so that initially, $P(z = 0) = 1 + \beta_0$ (in the present study, we assume $\beta_0 = 0.15$). Initially, fluid velocity $\mathbf{u} = (0, 0, 0)$ and constant temperature $T = P/\rho = 1 + \beta_0$ is assumed so that the plasma density ρ initially satisfies

$$\rho(z) = P(z)/(1 + \beta_0). \tag{2}$$

The normalization of quantities, based on the initial quantities, is self-evident. Distances are normalized by the half-thickness of the current sheet, d_0; $\mathbf{B}$, by the field strength in the magnetic field region, B_{x0}; P, by $B_{x0}^2/(2\mu_0)$; ρ, by $\rho_i = \rho(z = 0)$; $\mathbf{u}$, by $V_{Ax0} (= B_{x0}/\sqrt{\mu_0 \rho_i})$; time t, by d_0/V_{Ax0}; current density $\mathbf{J}$, by $J_0 = B_{x0}/(\mu_0 d_0)$. Note that the Alfvén velocity in the ambient magnetic field region $(1 < z < Z_1)$ in the initial state is given by $V_{Ae} = V_{Ax0}/\sqrt{\rho_e}$ (ρ_e is the density in that region).

Here, the conventional axis symmetry boundary conditions are assumed in the (x, y), and (y, z) planes. Hence, the computational region can be restricted to the first and second quadrant, and it can be regarded as a rectangular box, i.e., $0 < x < L_x$, $-L_y < y < L_y$, and $0 < z < L_z$. In addition, for simplicity, the conventional symmetry boundary (wall boundary) condition is assumed in the outer boundary plane $x = L_x$, and free boundary conditions are assumed in the other boundary planes ($y = -L_y, L_y$ and $z = L_z$).

Current-driven anomalous resistivity has been studied theoretically and experimentally (Lui, 2001; Treumann, 2001; Ono et al., 2001). Here, as in the case of the 2D model, the anomalous resistivity model is assumed to be of the form

$$\begin{aligned} \eta(\mathbf{r}, t) &= k_R[V_d(\mathbf{r}, t) - V_C] \quad \text{for} \quad V_d > V_C, \\ &= 0 \quad \text{for} \quad V_d < V_C, \end{aligned} \tag{3}$$

where $V_d(\mathbf{r}, t) = |\mathbf{J}(\mathbf{r}, t)/\rho(\mathbf{r}, t)|$ is the relative electron-ion drift velocity, and V_C is the micro-instability threshold. In the present study, we assume $k_R = 0.003$ and $V_C = 12$.

In order to disturb the initial static configuration, a localized 3D resistivity model of the form

$$\eta(\mathbf{r}) = \eta_0 exp[-(x/k_x)^2 - (y/k_y)^4 - (z/k_z)^4] \tag{4}$$

is assumed about the origin. As in the case of previous 2D simulations, we assume $k_x = k_z = 0.8$ and $\eta_0 = 0.02$. In addition, k_y provides the 3D effects. Previous studies have shown that k_y specifies the effective extent of the diffusion region in the y-direction and that magnetic reconnection cannot effectively grow in the case of small k_y, i.e., $k_y < 6$ (Kondoh et al., 2006). Therefore, we assume $k_y = 8$ in the present study. The disturbance (4) is imposed only in the initial time range $0 < t < 4$, and the anomalous resistivity model (3) is assumed for $t > 4$. Hence, the fast reconnection mechanism may be triggered at $x = 0$ in this model.

It should be noted that sufficiently small mesh sizes are required for precise computations of the spontaneous fast reconnection evolution; hence, we assume $\Delta x = 0.04$, $\Delta y = 0.2$, and $\Delta z = 0.015$. Furthermore, the magnetic field region size is assumed to be $Z_1 = 4$, and the dimensions of the entire computational region are assumed to be $L_x = 14$, $L_y = 20$, and $L_z = 9.6$.

3. Results

Fig. 1 shows the propagation of a plasmoid. That is, the back isosurface shows the plasmoid at time $t = 30$. This plasmoid propagates along the x-direction (earthward) and swells. Then, it collides with the $x = L_x$ wall boundary at $t = 42$ (front isosurface). The solid lines denote the magnetic field lines in the x–y plane at $t = 30$. The satellites in this figure denote the positions of virtual satellites located in the simulation domain. The inset shows the time profile of the reconnection electric field ηJ at the origin. The reconnection electric field rapidly increases around $t =$ 30, shown by the vertical dotted line. Hereafter, the results of observations after time $t = 30$ are shown by these virtual satellites located at different positions.

3.1. X-direction

First, we show time variations in some physical values observed by virtual satellites located at different