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Cascading fragmentation in CME-generated current layer

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Introduction

Its is now commonly assumed, that magnetic flux ropes on the Sun can become unstable when the amount of their twist exceeds some limit giving rise to CMEs. As a consequence, current layers are formed behind CMEs where reconnection can take place causing the effects connected with solar flares. While a lot of attention has been paid to CME/flux-rope dynamics, not too much effort is devoted to the question of the current-layer formation and its subsequent fragmentation.

We start with Titov-Demoulin equilibrium (*Titov & Demoulin, 1999*) for a twisted flux rope. Then, adding some extra twist via foot-point motions the flux rope becomes unstable. We study formation of the current layer and its fragmentation. In order to address both the large-scale 3D aspects of CS formation and the energy cascade towards smaller scales we use an approach combining moderately resolved 3D MHD model with the high-resolution 2.5D AMR MHD simulations. We have found, that the current layer decays in a cascade of tearing and *fragmenting* coalescence processes leading to the consecutively smaller magnetic-field and current-density structures. Spontaneous fragmentation of CS has significant consequences for particles accelerated in solar flares and their observational signatures.

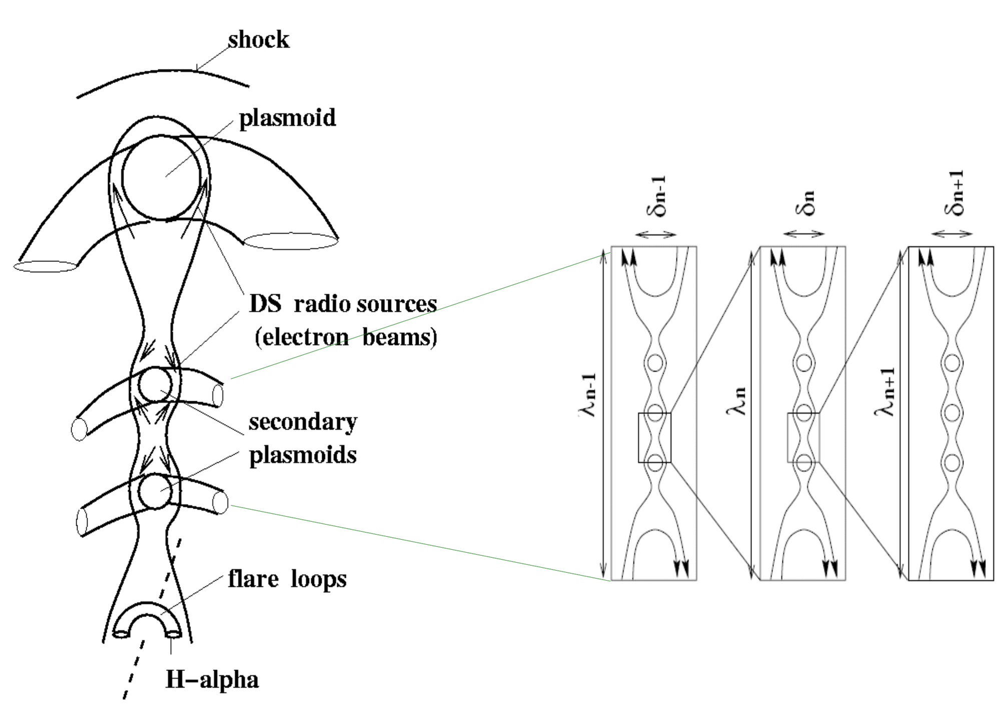

Fig. 1: Scheme of the cascading (fractal) reconnection concept according *Shibata and Tanuma (2001)* (right) and its connection to interpretation of multiple Drifting Pulsating Structures observed occassionally in radio spectra by *Karlický (2004)* (left).

