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MAGNETIC FIELD AND SHOCK BEHAVIOR IN THE TIME-DEPENDENT PETSCHEK RECONNECTION MODEL

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Abstract. In various space plasma environments, like the solar corona, Earth's magnetopause or in the magnetotail, magnetic reconnection can be observed. During the reconnection process, magnetic energy is converted into plasma energy, which is of crucial importance for the plasma and magnetic field environment. Due to the fact, that nature shows impulsive and burst-like energy release, time dependent reconnection is a suitable approach to describe this phenomena. The steady-state model proposed by Petschek is understood as a border-case for time-dependent reconnection. In this time-dependent reconnection model, the shocks bound the outflow region and propagate with the outflowing plasma in opposite directions after reconnection ceased. In general, the reconnection X-line is assumed as stationary. Various spacecraft observations in Earth's magnetotail give raise to the assumption of a tailward directed motion of the reconnection line. Due to this observations, a model for non-steady X-line behavior as an extension of the time-dependent model of Petschek magnetic reconnection is presented. The behavior of the shock, as well as the magnetic field structure are discussed. Examining the shock structure, a strong asymmetry in the shape appears between opposite propagating shocks, depending on the velocity of the X-line. The magnetic field inside the outflow regions also exhibits this asymmetry by comparing the magnetic field inside opposite moving outflow regions. For the magnetic field evaluated in the inflow regions, the typical bipolar behavior around each shock is maintained and asymmetry in the field strength appears too.

1. Introduction

The process of magnetic reconnection, which leads to a conversion of magnetic field energy to kinetic energy of the involved plasma, has been first discussed in its steady-state form by Petschek (1964). This solution can only be understood as the quasi-steady limit of an inherently time-dependent process (e.g., Biernat et al., 1987; Semenov et al., 1992; Rijnbeek and Semenov, 1993). 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 current 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. With a decoupling of magnetic field and plasma, the magnetic field is free to reconnect. The disruption of the current sheet is naturally associated with the formation of outward propagating slow-mode shocks, which are a typical feature of Petschek-type reconnection (Heyn, 1988). The incoming 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. In an idealized situation, the magnetic field is only x-directed in the inflow region and only z-directed in the outflow region.

2. Structure of the Petschek-shocks

We consider an infinitely long thin current sheet, separating two antiparallel magnetic fields of same field strength. Additionally, we consider two identical, uniform plasmas, one at each side of the current sheet. The current layer itself is modelled as a tangential discontinuity. The background magnetic fields and the total pressure are assumed to be constant. The shape of the shock is denoted by

$$f^{\pm}(x,t) = \mp \frac{c}{v_A B_0}\left(1 \mp \frac{U}{v_A}\right)^{-2}(x-Ut)\, E_r\left(\frac{x \mp v_A t}{U \mp v_A}\right), \quad (1)$$

where c, v_A, B_0, U, $E_r\left(\frac{x \mp v_A t}{U \mp v_A}\right)$ are speed of light, Alfvén velocity, background magnetic field, velocity of the reconnection line and reconnection electric field as a function of its argument, respectively (Biernat et al., 1987). Since the reconnection line is moving with constant speed U along the x-axis, we have to distinguish between $x > Ut$ and $x < Ut$, which we denote by plus and minus signs, respectively. For the case $U = 0$, the shape of the plasma containing shock structures moving in positive and negative x-direction is symmetric with respect to the z-axis. This symmetric behavior gets lost for the situation $U \neq 0$. For increasing time, the structure gets enhanced and blows up in z-direction.

Fig. 1 shows the situation for a moving reconnection line with a velocity $U = 0.5\ v_A$ in positive x-direction. During this motion, the rightward evolving shocks, containing plasma that propagates in positive x-direction, get squeezed in x-direction, whereas the leftward evolving shocks, that consist of plasma propagating in negative x-direction get stretched in x-direction. For the z-elongation of the shocks the situation is vice versa.

