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A 2D NUMERICAL STUDY OF RECURRENT DRIVEN RECONNECTION PROCESSES AT THE MAGNETOPAUSE

W.-H. Ip and S.-P. Jin*

Max-Planck-Institut für Aeronomie, D-3411 Katlenburg-Lindau, Federal Republic of Germany

Abstract. Two-dimensional (2D) compressible MHD simulations are performed to explore the time-dependence of driven reconnection process in the vicinity of the magnetopause. It is found that recurrent formation of magnetic islands/plasmoids occurs when the magnetic Reynolds number is sufficiently large ($R_m = 4000$). This result is in line with the bursty reconnection model for the flux transfer events (FTEs) as advocated by Scholer (1988) and Southwood et al. (1988). Furthermore, the formation of magnetic islands in a multiple X-line configuration is also consistent with the Lee-Fu model (1985). In other words, the present results represent a new class of hybrid FTE model. With appropriate scalings, the characteristic time interval between the formation of magnetic islands is estimated to be on the order of 8 min. This time scale is compatible with the quasi-periodicity sometimes found in optical and/or radar ionospheric signatures which might be associated with FTEs.

1. Introduction

The first reports of the flux transfer events (FTEs) were given by Haerendel et al.(1978) and Russell and Elphic (1978). The signature of a twisted magnetic flux tube was interpreted by Russell and Elphic (1978) in terms of erosion of the magnetospheric magnetic field via sporadic reconnection at localized regions of the magnetopause. Lee and Fu (1985) subsequently proposed a model of multiple X-line formation across the magnetopause to account for the twisting of the magnetic field in the central part of the FTEs. The multiple X-line configuration was studied in a number of 2-dimensional (2D) computer simulations (Fu and Lee, 1985; Shi et al., 1988). A 3D global scenario was also explored by Ogino et al. (1990) who pointed out that by means of magnetic field reconnection near the cusp region during intervals of southward interplanetary magnetic field with a strong $B_y > 0$ component, the open flux tubes could indeed be twisted.

Another class of models was put forward by Southwood et al. (1988) and Scholer (1988) independently in which the FTEs are supposedly 2D magnetic structures generated in bursty reconnection process with one single X-line. According to Southwood et al. (1988) the presence of a velocity shear across the magnetopause may provide a convenient mechanism of 3D flux tube twisting. Furthermore, such an elongated open-field line structure should lead to a mapping of the FTEs to transient ionospheric features stretched across a large longitudinal range in the dayside polar cap boundary. As a matter of fact, both ground-based optical and radar observations have become powerful tools in the diagnosis of FTEs. For example, measurements of the plasma flow patterns associated with midday auroras by the EISCAT radar facility have indicated that the voltage across the transient ionospheric features could be as high as 50 KV (Sandholt et al.,1990). Another interesting property of the FTEs is that the mapping of the magnetic flux rope structures with a diameter of about 1 R_E (Earth radius) to the ionosphere should produce plasma signatures with a latitudinal extent of a few hundred km. This spatial relation appears to be satisfied by the ionospheric patterns observed at the dayside polar cap boundary (Lockwood et al. 1990; Elphic et al., 1990).

Most interestingly, the occurence of such auroral events appears to have a periodicity of about 5-10 minutes (Lockwood et al. 1989). This peculiar feature which has also been seen in FTEs (Rijnbeek et al., 1984) remains so far unexplained. This also means that if the ionospheric transients are indeed connected with the FTEs, such quasi-periodicity must also be intrinsic to the dayside reconnection process.

In this report, we present theoretical results from a numerical study using a compressible MHD code to simulate temporal evolution of localized reconnection process. This numerical code was used before in a parameter study of the effect of the magnetic Reynolds number (R_m) which is defined as, $R_m = V_A l_0/\eta_m$, where V_A is the Alfven speed, l_0 is the characteristic length scale of the simulation box and η_m is the electrical resistivity. We found that for small values of R_m the system will reach a steady state pattern with one single X-line at the center whereas recurrent multiple X-line formation will take place when R_m exceeds a certain critical value (R_m^*); see Jin and Ip (1991). It should be mentioned that Sato and Hayashi (1979) have performed compressible MHD simulation of the reconnection process and discovered that a quasi-stationary condition characterized by a single X-line with a pair of slow mode shocks attached to the diffusion region can be established. Their result is in agreement with what we obtained for $R_m < R_m^*$. On the other hand, the new finding of multiple magnetic island formation with $R_m > R_m^*$ indicated to us that such a dynamical effect could be related to the time variation of the FTEs. The main emphasis here thus is to see under what circumstances could a steady stream of magnetic bubbles be formed in the vicinity of the magnetopause in a time interval of a few minutes. Our model calculations therefore complement previous work on unsteady magnetic reconnection (Biskamp, 1986; Fu and Lee, 1985, 1986; Shi et al., 1988). Some of these investigations have also addressed the issue of recurrent reconnection process of the FTEs but with different emphases (i.e., Fu and Lee, 1985).