Model

We describe the evolution of magnetised plasma by the set of compressible MHD equations in the form:

$$\frac{\partial \rho}{\partial t} + \nabla\cdot(\rho \boldsymbol{u}) = 0$$

$$\rho\frac{\partial \boldsymbol{u}}{\partial t} + \rho(\boldsymbol{u}\cdot\nabla)\boldsymbol{u} = -\nabla p + \boldsymbol{j}\times \boldsymbol{B} + \rho \boldsymbol{g}$$

$$\frac{\partial \boldsymbol{B}}{\partial t} = \nabla\times(\boldsymbol{u}\times \boldsymbol{B}) - \nabla\times(\eta \boldsymbol{j})$$

$$\frac{\partial U}{\partial t} + \nabla\cdot \boldsymbol{S} = \rho \boldsymbol{u}\cdot \boldsymbol{g}$$

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

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

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

Here, all the non-ideal MHD effects due to kinetic plasma processes on microscale which enter the MHD dynamics are represented by the term $\eta \boldsymbol{j}$. To simulate the presence of small-scale kinetic effects (e.g. Bunemann instability) we use the following prescription for anomalous resistivity η:

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

This formula mimics the onset of plasma instabilities in highly filamented current sheet (CS) in which the electron current-carrying drift velocity v_D exceeds some threshold (*Büchner & Elkina, 2006*).

We first solve this set of equation in full 3D geometry in order to investigate large-scale aspects of CS formation behind ejected flux-rope. Then, in order to extend the range of scales covered by the simulation, we use Adaptive-Mesh-Refinement (AMR) technique which resolves the smaller-scale dynamics in the regions of enhanced current-sheet filamentation (see *Bárta et al. 2010, 2011a* for details).

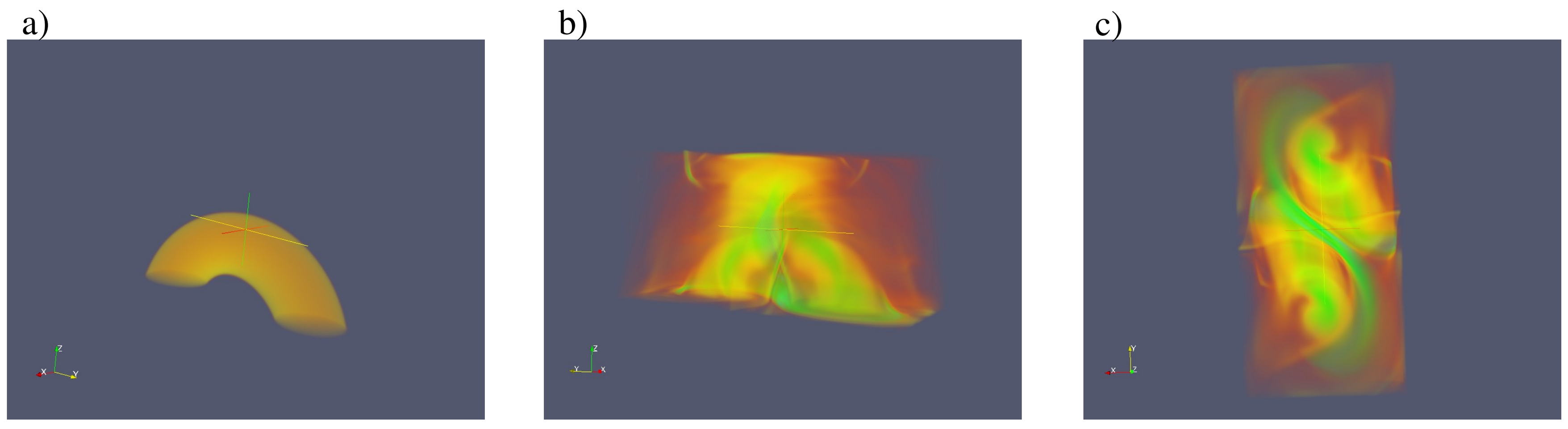

Fig. 2: Formation of CS behind ejected flux-rope. Current density is displayed. (a) initial state t=0, (b) state at t=110 Alfven times, (c) as in (b) but viewed from the bottom.

