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MHD MODEL OF FTE IN COMPRESSIBLE PLASMA

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Abstract. We present here a simple model of the time-dependent Petschek-type reconnection where effect of surface waves is neglected. Reconnection is assumed to be caused by local enhancement of the electrical resistivity in the diffusion region. Then, the current sheet (magnetopause) has to decay into a system of large-amplitude MHD waves, propagating outward from the reconnection line and producing disturbances in the surrounding media. We can find a system of MHD discontinuities, their shapes in course of time and MHD parameters inside all regions among different discontinuities. The model is applied for the case of reconnection at the magnetopause, so-called, FTEs and for the magnetospheric substorm.

1. Introduction

Various phenomena observed at the magnetopause can be explained as aspects of the non-stationary Petschek-type reconnection (*Rijnbeek et al.*,1992). The reconnection is initiated locally in a small part of the current sheet (diffusion region), which acts as a source of disturbances that propagate into the system at large through plasma waves. As these large-amplitude waves propagate along the current sheet, they form an outflow (field-reversal) region for the accelerated plasma (*Petschek*, 1964, *Semenov et al.*, 1983). Using analytical methods it was possible so far either to solve the Riemannian problem of decay of current sheet for steady-state case (*Heyn et al.*, 1988), or calculate motion of the outflow region along the current sheet in the frame of incompressible MHD (*Semenov et al.*,1992). Here we present the model where propagation of all types of MHD discontinuities is taken into account.

Our model is based on the general reconnection theory (*Heyn and Semenov*, 1995a,b). The main difficulty of this theory is coupling of MHD modes, which results in excitation of the surface waves. For three-dimensional reconnection considered here this part of the problem can not be solved so far, therefore, we made an assumption that disturbances produced by the surface waves can be neglected compared with those from the outflow region. This natural assumption makes our model of three-dimensional time-dependent reconnection in compressible plasma relatively simple.

2. Description of the model

Details of the theory of reconnection in compressible plasma can be found in (*Heyn and Semenov*, 1995a,b), and here we give only the most necessary information. In the model, the large-scale behaviour outside the diffusion region is governed by the equations of the ideal MHD. The reconnection rate $E^*(t,y)$ is assumed to be a known function of both space and time. We consider only weak reconnection when $E^* << E_A = v_A B_0/c$, where E_A is based on the Alfvén velocity and background magnetic field. Then, the general problem splits into two parts:

1) non-linear decay of a current sheet into the Alfvén waves, slow waves and contact discontinuity;

2) determining of shapes of all discontinuities, finding a small normal to the current sheet components of the plasma velocity and magnetic field in the outflow region as well as small disturbances in the inflow region.

From the solution of the Riemannian problem the number and types of all MHD waves and discontinuities as well as tangential components of $\mathbf{v}$ and $\mathbf{B}$, density and pressure can be obtained (*Heyn et al.*,1988).

To find shapes of all discontinuities we have to know displacement vectors ζ_i in all regions. In the general theory ζ_i are obtained from the very complicated equation for the surface waves, and for the three-dimensional case it is not yet possible to solve this equation. Fortunately, usually the amplitude of the surface waves is much smaller then that of outflow region (*Semenov et al.*, 1992), and if we are interested in the large-scale disturbances it is possible to neglect the effect of the surface waves completely. Practically, it means that instead of finding ζ_i from the surface wave equation we have to use model displacement vectors (*Semenov et al.*, 1996). Of course, such a procedure is not unique, but if we will use some natural criteria the choice turns out to be not very wide.

If we know displacement vector than shapes of all discontinuities are just combinations of different Φ – functions:

AS$^-$C$\tilde{\text{S}}^-\tilde{\text{A}}$

$$
\begin{aligned}
&Z_A = \Phi_c + \Phi_2(\mathbf{w}_S^{(0)}) - \Phi_1(\mathbf{w}_S^{(0)}) + \Phi_1(\mathbf{w}_A^{(0)}) && (A),\\
&Z_S = \Phi_c + \Phi_2(\mathbf{w}_S^{(0)}), && (S),\\
&Z_{\tilde{S}} = \Phi_c + \tilde{\Phi}_2(\tilde{\mathbf{w}}_{\tilde{S}}^{(0)}), && (\tilde{S}),\\
&Z_{\tilde{A}} = \Phi_c + \tilde{\Phi}_2(\tilde{\mathbf{w}}_{\tilde{S}}^{(0)}) - \tilde{\Phi}_1(\tilde{\mathbf{w}}_{\tilde{S}}^{(0)}) + \tilde{\Phi}_1(\tilde{\mathbf{w}}_{\tilde{A}}^{(0)}) && (\tilde{A}).
\end{aligned} \tag{1}
$$