2. Model calculations

The basic approach of our numerical calculations is based on the idea of driven reconnection. That is, on opposite sides of the simulation box, continuous inflows toward the central axis are imposed. Also, the electrical resistivity (η_m) is taken to be uniform everywhere. The 2D computation is executed on one quadrant of the simulation box which extends from 0 to $L_x = l_0$ and to $L_z = 3.1 l_0$ in the x and z directions, respectively. In the following, both x and z are normalized by l_0. The area

*Permanent addreess: at Dept. of Earth and Space Science, University of Science and Technology of China, Hefei, Anhui, People's Republic of China

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is divided into 23×31 grid points. Also note that the x axis is normal to the current sheet while the z axis is aligned with it. The introduction of a magnetic flux function which related to the magnetic field by $\mathbf{B} = \hat{y} \times \nabla A$ converts the equation of magnetic induction into a scalar equation. The normalized magnetic flux function at time $t = 0$ is given by

$$A = \begin{cases} \frac{2w}{\pi} \cos \frac{\pi x}{2w} - w & 0 \le x \le w \\ -x & w < x \le 1 \end{cases} \tag{1}$$

with the corresponding normalized magnetic field given as

$$B = \begin{cases} \sin \frac{\pi x}{2w} & 0 \le x \le w \\ 1 & w < x \le 1 \end{cases} \tag{2}$$

where $w = 1/16$ (in unit of l_0) is the characteristic half thickness of the current sheet. We assume the system to be initially in a static isothermal state with the velocity and temperature given as $V_x = V_z = 0$ and $T = T_0$, respectively. Furthermore, the initial state is in mechanical equilibrium; the total pressure remains constant inside and outside the current sheet, hence the normalized plasma density is expressed as: $\rho = 1 + 1/\beta - B^2/\beta$. Here, β is the ratio of the plasma pressure to the magnetic pressure outside the current sheet at $t = 0$. In the present study we take $l_0 = 9600$ km, $w = 600$ km, $\rho_0 = 1.67 \times 10^{-23}$ g/cm^3 (corresponding to $n_{ion} = 10$ protons/cm^3), $B_0 = 26.34$ nT and $T_0 = 10^5$ K, hence $\beta = 0.1$. The Alfven velocity is $V_A = 181.8$ km/s and the characteristic time is then given by $t_A = l_0/V_A = 52.81$ s.

As usual, the numerical computation is carried out in one quarter of the simulation system by assuming symmetric boundary conditions at x = 0 and z = 0. At the inflow boundary at $x = L_x$ for $t \le 18t_A$ an inward plasma velocity is defined as

$$V_x = \begin{cases} -C_1 V_A & 0 \le z \le 1.0 \\ -C_1 V_A \sin[(1.5 - z)\pi] & 1.0 < z \le 1.5 \\ 0 & 1.5 < z \le 3.1 \end{cases} \tag{3}$$

For $t > 18t_A$ the imposed plasma inflow velocity along the entire boundary at $x = L_x$ is given to be

$$V_x = \begin{cases} -C_2 V_A & 0 \le z \le 2.5 \\ -C_2 V_A \sin[(3 - z)\pi] & 2.5 < z \le 3 \\ 0 & z = 3.1 \end{cases} \tag{4}$$

Along the same boundary at $x = L_x$, we set $V_z = 0$, $T = T_0$, $\rho = \rho_0$ and $\frac{\partial^2 A}{\partial x \, \partial t} = 0$, (i.e., $\frac{\partial B_z}{\partial t} = 0$).

For the boundary condition at $z = L_z$ we have $V_x = 0$ (following the convention of Fu and Lee, 1986) and the values of V_z, ρ , T are determined by the linear extrapolation method. Furthermore, $\frac{\partial A}{\partial t} = 0$ for $V_z \le 0$; $\frac{\partial A}{\partial t} + V_z \frac{\partial A}{\partial z} = 0$ for $V_z > 0$.