Results

1. Cascading reconnection and fragmentation of the CS

We studied formation and fragmentation of CS behind an ejected flux-rope using approach that combines large-scale 3D MHD simulation (CS formation) with high-resolution 2.5D AMR MHD description of CS-cross-section in the plane perpendicular to the PIL. We have found that a cascade of two mechanism plays a role in energy transfer form large to small scales in the process of flare reconnection. The two key mechanisms are the cascading tearing in stretched parts of CS and fragmenting coalescence in the CS formed between approaching/merging plasmoids. *Fragmenting coalescence* changes the former common view on plasmoid coalescence as a process of simple merging leading solely to the energy transport from small to large scales (inverse cascade). It can also increase the energy release rate in flare reconnection.

2. Observational consequences of cascading fragmentation

The results of above-mentioned simulations have important consequence for particle acceleration in flares which can be manifested by phenomena observed on various wavelengths. A possibility to observe multiple pairs of flare Hα ribbons – or at least a significant structuring in a single pair – represents a clear prediction of the model based on a cascading reconnection. The fragmented current sheet hosts multiple X-points (possible acceleration sites) which are mapped to the chromospheric layers by corresponding magnetic field lines (magnetic separatrices). This can lead to the splitting or at least broadening of flare Hα ribbons as is shown in *Fig 5.*

