Cascading fragmentation in magnetic reconnection in solar flares: High-resolution DG FEM-based MHD simulations and their relation to observations

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Our advanced technology is threadened by Coronal Mass Ejections, which are giant plasma clouds expelled by the solar atmosphere. The team lead by Dr. Barta have modelled in unprecedented details the launch mechanism of coronal mass ejections. They compare it with the interaction of two honey or water streams. You can imagine two counter-streaming layers of honey injected next to each other. You can easily expect what happens in a moment: The streams are stopped and the energy of the flow is changed to heat. It is well known effect of viscosity. However, such highly sheared streams are quite soon destroyed even in case of as low-viscid fluids as water or acetone. How is it possible? The stream destruction proceeds via cascade of *vortices* (eddies) formed in the boundary layer between the two (counter)streams. The flow structure this way fragments into smaller pieces, in which the dissipation is much efficient. This process is nothing else then generally known *turbulence* and it appears spontaneously whenever the stream is long or fast enough, and Nature has no direct means to stop it because the viscosity is low.

A similar question has worried a couple of generations of plasma astrophysicists studying solar flares. The flares are events of explosive release of energy stored in magnetic fields in the solar atmosphere. The magnetic field lines in a flare configuration form also two 'counter-streaming' bunches, in analogy with the honey shear flow. The laws of electrodynamics ensure that there must be electric current running between those anti-parallel magnetic field lines. In case this situation happened in environment with a high electrical resistivity, the current would be also dissipated to heat (like in an ordinary cooker or electric light bulb) and the counter-streaming magnetic field structure would be destroyed in a short time. This process is known as *reconnection* of magnetic field lines and represents a natural mechanism how the magnetic field energy is released in flares. Nevertheless, the hot and sparse plasmas in the solar atmosphere have extremely low resistivity, hence the question arises: Is the process of reconnection really at play in the flares? Our investigations say yes, but similarly to the fluids like water, also in the case of low-resistivity solar plasma we need some mechanism of fragmentation of the electric current structure to smaller pieces. And – in analogy with water turbulence – this fragmentation has been found to be mediated by spontaneous formation of a cascade of helices of magnetic field that are known as *plasmoids* – they play the role of eddies known from the classical fluid turbulence (see Fig. 1).

In order to prove and further study this fragmentation mechanism, large-scale numerical simulations have been run on supercomputers. Such simulations are divided among many computers, who all only see one part of the whole simulation domain. The points at which the density and velocity are know are called the *computing mesh.* However, plasmoids (and eddies) formed in the turbulence appear at many scales (see Fig. 1), so the mesh needs to encompass the entire system and follow and resolve the small structures at the places of their occurrence at the same moment. To achieve that, we are employing a novel self-adaptive *Finite Element Method* with an appropriate guess of system variables in between the mesh points. An example of the adaptive mesh and fine structure of the electric current density is shown in Fig. 2.

This problem may seem to be just of academic interest but the opposite is true. Solar flares connected with *Coronal Mass Ejections* are the main drivers of disturbances in the near-Earth space (a.k.a. *space weather*) which have increasing influence on our civilization depending on yet more complicated (and therefore sensitive) technology. And the process of reconnection plays central role in such possibly harmful events, so its understanding is essential.
Numerical simulations are one of the only tools to improve our models. However, only observations can prove that the modelled processes really appear at our Sun. And indeed, observational data ranging from radio to soft X-ray domain shows that plasmoid formation is a natural process in solar flares and thus our model of the turbulence would fit those observations.

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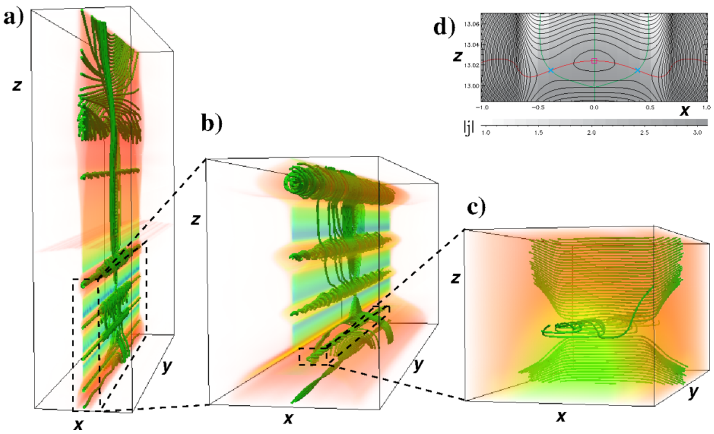

Fig. 1: *Consecutive zoom from (a) to (c) shows the cascade of plasmoid formation. (d) The smaller plasmoids are formed also in the interaction layer between two merging larger-scale plasmoids.*

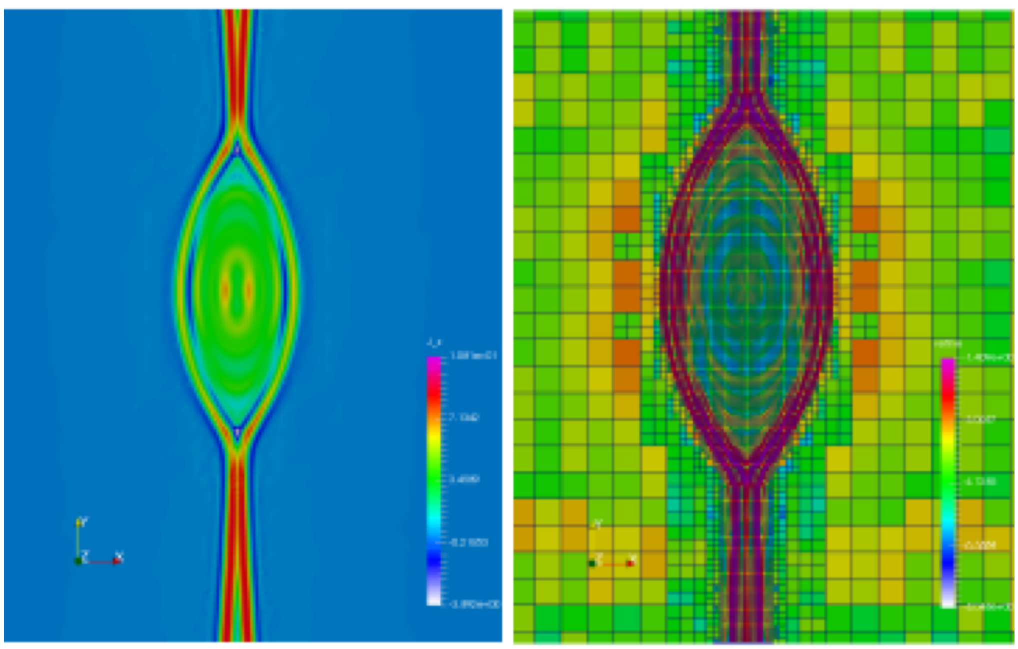

Fig. 2*: Left: Onion-like structure of the electric current in a cross-section of a plasmoid. The layers record the history of reconnection rate similarly as the tree-rings record warm and cold years. Such a detailed view on small structures is possible thanks to advanced FEM simulations whose mesh (and load-balanced distribution to supercomputer CPUs) is shown in the right part.*