The expressions given in Eqs.(3) and (4) for the inflow velocity at the boundary of the simulation box are obtained from many test runs with the aim of finding an optimal set of parameters which could reproduce the observed characteristics of the FTEs. The division of the time interval into two parts with $t = 18t_A$ as the demarcation point is mainly guarded by the fact that a large plasmoid of transient nature is generally created and then ejected at $t \le 18t_A$. As will be discussed in Sec.3, the magnitude of V_x and its dependence on z then determines the subsequent dynamical evolution and structure of the magnetic field configurations. The highly idealized inflow pattern adopted here represents one possible condition of driven reconnection even though numerous other possibilities certainly exist. Note further that except for the change in the inflow velocity at $t = 18t_A$, no other changes in the boundary condition were incorporated. Any time variation is therefore intrinsic to the driven reconnection process. This approach is different from that of Scholer (1989) in which a time-dependent spontaneous reconnection is triggered by the introduction of enhanced resistivity at the neutral point at a certain time interval.

The full viscous MHD equations are solved using a multiple-step implicit scheme (Hu, 1989). Note that the grid point spacing in the x direction is non-equidistant to allow adequate spatial resolution of the current sheet (there are five grid points across the current sheet). More details of this compressible MHD code which was used to study magnetic merging processes can be found in Jin and Hu (1989) and Jin and Ip (1991).

3. Simulation Results

The typical behaviour of a driven reconnection process with large value of $R_m(= 4000)$ is summarized in Figure 1. [note that in this run (case A) $C_1 = C_2 = 0.22$, i.e. no temporal change in the incoming flow pattern at the boundary]. After the ejection of a large magnetic island at $t > 16.39t_A$, a sequence of magnetic islands of variable sizes are formed in the later phase at different time intervals. Such pattern of multiple X-line formation is in line with the Lee-Fu model (1985), but with the added property of bursty reconnection as suggested by Southwood et al.,(1988) and Scholer (1988). The characteristic time of expulsion of plasmoids outside the simulation box is estimated to be on the order of 8 minutes. This value is very close to the periodicity detected in the transient ionospheric features in the dayside auroras (Lockwood et al., 1989; Sandholt et al., 1990). A linkage between the bursty reconnection process and the ionospheric dynamic events thus might be established. On the other hand, our present 2D model computation is limited by the assumption of symmetry on both sides of the magnetopause. Furthermore, whilst the first plasmoid formed is of Earth-size the subsequent magnetic islands are somewhat smaller. As shown in Figure 1, the sizes of these magnetic islands are $\sim 0.8 - 1.2R_E$ in the normal direction. [see, Figure 1 (b), 1 (e) and 1 (g)]. The presence of an axial component of the magnetic field at the centres of the magnetic islands is also not accounted for. [However, a velocity shear at the magnetopause (Southwood et al., 1988) or the presence of an axial magnetic field at the reconnection site may provide the twisting.]

One important feature of the compressible MHD treatment as adopted here is that the temperature and plasma density variations can be computed in a self-consistent manner. The temperature increase in the magnetic islands is found to be quite substantial indeed. The plasma heating effect during the reconnection process is illustrated in Figure 1 (i)-(p). The maximum temperature can be as much as a factor of 2-3 larger than the initial temperature (T_0). In the present treatment the temperature increase is mostly limited to the effects of adiabatic heating. The maximum outflow speed of hot plasma ejecting from the central X-line is on the order of $0.5V_A$ which is substantially below the full Alfven speed as predicted by the ideal reconnection model. Instead, significant fraction of the magnetic energy is converted into heat. This result is qualitatively in agreement with the work by Fu and Lee (1986). One major difference between their incompressible MHD treatment and our compressible calculations is basically that the plasma density variation is self-consistently taken into consideration in the present work. As a matter of fact, the compressibility of the plasma system introduced complications into the numerical

