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MAGNETIC RECONNECTION: HOW THE OUTFLOW REGIONS ARE AFFECTED BY PLASMA PROPERTIES

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Abstract. Magnetic reconnection in Earth's magnetotail is one of the most fundamental processes to understand magnetospheric physics and storm/substorm effects. With a reconnection model, based on time-dependent Petschek-type magnetic reconnection, we compute disturbances in the magnetic field and plasma behavior. Due to simplifications in the idealized model, it is necessary to compare theoretical results with a numerical simulation which implements a finite current sheet thickness and an inhomogeneous background plasma density distribution. In a first attempt, we work with an MHD simulation, based on the TVD Lax-Wendroff scheme.

1. Time-dependent Petschek-reconnection

Petschek's solution can only be understood as the quasi-steady limit of an inherently time-dependent process. The simplest illustration of this process is the disruption of an infinitely long current sheet by a local enhancement of the electric resistivity somewhere in the sheet, resulting in a break-down of the ideal MHD frozen-in constraint in a small diffusion region, or – in three dimensions – along the X-line. The break-down of ideal MHD leads to the evolution of a reconnection electric field an reconnection is initiated (switch-on phase). When reconnection ceases, the reconnection electric field drops to zero and the outflow regions detach from the initial reconnection site (switch-off phase). With a decoupling of magnetic field and plasma, the magnetic field is free to reconnect (Petschek, 1964). The disruption of the sheet is naturally associated with the formation of outward propagating shocks (S^- in Figure 1), which are a typical feature of Petschek-type reconnection. Plasma gets accelerated during the process of reconnection and leaves the reconnection site via the outflow region with Alfvénic speed v_A. The initially antiparallel directed magnetic fields are connected via the shocks, which bound the outflow region.

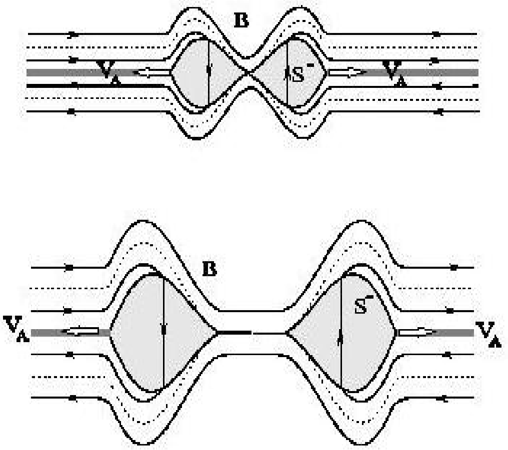

Fig. 1: Time-dependent Petschek-reconnection after Biernat et al. (1987) and Semenov et al. (2004) (upper sketch: switch-on phase, lower sketch: switch-off phase). Heated and accelerated plasma, enclosed by the shocks (S^-), leaves inside the outflow regions (grey) the reconnection scene with local Alfvénic speed v_A. The magnetic fields are connected via the shocks. The dotted line represents the separatrix (from Semenov et al., 2005).

2. Analytical model

Analytical solutions for impulsive reconnection can be found by using the ideal MHD equations and Rankine-Hugoniot jump relations (Biernat *et al.*, 1987, Semenov *et al.*, 2004). We consider a two dimensional current sheet, modelled as tangential discontinuity, separating two identical, uniform, incompressible and initially stationary plasmas with opposite oriented magnetic fields. The reconnection electric field is modelled as a pulse (compare Figure 5), active for a certain time period (switch-on phase). For Figure 2 the electric field is active until t = 1, for Figure 5 until t = 15. We find the shape of the shock f and the magnetic field B_Z as boundary condition at z = 0 to be

$$f^{\pm} = \pm x E_r (t \mp x),$$
$$B_z(x,t,z=0) = \pm 2\, E_r(t \mp x) - x\, E_r{}'(t \mp x),$$

where plus and minus denote positive and negative directions in x, respectively. E_r denotes the reconnection electric field and E_r' its derivative.