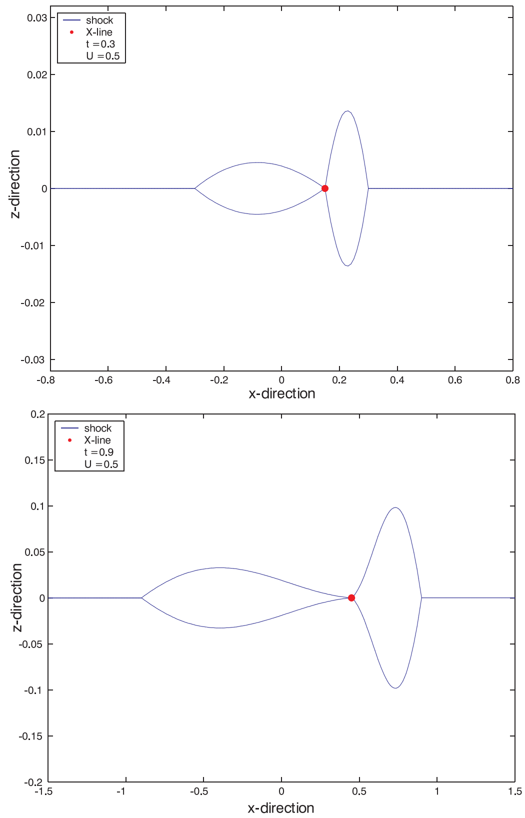

Fig. 1: Structure of the shocks during active reconnection (switch-on phase) for times $t = 0.3$ and $t = 0.9$ and a velocity of the reconnection line $U = 0.5\ v_A$. The X-line is denoted by a dot in the center. Mind the different scaling in the upper and lower panel.

Fig. 2 shows the situation during switch-off phase for different velocities of the reconnection line. The outflow regions detach from the original site of reconnection when reconnection ceased. Since the previously generated MHD waves continue to propagate, the outflow regions now appear as a pair of solitary waves propagating in opposite directions along the current-sheet. The lower panels of Fig. 2 show what happens, if the reconnection line does not display a steady-state behavior during the reconnection process. While reconnection is in progress, the reconnection line moves with a velocity of $U = 0.3\ v_A$ (middle panel of Fig. 2) and $U = 0.5\ v_A$ (lower panel of Fig. 2) in positive x-direction. After detaching, the shocks propagate with their asymmetric structure in opposite directions, growing in size and changing in shape.

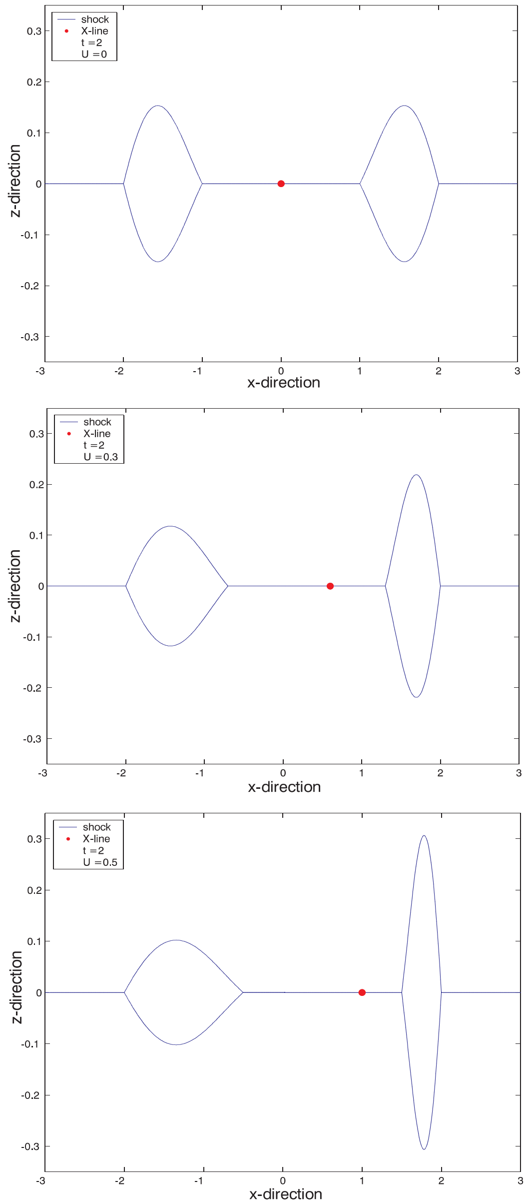

Fig. 2: Shape of the shock structures during switch-off phase. The different panels give a temporal snapshot for three different velocities of the reconnection line.

3. Magnetic field behavior in the outflow region

In our idealized model, we work with a magnetic field in the outflow region, that is only z-directed. Therefore, the magnetic field z-component can be calculated as

$$B_z^{(0)} = -\frac{1}{(U \mp 1)} E_r\left(\frac{x \mp t}{U \mp 1}\right). \qquad (2)$$

The behavior of the magnetic field z-component in the outflow-region is shown in Fig. 3. In the case of a fixed X-line (upper panel), the magnetic field shows a highly symmetric behavior in the leftward and rightward propagating shock structures. The magnetic field is plotted for three times during active reconnection. It can be seen that the magnetic field strength increases with time continuously in both shock structures and that a clear bipolar behavior is exhibited. This is due to the fact that the reconnected magnetic field in the rightward propagating outflow region is opposite directed than in the leftward propagating structure. In the lower panel an X-line motion with $U = 0.5\ v_A$ in positive x-direction is assumed. The magnetic field in the leftward propagating shock structure has finite values over a larger x-range, due to the size of the shock structure that is stretched in x-direction.