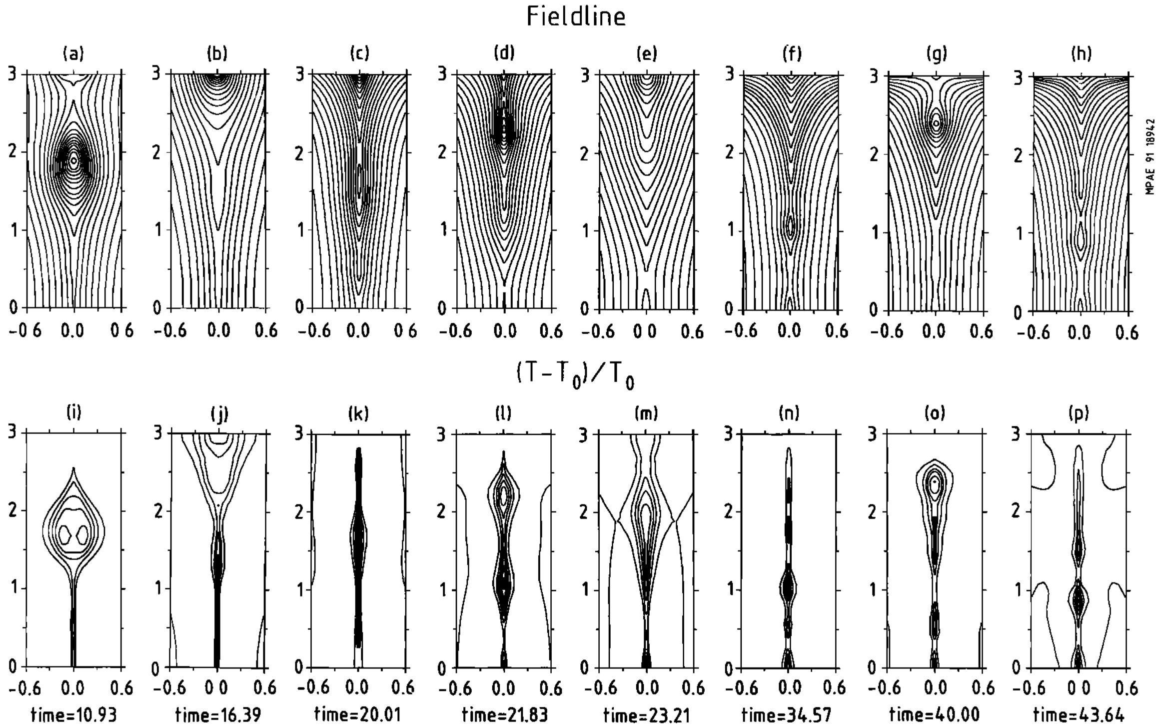

Fig. 1 Time evolutions of the magnetic field structures (a-h) and the relative temperature enhancement profiles (i-p) for Case A with R_m = 4000 and $C_1 = C_2 = 0.22$. [The contour values of $(T - T_0)/T_0$ from the outside to the inside are: 0.2 (0.2) 1.0 at $t = 10.93t_A$, $20.01t_A$, $23.21t_A$; 0.2 (0.2) 0.8 and 0.9 at $t = 16.39t_A$; 0.2 (0.2) 1.2 at $t = 21.83t_A$; 0.1 (0.3) 1.0, 1.2 and 1.5 at $t = 34.57t_A$, $t = 40.00t_A$; 0.1 (0.3) 1.6 at $t = 43.64t_A$, respectively.] After the ejection of the transient magnetic island at $t = 16.39t_A$, three plasmoids are generated subsequently at an average time interval of about 8 min.

simulations in the sense that the inflow velocity at the boundary must be adjusted carefully so that the formation and motion of the plasmoids could follow the expected patten. For example, the initial state is characterized by dynamical equilibrium with the central current sheet being a region of enhanced plasma density. The first pair of plasmoids formed thus would be endowed with a high mass content and consequently a sizable dimension. One empirical way to maintain a similar characteristic size for plasmoids/magnetic islands that are generated in the later stage is to broaden the inflow region after the initial phase ($t < 18t_A$) as described in Eqs. (3) and (4). This is to allow more mass to be fed into the central region as the source material for the plasmoids. This additional consideration does not arise in the incompressible scheme in which the plasma density is kept constant.