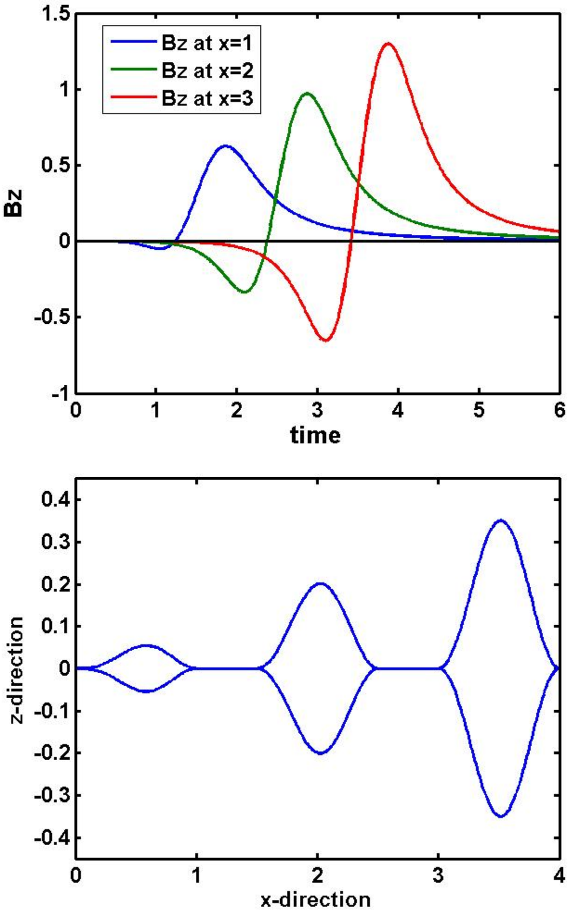

Fig. 2: Evolution of the shocks and B_Z signals at different positions. Upper panel: Disturbances in B_Z at various positions for x. Lower panel: Growth of the outflow region during the switch-off phase for times t=1, t=2.5 and t=4.

3. Numerical Model

A TVD-Lax-Wendroff scheme is used to generate a numerical two-dimensional self-consistent solution of the compressible MHD equations. With this scheme it is possible to investigate reconnection associated disturbances in a plane current sheet configuration, generated by a non-stationary pulse of reconnection. In contradiction to the zero-width current sheet in the analytical model, the current sheet thickness is defined in the simulation via $l/L_0=0.06$, where L_0 is the length unit and l the parameter defined in Equation set (1). This width corresponds to a thin current sheet.

The computational domain is given by X,Z-grid points, where the elongations correspond to $-40<L_X<40$ and $-5<L_Z<5$.

The current sheet is modelled as a thin plain current sheet in Harris-equilibrium,

$$B_x(z) = B_0 \tan(z/\lambda), \qquad B_0 = 1, \qquad (1)$$
$$\rho(z) = \rho_\infty + \frac{\rho_0}{\cosh^2(z/\lambda)}, \quad \lambda = 0.06, \quad \rho_0 = \frac{2}{3}, \quad \rho_\infty = 1,$$
$$p(z) = p_\infty + \frac{p_0}{\cosh^2(z/\lambda)}, \quad \lambda = 0.06, \quad p_0 = \frac{3}{4}, \quad p_\infty = 0.5.$$

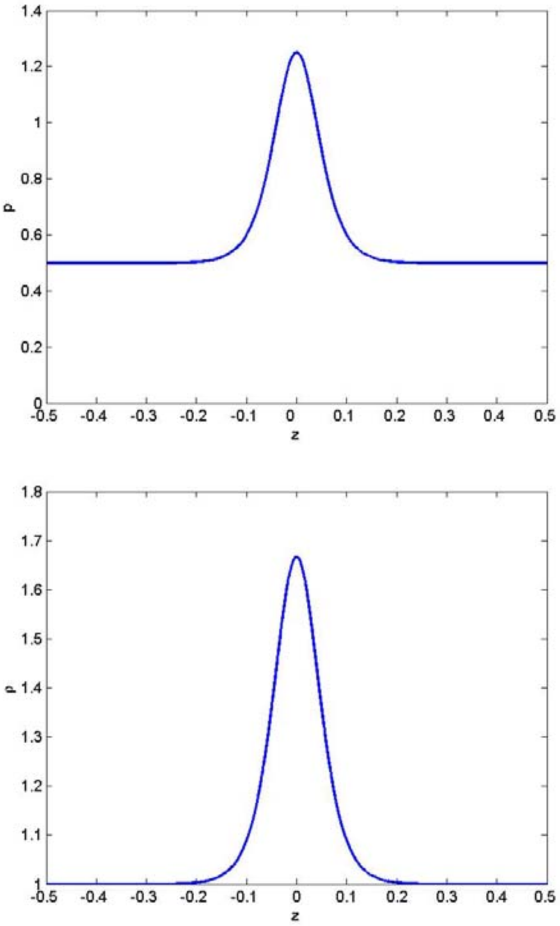

Fig. 3: Plasma pressure (upper panel) and density profiles (lower panel) in the numerical simulation.

Outside the thin current sheet, the values for B_X and ρ tend towards the values $B_X = \rho = 1$, which correspond to values we use in our theoretical model with a zero-width current sheet. In this simulation, reconnection is initiated, when a time-dependent local resistivity is established inside the current sheet.