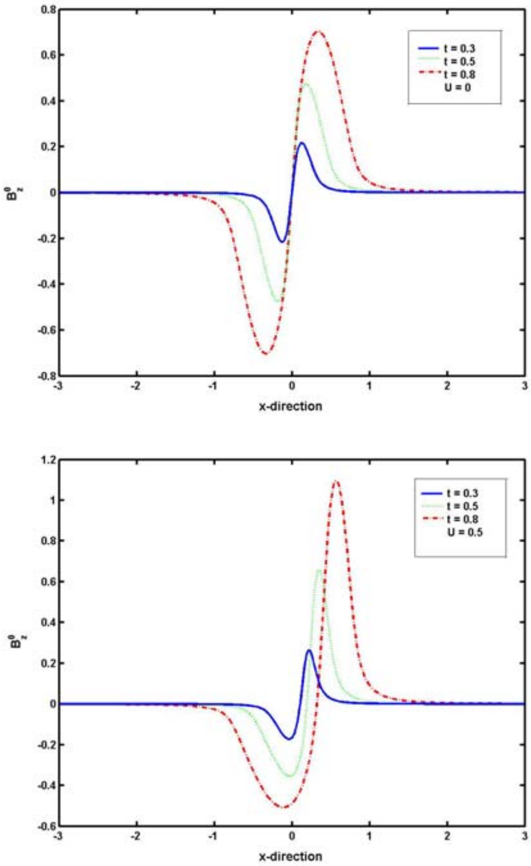

Fig. 3: Behavior of the magnetic field z-component in the field reversal region during switch-on phase for a magnetic field topology with rightward and leftward directed background magnetic field in the upper and lower half-plane, respectively.

The field strength does not reach values comparable to the situation for $U = 0$. An opposite situation is given in the rightward bulge, due to a compression of the outflow region in x-direction.

4. Magnetic field behavior in the inflow region

In the inflow region the disturbed magnetic field z-component for $z = 0$ is established in the form

$$B_z^{(1)}(x,0,t) = -\frac{1}{U \mp 1} E_r\left(\frac{x \mp t}{U \mp 1}\right) \pm \pm \frac{1}{(1 \mp U)^2}\left(E_r\left(\frac{x \mp t}{U \mp 1}\right) + \frac{x - Ut}{U \mp 1} E_r{}'\left(\frac{x \mp t}{U \mp 1}\right)\right), \tag{3}$$

where E_r' denotes the derivative of the electric field with respect to x (Kiehas, 2005). For computing B_x and B_z in space, we solve a Dirichlet problem in the half plane via the Poisson integral,

$$B_x^{(1)}(x,z,t) = \frac{1}{\pi}\int_{-t}^{t} \frac{(x-\xi)B_z^{(1)}(\xi,0,t)}{(x-\xi)^2 + z^2} d\xi, \tag{4}$$

$$B_z^{(1)}(x,z,t) = \frac{z}{\pi}\int_{-t}^{t} \frac{B_z^{(1)}(\xi,0,t)}{(x-\xi)^2 + z^2} d\xi, \tag{5}$$

where $B_z^{(1)}(\xi,0,t)$ is the magnetic field along the x-axis from Eq. (3) (e.g., Vladimirov, 1984).

The upper panel of Fig. 4 shows the behavior of the magnetic field x-component in the inflow region for the case of a steady X-line during switch-off phase. Discussing the behavior of the magnetic field from left to right, the first signature is a decrease in the field strength. This is due to an increase in the magnetic field z-component, resulting from a change in the magnetic field topology due to the appearance of the shock.

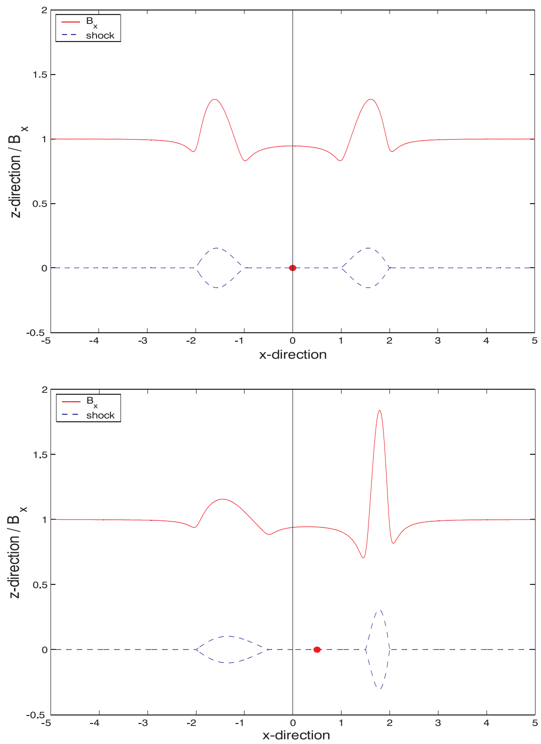

Fig.4: Behavior of the magnetic field x-component in the inflow region during switch-off phase, plotted for $t = 2$. The actual positions of the shocks are displayed as well.

