"Physics of Auroral Phenomena", Proc. XXVII Annual Seminar, Apatity, pp. 31-34 , 2004

Polar Geophysical Institute

A GENERAL ANALYTICAL SOLUTION OF THREE DIMENSIONAL TIME DEPENDENT MAGNETIC RECONNECTION IN A COMPRESSIBLE PLASMA

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Abstract

An analytical solution of three-dimensional time dependent Petschek type reconnection in compressible plasma [1] is extended to the general case of skewed fields, plasma velocities as well as an X-line of finite length. In this model it is assumed that all dissipative processes responsible for reconnection are localized in an idealized reconnection line of effective finite length and can be taken into account by specifying a time and space varying reconnection rate. An electric field pulse launches a series of large amplitude non-linear MHD waves, which redistribute the initial current and form a structured region with accelerated and heated plasma inside. In this way, magnetic energy is effectively converted into kinetic and internal energy of the plasma. The time-coordinate representation of the solution is given in form of convolution integrals over the reconnection initializing electric field, which allows to compute all related quantities like magnetic fields, pressure, plasma density, plasma velocities as well as shape of moving waves. As an example, reconnection of flux tubes in sheared magnetic field geometry with initial plasma velocities is analyzed.

Introduction

Magnetic field line reconnection is a fundamental plasma process which is important in numerous cases such as the solar wind interaction with planetary magnetospheres, the energy release in solar flares, transport processes in fusion devices, etc. The 'fast' reconnection model originally proposed by Petschek [2] considers the global evolution of magnetic flux tubes, which have been locally reconnected across an initially magnetically closed current carrying surface. In terms of ideal magnetohydrodynamics (MHD) this is described as a broken tangential discontinuity: a local dissipative electric field [3,4,5] tangential to the surface leads to a 'breaking' and 'reconnection' of magnetic flux tubes. The tangential electric field itself is then transported over the surface by large amplitude MHD waves. This leads to an effective nonlinear release of energy stored within the current surface. More specifically, the surface breaks into a thin boundary layer (BL) which collects plasma from the adjacent reconnected flux tubes and accelerates this plasma to Alfvèn speed velocities.

Reconnection in nature is often observed as a time-dependent process of patchy character. To explain these features, the existing analytical solutions for either steady state reconnection in a compressible plasma [6] or time-dependent reconnection in an incompressible plasma [7] have to be extended to cover such an unsteady and patchy behavior. In the present paper, the solution of time varying reconnection in a compressible plasma obtained earlier [8, 9,1] is extended to the more general case where skewed fields are reconnected at an X-line of finite length and plasma can have initial velocities.

In the present study, the shape as well as the spatial localization of the reconnection electric field is assumed a priori and from this the plasma flow and magnetic field in the outer, ideal region is computed. For reconnection with $B_n/B_0 \ll 1$ (B_n the magnetic field component normal to the surface), i.e., a sufficiently small dissipative electric field, there are a number of simplifications, which allow for analytical progress. First of all, in the case of homogeneous initial conditions above and below the current surface, the de Hoffmann-Teller velocities are constant in lowest order with respect to B_n/B_0. Therefore, the solution of the corresponding Riemannian problem to some extent does not dependent on the actual normal component of the magnetic field which causes the decay. Therefore, a part of the problem can be solved solely in terms of these de Hoffmann-Teller velocities [6].

The perturbations in form of shocks and discontinuities moving within the BL act as sources for the perturbations in the surrounding medium. The solution in these outer regions is found from the solution of the linearized compressible ideal MHD set of equations supplemented with the appropriate boundary conditions, in particular, total pressure balance as well as mass and magnetic flux conservation at the location of the initial current surface (z=0).

We constructed explicitly the outer solution of time varying reconnection of magnetic flux tubes in compressible plasma. Results for reconnection in skewed magnetic field structures are presented in order to illustrate the method.