AR$^-$C$\tilde{\text{S}}^-\tilde{\text{A}}$

$$
\begin{aligned}
&Z_A = \Phi_c - \int_1^{\eta^*} \frac{d\eta'}{\eta'} \Phi_{\eta'}(\mathbf{w}_R^{(0)}(\eta')) + \Phi_1(\mathbf{w}_A^{(0)}), && (A),\\
&Z_{R_{\eta=1}} = \Phi_c - \int_1^{\eta^*} \frac{d\eta'}{\eta'} \Phi_{\eta'}\mathbf{w}_R^{(0)}(\eta')) + \Phi_{\eta=1}\left(t - \frac{x}{w_x^{(0)}(\eta)}, y - \frac{w_y^{(0)}(\eta)}{w_x^{(0)}(\eta)}x\right), && (R^-),\\
&Z_{R_{\eta=\eta^*}} = \Phi_c + \Phi_{\eta=\eta^*}\left(t - \frac{x}{w_x^{(0)}(\eta)}, y - \frac{w_y^{(0)}(\eta)}{w_x^{(0)}(\eta)}x\right), && (R^-),\\
&Z_{\tilde{S}} = \Phi_c + \tilde{\Phi}_2(\tilde{\mathbf{w}}_{\tilde{S}}^{(0)}), && (\tilde{S}),\\
&Z_{\tilde{A}} = \Phi_c + \tilde{\Phi}_2(\tilde{\mathbf{w}}_{\tilde{S}}^{(0)}) - \tilde{\Phi}_1(\tilde{\mathbf{w}}_{\tilde{S}}^{(0)}) + \tilde{\Phi}_1(\tilde{\mathbf{w}}_{\tilde{A}}^{(0)}), && (\tilde{A}),
\end{aligned} \tag{2}
$$

where the function Φ is defined by the reconnection rate:

$$
\Phi(t,y) = \frac{c}{B_x^{(0)}} \int_0^t d\tau\, E^*\left[\tau, y - \frac{cE_z^{(0)}}{B_x^{(0)}}(t-\tau)\right]. \tag{3}
$$

Physically the function Φ_c defines the area where reconnected magnetic flux tube crosses the current sheet. These simple formulas describe propagation of different waves and discontinuities in course of reconnection and allow also to find MHD parameters in all regions.

3. Some results

We chose reconnection rate to be pulse-like: $E^*(t,y) = .5sin^2(\pi t)cos^2(\pi y/2)$ for $0 < t < 1$, $-1 < y < 1$ and 0 otherwise, here y axes is directed along the reconnection line. Parameters of the current sheet in the boundary normal coordinate system (L,M,N) were chosen to be:

magnetosphere: $B_L = 50$ nT, $B_M = 1$ nT, $v_L = v_M = 0$, $\rho = 1cm^{-3}$, $p = .49$ nPa;

magnetosheath: $B_L = -30$ nT, $B_M = 30$ nT, $v_L = 25km/s, v_M = 100km/s$, $\rho = 10cm^{-3}$, $p = .77$ nPa;

Projection of the reconnection structure on the plain of the current sheet, 3-D view of the outflow region for the case $AS^-C\tilde{S}^-\tilde{A}$ are shown in Figure 1. Complicated structure of MHD discontinuities propagating along the current sheet in both half-spaces can be seen. It is interesting that at the switch-off phase for $t > 1$ the most part of the boundary of the outflow region is tangential discontinuity rather than shocks, as it was for the steady-state case or switch-on phase of reconnection.

For interpretation of experimental data it is very important to know behaviour of MHD parameters along a trajectory of a satellite. An example of trajectory data for the position marked by $*$ on the Figure 1a is shown in Figure 2. Usually outflow region moves much faster than a satellite, therefore satellite can cross only a part of the reconnection layer, but if the magnetopause itself can move in normal direction and the satellite is near the diffusion region then crossing of all discontinuities turns out to be possible. For the example presented here we chose the speed of satellite to be 20 km/s.

