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Multi-scale MHD approach to the current sheet filamentation in solar coronal reconnection

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Abstract

Magnetic field reconnection – considered now as a key process in the commonly accepted standard scenario of solar flares – spans over many mutually coupled scales from the global flare dimensions (≈10 Mm) down to the scale, where non-ideal kinetic plasma effects takes place (≈10 m). Direct numerical simulation covering all the scales is, therefore, impossible. Nevertheless, the filamentary nature of the current sheet fragmentation together with rescalability of ideal-MHD equations – which governs the processes before reaching the scales of non-ideal plasma response – allow to describe the large- and intermediate-scale dynamics of reconnection flow with highly reduced request for number of grid points. Since the smaller-scale (and faster) dynamics sets-in only in regions of enhanced current sheet filamentation, we focus just on these areas, which occupy only a small fraction of the total volume. Generally, as the fragmentation continues, it forms a cascade of filamentation until kinetic non-ideal processes come to play. Information relevant for description of the smaller-scale physics occupies only a small fraction of grid-cells describing the large-scale dynamics. Thus, one can subsequently zoom-in onto the regions of continuing current filamentation. The current-sheet fragmentation cascade anticipated by Shibata and Tanuma [Shibata, K., Tanuma, S. Plasmoid-induced-reconnection and fractal reconnection. Earth, Planets, and Space 53, 473–482, 2001], creates multiple dissipative regions in a single current sheet, which can play a key role for DC-field particle acceleration in a flare reconnection. The main goal of the paper is to numerically investigate the relevance of cascading reconnection for solar flares. The numerical algorithm implemented for that purpose and first results are presented in this research note. Proposed algorithm – though motivated by the self-similar nature of MHD equations – belongs in fact to the class of block-structured Adaptive Mesh Refinement codes.

Keywords: Solar flares; Magnetic reconnection; Numerical MHD

1. Introduction

Magnetic field reconnection is now considered as a key process in the commonly accepted standard scenario of solar flares. Nevertheless, its classical picture with a single dissipative region (X-points or X-lines in the frequently presented 2D and 2.5D flare scenario cartoons) suffers in many respects. Above all, there is a large scale-gap between the dimension at which the energy enters the system – i.e. the size of coronal magnetic flux-tubes, and the scale of non-ideal plasma response (Büchner, 2006). A similar problem has to be faced in the classical fluid dynamics (FD): the energy-input scale (typically the tube diameter in engineering applications) is many orders of magnitude larger than the viscous (basically molecular) scale. From the dynamics of viscous fluids it is well known, that the intermediate scales are filled by a (turbulent) cascade of subsequently smaller vortices, through which the energy is transferred in k-space to shorter scales.

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Shibata and Tanuma (2001) suggested the concept of cascading or *fractal reconnection* to bridge the scale-gap in the flare reconnection. In their 2D scenario the solar flare reconnection proceeds through a cascade of subsequent tearing modes until the dissipation scale is reached, where the anomalous resistivity sets-in due to kinetic effects (see Fig. 1). The role analogical to vortices in FD is played here by magnetic islands, which represent the 2D projection of magnetic flux-ropes, also called plasmoids. In their 2D model cartoon multiple magnetic islands (flux-ropes/plasmoids) at various scales are formed interleaved by magnetic X-lines.

Such picture of fractal/turbulent reconnection can – besides the problem of the scale-gap – help to resolve a caveat of the classical global Petschek-type (Petschek, 1964) reconnection scenario – the serious problem of particle acceleration in solar flares. Standard scenarios with a single dissipative region suffer by the insufficient volume for acceleration of the huge number of particles inferred from HXR observations (e.g. Vlahos, 2007). Because many dissipation regions separates multiple plasmoids in the small-scale regime of reconnection the total volume of all dissipation regions is much larger, allowing for possible reconciliation between observed and modelled fluxes of energetic particles. At the level of kinetic scale such a *multi-island* picture was studied, e.g., by Drake et al. (2005).

Moreover, there is an observational support for a multi-scale multi-plasmoid (or, briefly, turbulent) reconnection scenario. Kliem et al. (2000) suggested, that radio emissions in form of so called Drifting Pulsating Structures (DPS) can be interpreted as consequence of plasmoid formation and dynamics. Karlický (2004) found also cases of many DPSs observed simultaneously in different frequency ranges and with different frequency bandwidths. He interpreted such observations by a multi-plasmoid scenario (Fig. 1). The statistical distribution of the time-scales of single radio pulses observed in DPSs (Karlický et al., 2005) is closely related to the particle acceleration in DC field of interacting plasmoids (Drake et al., 2005; Karlický and Bárta, 2007) Its observed power-law form can be easily understood within the cascading-reconnection concept.