Results and Discussion

The derivation of a solution for the case when plasma has initial velocities is similar to our paper [1]: one should replace $\omega \to \omega - (\mathbf{k}\cdot\mathbf{v}^{(0)})$ everywhere. As a result the topology of Cagniard contours in the complex plane is changed and poles start to contribute to a value of integrand. Here we present results only because of limited space.

To model a pulse of reconnection one has to specify the dependence of the reconnection rate as a function of time, e.g., as shown in Figure 1,

$$E^*(t,y) = 12t^2 e^{-4t} \frac{a}{p(a^2+y^2)}$$

with maximal reconnection rate $E^*_{\max} = 0.2$. As a function of *y*, the electric field has a maximum at the origin and then decreases with *y*, the constant *a* represents an effective length L_X of the reconnection line. The initial parameters of the current surface (tangential discontinuity) and the corresponding solution of the Riemannian problem are presented in Table 1.

Within the time-dependent model of reconnection it is possible to distinguish different phases of the process in terms of a pulsating reconnection rate. During the active phase (the time period when magnetic field lines are reconnected along the X-line, $0<t<2$ in our case) and in the nearest vicinity of the reconnection line time dependent reconnection is very similar to the steady-state Petschek model even for the case of skewed magnetic fields. Thus, for very small periods in a very localized region, one can expect behavior similar to classical stationary reconnection. However, most of the time when active reconnection has already stopped, thin boundary layer structures are formed which propagate along the current surface. During this passive phase ($t>2$) the whole MHD structure is essentially three-dimensional and it looks quite different when compared to the stationary Petschek process (Figure 2).

For the case of skewed fields all shocks and discontinuities launched by reconnection move not only with different de Hoffmann-Teller velocities but also they move in different directions. As a result, the BL regions, which consist of accelerated and heated plasma, are highly elongated with progressively increasing distance between all discontinuities. This can be clearly seen in Figure 3 where the cross section of the BL region is shown.

Each discontinuity produces disturbances in the outer regions corresponding to the poles of the source term. Although the whole structure looks complicated, it is still possible to identify the basic features of skewed field reconnection.

First of all, one has to find the location of the BL region. The Alfvén discontinuities above and below the current surface propagate with different Alfvèn velocities. The cross section of the BL region through its center in the diagonal direction is shown in the Figure 3. The single discontinuities can be observed.

Each discontinuity looks similar to a hill on top of the current surface. The behavior of the MHD perturbations in the outer regions is similar to that found for a moving object such as a wing in pure hydrodynamics. As can be seen from Figure 4, the density and the total pressure are increased in the front of of moving discontinuities and decreased in the wake.

Any enhancement of the total pressure in the front region must be compensated by a corresponding increase in total pressure in the lower half space. To establish pressure balance, the upper hill is pushed downward which results in the permanent generation of surface waves. This can be seen in Figure 3.

The scale of the MHD disturbances in the surrounding medium depends on the reconnected flux as well as the size and direction of the reconnected fields. The level of the disturbances in the outer regions strongly depends on the angle between the reconnected fields. In fact, the BL region collects all plasma from the reconnected flux tubes bounded by separatrices. Therefore, the amount of mass, energy and momentum of heated and accelerated plasma inside the BL region linearly increases with time. Contrary, the reconnected flux during the passive phase is not changed any more. Hence, the more the shocks above and below the current surface separate and the more elongated the BL structure is, the less pronounced are the signatures in the outer regions.

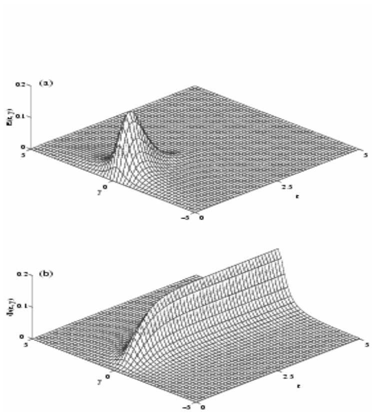

Figure 1: The time and space variation of the model reconnection electric field and the corresponding reconnected flux function (bottom).