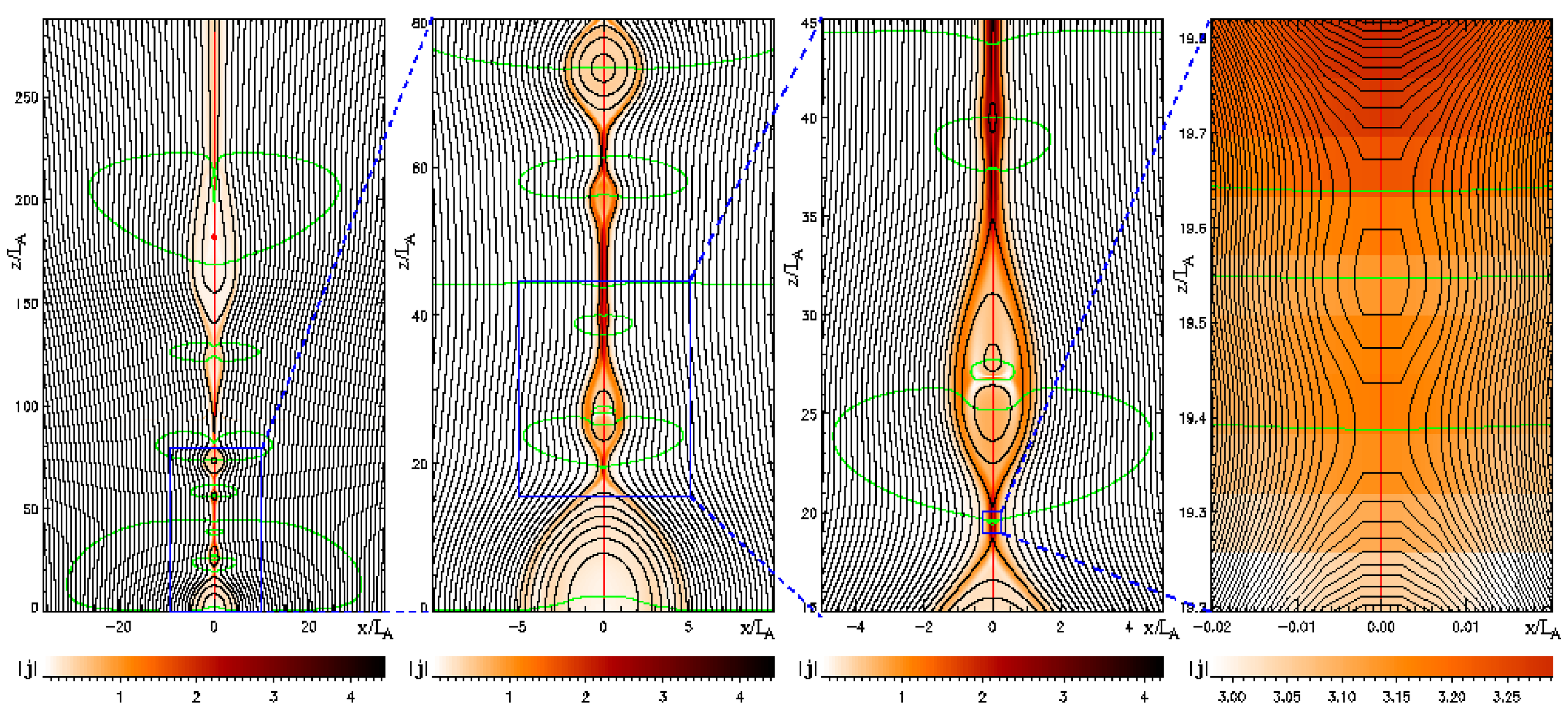

Fig. 3: Formation of small-scale magnetic structures (plasmoids) by secondary tearings in a tearing cascade – c.f. *Fig. 1*. Black lines are the magnetic field lines, red areas denotes the current density. Increasing zoom reveals smaller and smaller structures/plasmoids.

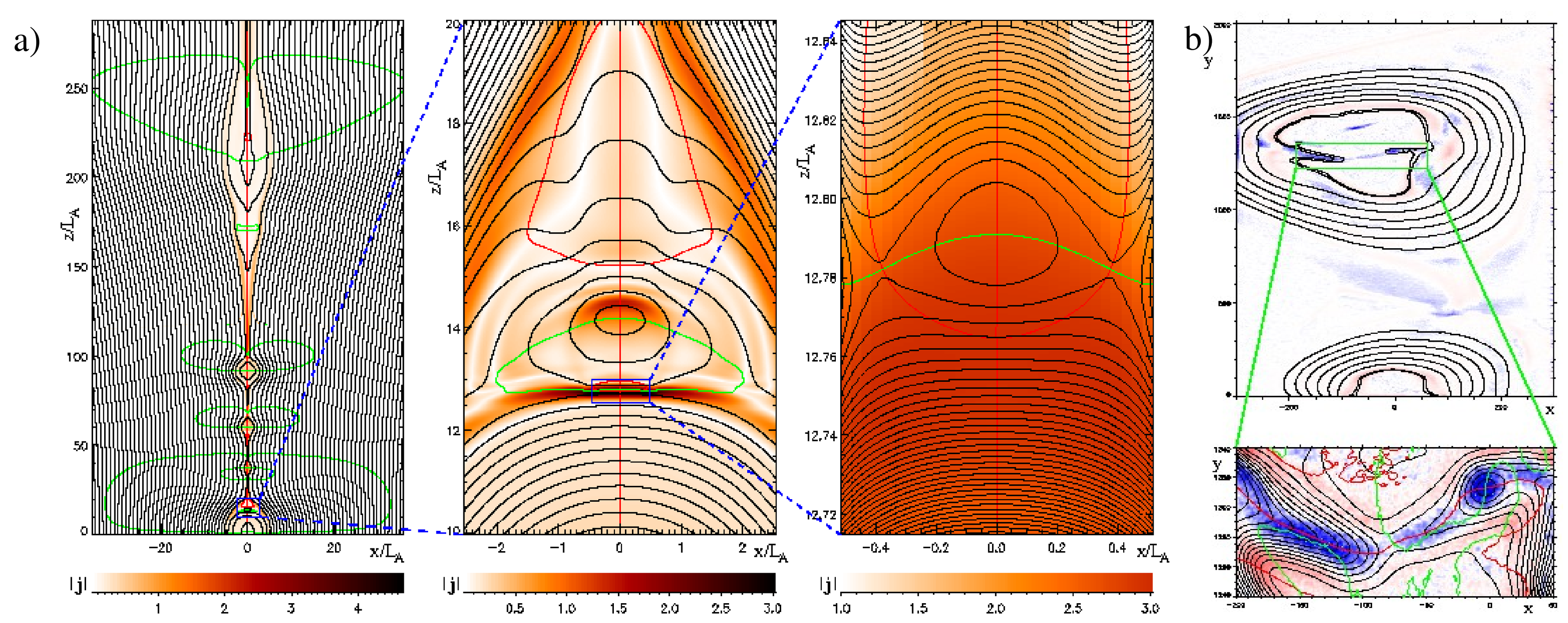

Fig. 4: Fragmentation of CS between merging plasmoids by *fragmenting* coalescence. This process represents a new mechanism that plays a significant role in energy transfer to small scales. (a) MHD simulation (*Bárta et al., 2011a*), (b) large-scale PIC simulations indicates that this process continues down to the dissipation scale (*Karlický & Bárta, 2011*).