Besides the case described above, runs with different inflow velocity profiles at the boundary and different values of R_m have been performed. It is found that an increase in the inflow velocity after the ejection of the first plasmoid [Case B: R_m = 4000, $C_1 = 0.22$ and $C_2 = 0.26$.] would lead to the formation of a stagnant plasmoid of sizable dimension in the central part of the simulation box after $t = 32t_A$. At the same time, it is found that the temperature increase in the plasmoids is also higher than that for Case A. Thus for high Reynolds numbers a recurrence of magnetic island formation is generally maintained even though different substructure could form with a change in the boundary conditions. On the other hand, for small R_m(= 1000) but with the same boundary condition as in Case A, the dynamical behaviour of the MHD system (in Case C) will gradually approach a steady state associated with one single X-line. No recurrent pattern of multiple X-line reconnection and plasmoids will take place. To underscore this point, a summary plot for the time variations of the reconnection flux is given in Fig 2. Here, the definition of the reconnection flux Φ is expressed as: $\Phi = (\triangle A)_t - (\triangle A)_0$, where $(\triangle A)_t$ and $(\triangle A)_0$ are the differences between the maximum and the minimum of the normalized magnetic flux function A at time t and at $t = 0$, respectively. The value of Φ tends to peak at the time when a magnetic island structure leaves the simulation box. It can be seen that in Figure 2 (c) for which $R_m = 1000$, the Φ value peaks only once at $t = 15t_A$ when the transient plasmoid leaves the system. For the rest of the time, the Φ value approaches a steady plateau. In contrast, for $R_m = 4000$ [e.g., Figure 2 (a) and Figure 2 (b)] the Φ values reach several peaks afterward. Interestingly, the time interval for such intermittent formation of magnetic islands is between 6 and 8 min.

4. Summary

Making use of a 2D compressible MHD code we have explored the time-dependent behaviour of driven reconnection process. The present formulation permits numerical computations for a relative large time interval [$t_{max} \gtrsim 46t_A$ (i.e $\gtrsim$ 40 min.)] under the condition of high Reynolds number (R_m = 4000); it is found that – if given appropriate values of the plasma parameters and scale size of the system – a recurrent formation of magnetic islands can take place with a quasi-periodicity of about 8 minutes. Such a time variation of the driven reconnection at the magnetopause might provide a link to the periodicity of ionospheric transient features associated with FTEs (Lockwood et al., 1989). From a systematic study of the effect of the boundary conditons (i.e., a variation of the inward plasma flow pattern) we also found that an increase of the inflow velocity could lead to the formation of central magnetic islands.

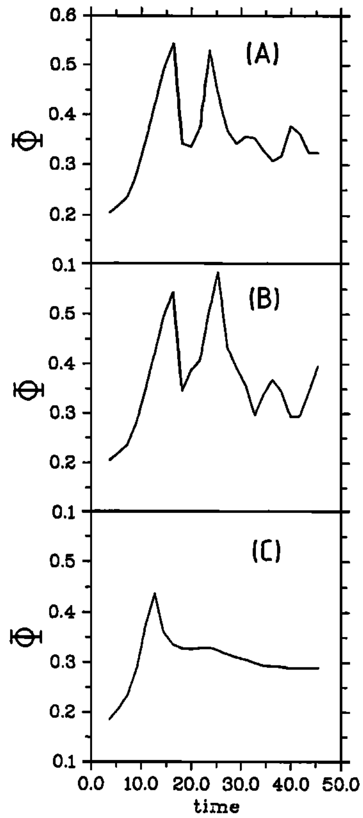

Fig. 2 A comparison of the reconnection fluxes [$\Phi = (\Delta A)_t - (\Delta A)_0$] computed for the three cases: (A) $R_m = 4000$, $C_1 = 0.22$, and $C_2 = 0.22$; (B) $R_m = 4000$, $C_1 = 0.22$ and $C_2 = 0.26$; and (C) $R_m = 1000$, $C_1 = C_2 = 0.22$. The effect that for small magnetic Reynolds number (e.g., Case C) the system will eventually reach a steady state can be seen in the gradual flattening of the corresponding Φ value to a constant value. On the otherhand, three peaks in Case A and two in Case B appear in the time interval between 20 and 45 t_A.

Finally, because of the limitation of our 2D model calculations, many uncertainties still remain concerning the physical connection between the FTEs and the ionospheric transients detected in the dayside auroral activities on the one hand, and the possible inference of the quasi-periodicity of the magnetic island formation on the other hand. The present preliminary results are nevertheless promising in establishing a possible link of the FTEs to the ionospheric signatures observed from ground-based optical and radar measurements.

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W.-H. Ip and S.-P. Jin, Max-Planck-Institut für Aeronomie, D-3411 Katlenburg-Lindau, F.R. Germany

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