Around the peak of the shock, the magnetic field strength in *x*-direction is maximized. The lower panel shows the situation for the case of a moving X-line with $U= 0.5\ v_A$. It can be seen that the maximum field strength around the leftward propagating shock is smaller than in the case $U = 0$, due to a smaller elongation of the shock in *z*-direction. For the shock moving rightward, the situation is vice versa.
Fig. 5 shows the behavior of the magnetic field *z*-component under the same conditions.

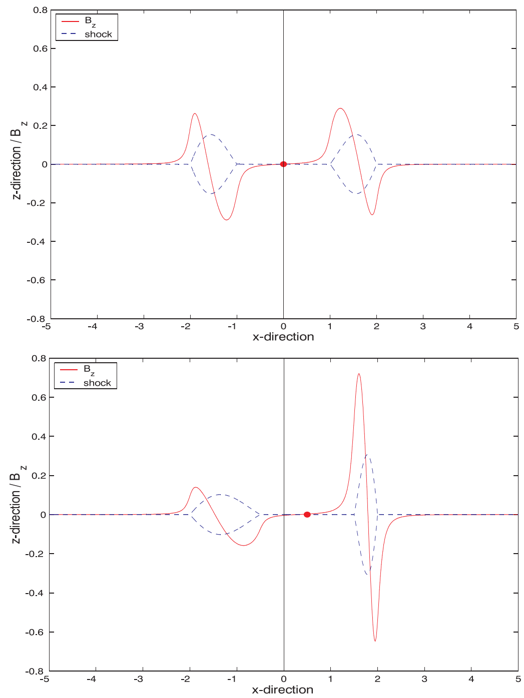

Fig. 5: Same as Fig. 4 for the magnetif field *z*-component.

5. Conclusions

We present an overview of the behavior of the magnetic field and the shocks in the time-dependent Petschek model of reconnection for a moving X-line. It is shown, that the shock structures, generated on the left-hand and right-hand side of the diffusion region, lose their symmetric structure under the assumption of moving X-line behavior. The degree of asymmetry depends on the velocity of the X-line and increases with speed of the X-line. In the outflow region, the typical bipolar behavior of the magnetic field is accompanied by an asymmetry, appearing in the outflow regions left- and rightwards of the reconnection site. In the outflow region, propagating in the same direction as the X-line is moving, the magnetic field strength is enhanced, compared to the case for a steady X-line, whereas a decrease can be seen in the opposite outflow region. In the inflow region the magnetic field displays asymmetric behavior as well, resulting in a stronger decrease of the magnetic field *x*-component in the area between the (initial) X-line and the rightward propagating outflow region and an enhancement around the peak of this structure. An enhancement is also seen for the *z*-component of the magnetic field. By using these results, we show, how a moving X-line changes the shape of the shocks and the behavior of the magnetic field.

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References:

Biernat, H. K., M. F. Heyn, and V. S. Semenov, 1987, Unsteady Petschek reconnection, J. Geophys. Res., 92, 3392.

Heyn, M. F., H. K. Biernat, and R. P. Rijnbeek, 1988, The structure of reconnection layers, J. Plasma Physics, 40, 235.

Kiehas, S. A., 2005, Time-dependent Petschek-type magnetic reconnection for a moving X-line with applications to Earth’s magnetosphere, Diploma thesis, University of Graz, Austria.

Petschek, H. E., 1964, Magnetic field annihilation, in: Physics of Solar Flares, ed. W. N. Hess (NASA Spec. Publ. 50), 425.

Rijnbeek, R. P., and V. S. Semenov, 1993, Features of a Petschek-type reconnection model, Trends in Geophys. Res., 2, 247.

Semenov, V. S., I. V. Kubyshkin, M. F. Heyn, and H. K. Biernat, 1992, A comparison and review of steady-state and time-dependent reconnection, Planet. Space Sci., 40, 63.

Semenov, V. S., I. V. Kubyshkin, R. P. Rijnbeek, and H. K. Biernat, 2004, Analytical theory of unsteady Petschek-type reconnection, in: Physics of magnetic reconnection in high-temperature plasmas, edited by M. Ugai, Research Signpost, Trivandrum, India, p. 35-68.

Vladimirov, V. S., 1984, Equations of mathematical physics, Mir Publishers, Moscow.