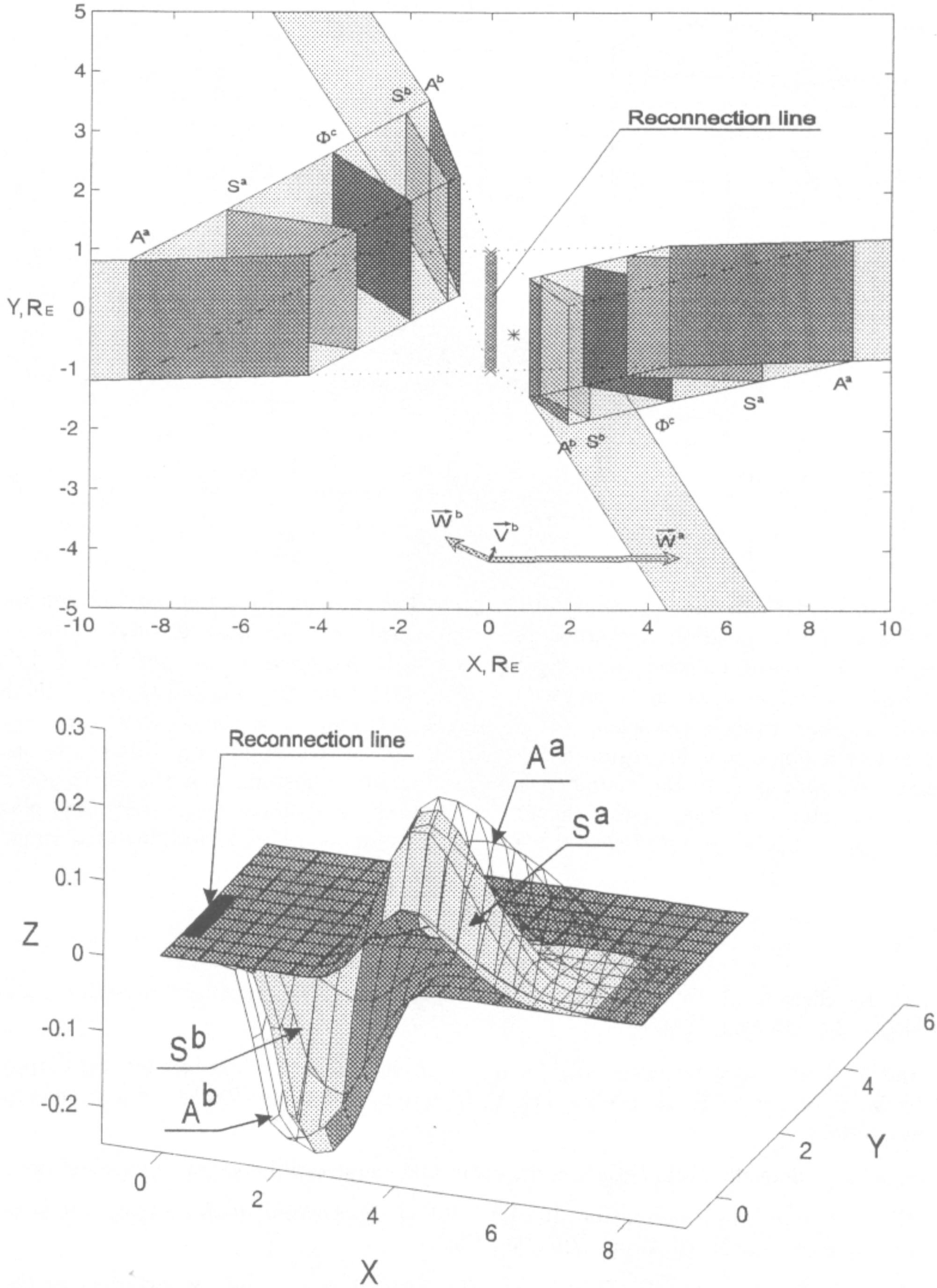

Figure 1: Switch–off phase of reconnection in compressible plasma. a). Projection of the reconnection structure on the plain of the current sheet; b). 3–D view of cross–section of the right outflow region for $y = -.8$.

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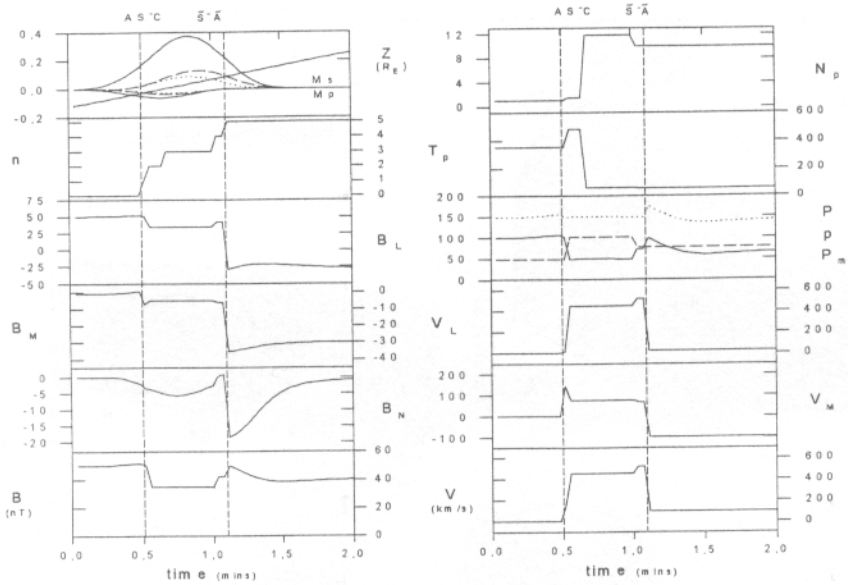

Figure 2: Behaviour of MHD parameters along the trajectory of the satellite for outbound crossing. Speed of the satellite is 20 km/s, position is marked by $*$ in Figure 1a. The dashed vertical lines enclosed the outflow region. For the right panel from top to bottom the parameters are: position of the satellite (straight line) with respect to separatrix (solid line), Alfvén discontinuities (dashed lines) and slow shocks (dotted lines); n–number which shows where the satellite is with respect to the structure $AS^-C\tilde{S}^-\tilde{A}$, for magnetoshere inflow region $n = 0$, for region between A and S^- $n = 1$, and so on; three components and modulus of magnetic field (nT) in the boundary normal coordinate system. For the left panel from top to bottom the parameters are: the number density (cm^{-3}); the temperature ($K \cdot 10^5$); the plasma (p), magnetic (P_m) and total pressure (P) ($nPa \cdot 10^{-2}$); L , M components and modulus of plasma velocity (km/s).

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