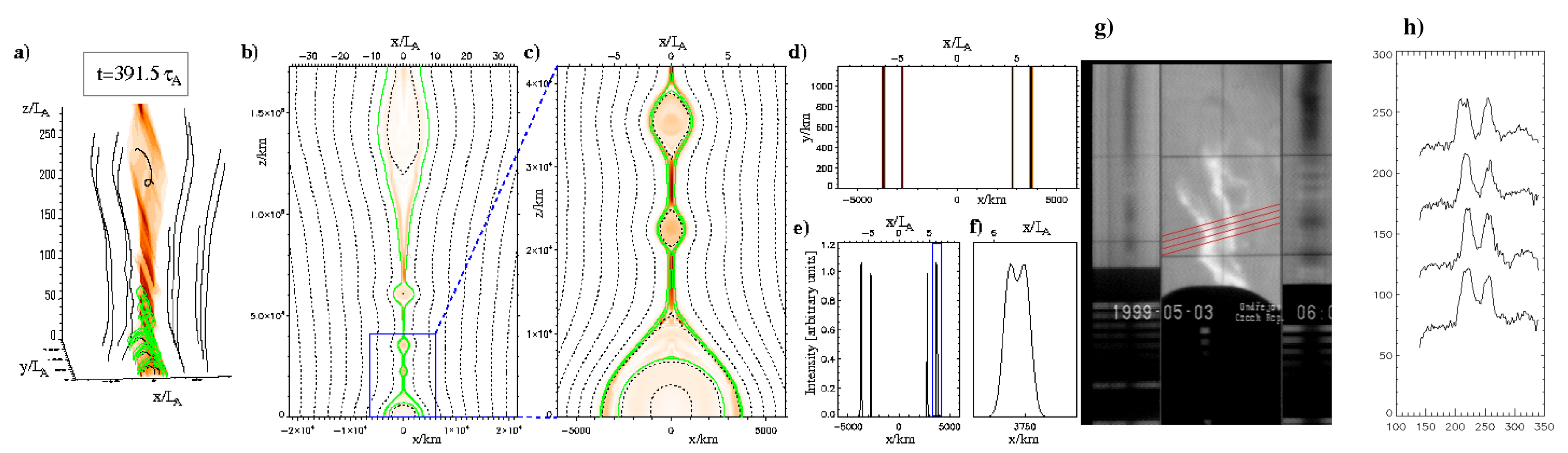

Fig. 5: Plasmoid/loop-top interaction and possible splitting/broadening of flare ribbons. Panel *a)* shows 3D view of magnetic field (lines) and current density (background color) in the fragmented CS. Multiple X-points embedded in the CS are connected by magnetic separatrices (green lines; supposed paths of energetic electrons propagation) with chromosphere. Panels *b), c)* show the detailed view on the same situation in 2D projection. Panels *d)* displays predicted (splitted) Hα emission ribbons, panels *e)* and *f)* their profiles along the x-axis [(f) being a zoom to the blue rectangle in (e) showing emission structuring in outer ribbon]. In the extreme case of large-scale plasmoid interacting with the arcade one should see even chromospheric rebrightenings. Panel *g)* presents a slit-jaw Hα image of two-ribbon flare taken by the Ondřejov MFS. Panel *h)* shows intensity profiles taken along the four red lines indicated in panel *g)*. Some broadening/splitting at the intensity maxima is visible. See *Bárta et al., (2011b)* for details.

Conclusions

We studied the flare-CS formation and fragmentation via 3D and 2.5D MHD simulations. We identified two basic mechanism of CS fragmentation which work together in a cascade form large to small scales. The cascading reconnection has significant impact on particle acceleration in solar flares. We studied possible manifestation of particles accelerated in a cascading solar flare reconnection in observed data.

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