Does the flap of a magnetic butterfly's wings in Berlin set off a coronal mass ejection in the sun?

Topology-driven three-dimensional magnetic reconnection

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In Short

- Magnetic reconnection is a process through which magnetic field lines are cut and reconnected in small regions of space, leading to changes in the large scale magnetic field structure.
- This process is often studied in simplified two dimensional models, which cannot explain the rapidity of magnetic reconnection as observed in space.
- We consider a purely three-dimensional model which could explain fast reconnection. It is based on the idea that in three dimensions, magnetic field lines can become highly entangled, i.e. field lines that are far apart from each other at some point can come exponentially close to each other at another.
- When magnetic field lines come exponentially close to each other, even a small flap of a magnetic butterfly (i.e. a small displacement of the magnetic field line) can lead to magnetic reconnection.

In our everyday life, we usually encounter matter in a liquid, solid or gaseous state. This is, however, not the case for most of the matter in the universe. Most of the visible matter is in the so-called "plasma state", which is a quasi-neutral gas consisting of ions and free electrons. It affects and is affected by electromagnetic fields, leading to complex dynamics. It can be described as a single electrically conducting fluid in the framework of magnetohydrodynamics (MHD). In the limit of infinite electrical conductivity (the so-called "ideal" case), Alfvén's theorem in combination with Walén's theorem states that magnetic field lines are "frozen" into the plasma, so that they retain their identity. This means that even though plasma motion can bring the magnetic field lines into more and more convoluted shapes, the magnetic fields lines cannot be cut and change their connection: two points connected at a certain time by a certain line will always remain connected by that same line. In reality, plasmas exhibit some electrical resistivity, and in this "non-ideal" case magnetic field lines can undergo reconnection.

This happens in astrophysical plasmas and leads to spectacular phenomena. Solar flares and coronal mass ejections, big eruptions on the Sun's surface, are believed to be caused by magnetic reconnection. Also the auroras observed in the sky are consequences of magnetic reconnection: particles from the Sun carried by the solar wind enter the high atmosphere as the solar wind's magnetic field lines reconnect with those of the magnetosphere. They excite molecules in the high atmosphere, which emit light when they de-excite.

The first model of magnetic reconnection has been proposed in the 1950s by Sweet and Parker. It is a two-dimensional model which considers oppositely directed magnetic field lines flowing towards each other and reconnecting in a region with high resistivity. Even though this model allowed great progress in understanding, it could not explain the speed of the phenomena observed, for example at the Sun's surface. Two-dimensional magnetic reconnection has been very actively studied and is now rather well understood. For reasons of simplicity, a lot of reconnection models are still effectively two-dimensional, where for example a symmetry is assumed in a certain direction for three-dimensional problems. These effectively 2D models are however still not able to explain the observed fast reconnection.

This is why purely 3D models of magnetic reconnection have begun to appear in the late 1990s. Several seem promising to explain fast reconnection, e.g. models based on the topology of the magnetic field [1] or on the influence of turbulence [2]. We investigate the former, which considers the natural tendency of 3D magnetic field lines to "exponentiate" apart or together. Contrary to the 2D case, magnetic field lines in 3D indeed tend to come closer or go further away from each other in an exponential way, as a consequence of Maxwell's equations. This means that magnetic field lines very distant at one location in e.g. the Sun, could be so close to one another at another location that they would be indistinguishable on the scale of an electron's motion. In this case even a tiny disturbance caused by a very low resistivity, a "magnetic butterfly's wing flapping", could rapidly break their connection and trigger magnetic reconnection, leading to a new configuration of magnetic field lines on a large scale, a release of kinetic energy and a solar eruption.

We study this model using a numerical experiment described in [1]. A plasma with a mean magnetic field in the z-direction is located between two per-

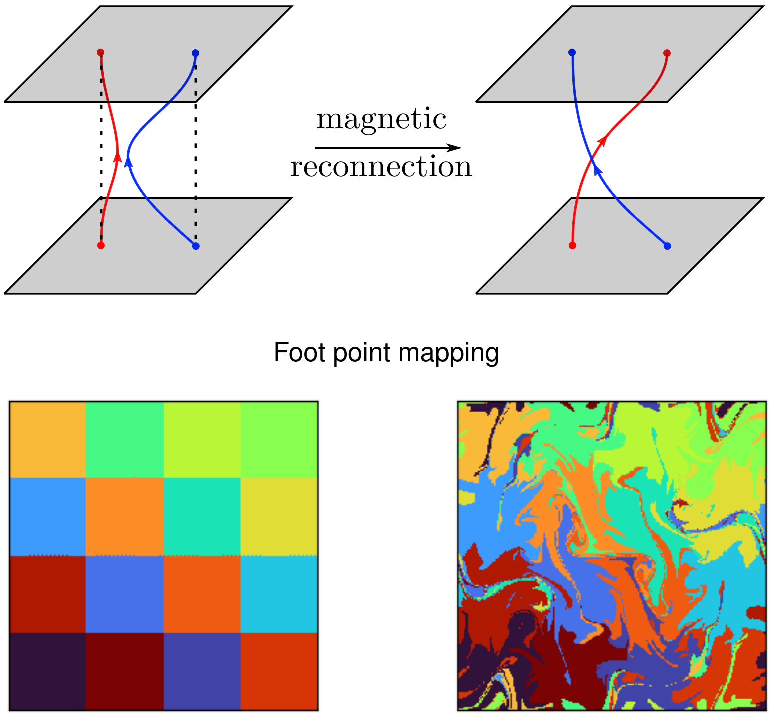

Figure 1: *Top: Schematic figure of the numerical experiment: magnetic field lines begin and end at two perfectly conducting plates, at which the field lines' foot points are fixed. Magnetic reconnection leads to a change in the foot point mapping. Bottom: The foot point mapping is visualized with a checkerboard pattern. Without reconnection the foot point mapping is unchanged and the checkerboard pattern is preserved (left). Once reconnection occurs, the mapping changes as visualized by the distortion of the pattern.*

fectly conducting plates at $z = 0$ and $z = z_{max}$, which keep the foot points of the magnetic field lines in place. The fluid is stirred in order to entangle the magnetic field lines. Initially, the system settles into a quasi-equilibrium state, which is disrupted as the magnetic field lines reconnect due to tiny disturbances. The occurence of reconnection is visible through the change of the footpoint mapping from the top to the bottom conducting plate, see figure 1. By measuring various quantities, such as the degree of entanglement and the reconnection rate, we can investigate whether a high entanglement can indeed act as a mechanism for magnetic reconnection.

In this project, we aim to perform several experiments using different parameters, for example varying the resistivity of the system (the strength of the "butterfly's flapping"). By comparing our results to what one would expect for fast reconnection observed in space, we aim at shedding some light on the ability of this topological model to explain reality.

WWW

https://www-astro.physik.tu-berlin.de/de/node/340

More Information

[1] A. H. Boozer, *Physics of Plasmas* **20**, 2013.

[2] A. Lazarian, G. L. Eyink, A. Jafari, G. Kowal, H. Li, S. Xu and E. T. Vishniac *Physics of Plasmas* **27**, 2020.

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