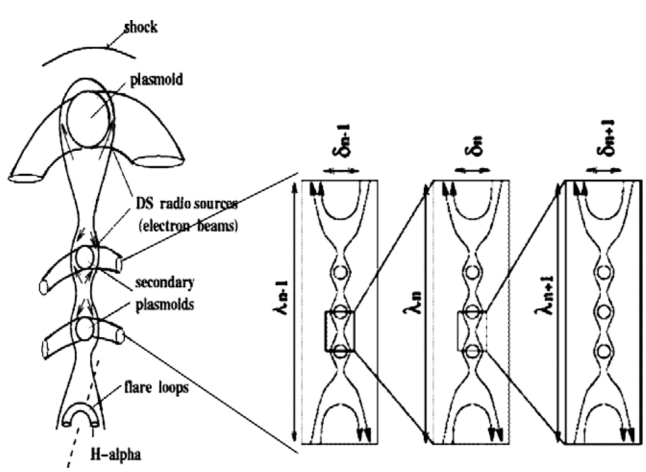

Fig. 1. Concept of fractal (cascading) reconnection (Shibata and Tanuma, 2001, right) and its linkage to the idea by of multi-plasmoid interpretation of several DPSs observed simultaneously in radio spectra (Karlický, 2004, left).

The concept of cascading reconnection involves the coupling of processes that act simultaneously in a broad range of scales. However, such a picture of reconnection has not been studied yet neither experimentally nor using numerical simulations. In the following we suggest a way how to handle the cascading numerically by a feasible approach based on an Adaptive Mesh Refinement approach to the solution of MHD equations.

2. Model

In a large range of scales the evolution of magnetised plasma can be adequately described by a set of compressible resistive one-fluid MHD equations (e.g. Priest, 1984):

$$\begin{aligned}
&\frac{\partial\rho}{\partial t}+\nabla\cdot(\rho\boldsymbol{u})=0\\
&\rho\frac{\partial\boldsymbol{u}}{\partial t}+\rho(\boldsymbol{u}\cdot\nabla)\boldsymbol{u}=-\nabla p+\boldsymbol{j}\times\boldsymbol{B}+\rho\boldsymbol{g}\\
&\frac{\partial\boldsymbol{B}}{\partial t}=\nabla\times(\boldsymbol{u}\times\boldsymbol{B})-\nabla\times(\eta\boldsymbol{j})\\
&\frac{\partial U}{\partial t}+\nabla\cdot\boldsymbol{S}=\rho\boldsymbol{u}\cdot\boldsymbol{g}.
\end{aligned}\qquad(1)$$

In a numerical scheme the set (1) is handled in its conservative form. That means, that the state is locally represented by the vector of basic variables $\boldsymbol{\Psi}\equiv(\rho,\rho\boldsymbol{u},\ \boldsymbol{B},U)$, where ρ, $\boldsymbol{u}$, $\boldsymbol{B}$, and U are the plasma density, plasma velocity, magnetic field strength and the total energy density, respectively. The energy flux $\boldsymbol{S}$ and auxiliary variables – plasma pressure p and current density $\boldsymbol{j}$ – are defined by the formulae:

$$\nabla\times\boldsymbol{B}=\mu_0\boldsymbol{j}$$

$$U=\frac{p}{\gamma-1}+\frac{1}{2}\rho u^2+\frac{B^2}{2\mu_0}$$

$$\boldsymbol{S}=\left(U+p+\frac{B^2}{2\mu_0}\right)\boldsymbol{u}-\frac{(\boldsymbol{u}\cdot\boldsymbol{B})}{\mu_0}\boldsymbol{B}+\frac{\eta}{\mu_0}\boldsymbol{j}\times\boldsymbol{B}$$

Microphysical (kinetic) effects enter the large-scale dynamics through the transport coefficients, here by means of resistivity η. As the MHD model is intrinsically incapable to describe consistently the influence of kinetic processes which determine the actual value of resistivity, the phenomenological expression

$$\eta(\boldsymbol{r},\boldsymbol{t})=\begin{cases}0: & |v_D|\leqslant v_{cr}\\ C\frac{(|v_D(\boldsymbol{r},t)|-v_{cr})}{v_0}: & |v_D|>v_{cr}\end{cases}\qquad(2)$$

is used. The relation above expresses the generally accepted fact, that kinetic instabilities generate fluctuating electric field when the current-carrying (electron drift) velocity $v_D=\frac{j}{ne}$ exceeds some threshold. Such behaviour is