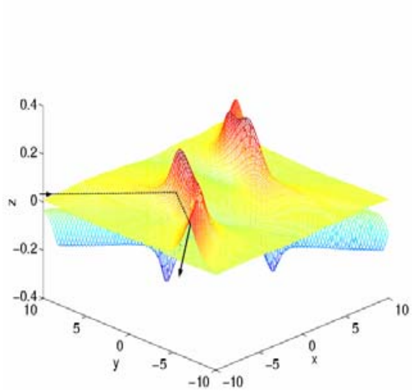

Figure 2: Reconnection of skewed magnetic fields at time t=4: separatrix surfaces. The arrows indicate the direction of the magnetic field above and below the current surface. The corresponding boundary layer structure inside the separatrix surfaces is shown in detail in Figure 3.

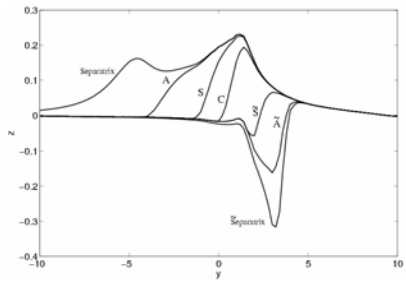

Figure 3: The evolution of the non-linear waves initiated by an electric field pulse is shown in a cross section of the boundary layer region corresponding to the direction of the internal magnetic field (central part of dashed line in Figure 2). Displayed are the separatrix, the Alfvén wave (A), the slow shocks (S), and the contact discontinuity (C).

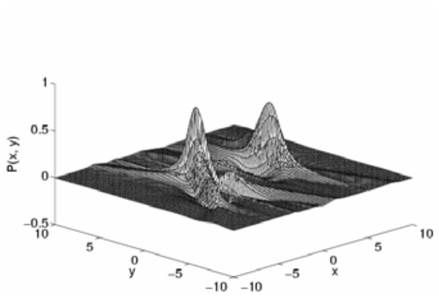

Figure 4: The distribution of the total pressure for z=0.

Table 1: Plasma parameters in the different regions and the corresponding de Hoffmann-Teller velocities for x>0.

Region	B_x	B_y	v_x	v_y	ρ	p
0 outer	1.1	0.8	0.1	0.18	0.4	0.185
1 *AS*	0.474	1.275	1.090	-0.571	0.400	0.185
2 *SC*	0.362	0.976	1.386	0.225	0.913	0.952
$\tilde{2}$ $C\tilde{S}$	0.362	0.976	1.386	0.225	1.229	0.952
$\tilde{1}$ $\tilde{S}\Gamma$	0.406	1.094	1.456	0.414	1.000	0.673
$\tilde{0}$ outer	-0.800	0.850	0.250	0.170	1.000	0.673

Wave	w_x	w_y
A	1.839	1.445
S	1.536	0.627
C	1.386	0.225
$\tilde{S}$	1.201	-0.273
$\tilde{A}$	1.050	-0.680

Conclusions

A new analytical solution of three-dimensional time dependent reconnection in compressible plasma with moving shocks is presented. In this model it is assumed that all dissipative processes responsible for reconnection are localized in an idealized reconnection line of effective finite length and can be taken into account by specifying a time and space varying reconnection rate.

Such an electric field launches a series of large amplitude non-linear MHD waves, which redistribute the initial current and form a structured BL region with accelerated and heated plasma inside. In this way, magnetic energy is effectively converted into kinetic and internal energy of the plasma.

The moving slow shocks and Alfven discontinuities excite disturbances in the surrounding media. Solutions for a space and time varying reconnection rate are obtained which include coupling of all types of MHD waves (MHD discontinuities and linear slow, fast and Alfven waves) under the pressure balance condition.

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