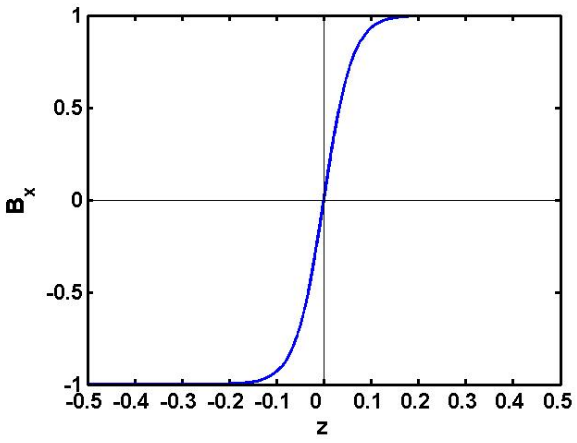

Fig. 4: Behavior of B_x in the numerical simulation.

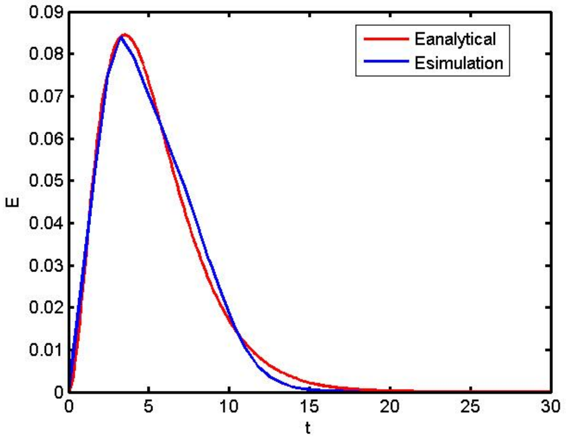

Fig. 5: The reconnection electric field calculated analytically (red) and the reconnection electric field from the numerical simulation (blue).

4. Summary

The simulations show typical effects, appearing in the case of an inhomogeneous background density distribution and compressibility. With the dependence of the outflow velocity on the plasma density, a gradient of v_A along z appears with Equation (1), due to the implementation of a current sheet with finite thickness. Therefore, the propagation velocity of the shocks is slower in the center of the current sheet than outside. This leads to the typical “crab-handed” shock structure (e.g., Abe and Hoshino, 2001). However, this effect does not strongly influence the general shape of the shocks, which is responsible for the disturbances, transported into the surrounding medium.

Compressibility leads to a compression of the outflow region in z-direction, which is also significant in the disturbances of magnetic field components in the inflow region, as shown in Semenov et al. (2005). This effect can be seen in the bigger elongation of the outflow region in the lower panel of Figure 6, since the theoretical model is calculated for the incompressible case.

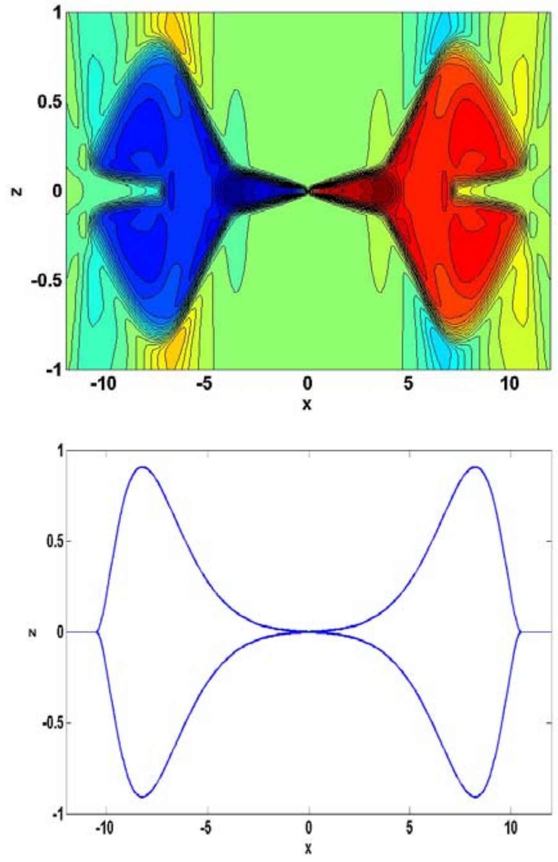

Fig. 6: Comparison of the outflow regions in the numerical simulation (upper panel) and the analytical model (lower panel) for t=14. The upper panel shows the x-component of the plasma velocity with colored intensity. Blue and red areas correspond to different directed plasma outflows.

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