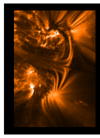
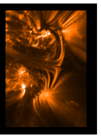


Topological Studies of Solar Magnetic Fields



Mark Cheung[1], Kevin Yang[1,2] & Marc DeRosa[1]

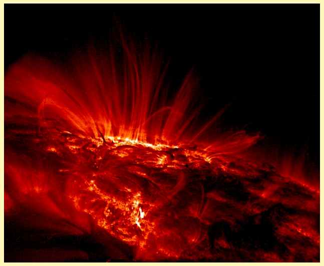
1. Lockheed Martin Solar and Astrophysics Laboratory 2. Gunn High School, Palo Alto

Abstract

The dynamics of the solar atmosphere is primarily driven by the evolution of intense magnetic field structures that pervade the atmospheric layers. Abrupt changes in solar magnetic fields are responsible for energetic phenomena such as solar flares and coronal mass ejections, some of which have consequences for space weather. In order to study how magnetic fields in the solar atmosphere evolve in response to the eruption of magnetic flux from the solar convection zone as well as to horizontal plasma motions, we have carried out a series of 3D simulations of different magnetic field configurations. In these simulations, neighboring magnetic field lines that are not aligned with each other reconnect, thereby changing the topology of the magnetic field and facilitating the release of stored magnetic energy.

Introduction

- The solar atmosphere is pervaded by strong magnetic fields.
- The evolution of magnetic fields threading ionized plasma is well-described by the magnetohydrodynamics (MHD) approximation, which combines the fluid equations with Maxwell's equations. In the ideal MHD limit (i.e. no magnetic diffusion), magnetic field lines are advected by plasma flows and the magnetic field exerts its influence on the plasma by means of the Lorentz force.



Above: Extra-Ultra-Violet (EUV) image of magnetic loops in the solar corona taken by NASA's Transition Region And Coronal Explorer (TRACE).

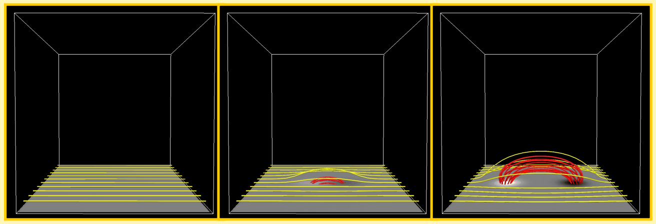
- At interfaces between magnetic sub-volumes, large gradients in the magnetic field (accompanied by large electric current densities and magnetic diffusion) allow neighbouring magnetic field lines to reconnect. This so-called magnetic reconnection changes the topological properties of the magnetic field and allows the magnetic field to relax to lower energy states. The magnetic energy released in the process is widely believed to be responsible for solar flares and coronal mass ejections.

Evolving magnetic active regions

To study how bundles of magnetic field lines emerging into the solar atmosphere interact with pre-existing field, we carried out a series of MHD simulations whereby a semi-torus of magnetic flux is pushed into a domain with a uniform background field.

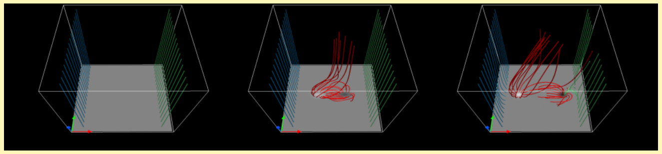
The system evolves by means of magnetofriction, which assumes that the plasma velocity is everywhere proportional and parallel to the local Lorentz force. A consequence of this assumption is that absent of external driving, the magnetic field contained within the volume relaxes towards a force-free state while the volume-integrated magnetic energy decreases monotonically with time.

These simulations were carried out on the Pleiades cluster at NASA Ames Research Center with a finite difference code written in Fortran 90. The Message Passing Interface (MPI) was used to parallelize the code by means of domain decomposition.



Above: Emergence of a magnetic bundle (from the photosphere) into a pre-existing horizontal coronal field. In this case, the two magnetic systems are aligned such that magnetic reconnection does not occur and the topology is preserved.

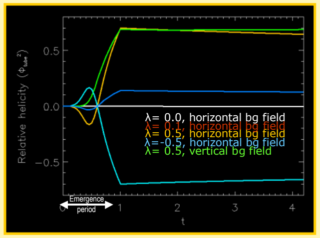
Change of magnetic topology from magnetic reconnection



Above: Emergence of a magnetic bundle into vertical background field (red is flux tube, blue and green are the vertical ambient field).

- The initial ambient coronal field is uniform and in the vertical direction.
- The toroidal field of the emerging tube is misaligned with the ambient field.
- Magnetic reconnection occurs, changing the magnetic connectivity of the system.
- The change in topology allows the magnetic field to relax to a lower energy state.

Evolution of magnetic helicity



Gauge-invariant definition of magnetic helicity (Berger & Field 1984; Finn & Antonsen 1985) :

$$H_{\rm rel} = \int (\vec{A} + \vec{A}_p) \cdot (\vec{B} - \vec{P}) dV$$

(A,B) <-> actual field configuration with ***curl A = B***

(***A_p,P***) <-> magnetic field satisfying the imposed normal field ***B_n*** at all boundaries such that ***curl B = 0*** (also called the potential field since ***B = grad F***)

Above: Time evolution of H_{rel} for different levels of twist. Helicity decays slowly after the initial emergence phase (t <1).

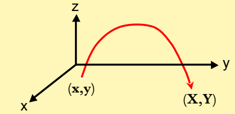
Magnetic helicity is a measure of the amount of twist and free energy of the system. The initial coronal magnetic field in the simulations has zero helicity but the helicity increases with the emergence of twisted magnetic flux bundles. Magnetic reconnection allows the system to reach lower energy states while keeping magnetic helicity approximately conserved.

To calculate ***A_p*** and ***P*** and therefore H_{rel}, we need to solve Laplace's equation (***ΔF = 0***) over the cartesian domain. The approach used to solve Laplace's equation involves performing a large number of Fast Fourier Transforms. For this particular series of MHD simulations, 256x256 (Nx times Ny) FFTs must be performed 640 times (Nz times 5) for each snapshot in order to calculate these quantities. Using IDL on a Linux machine with an Intel 3 GHz Core Duo CPU (with multithreaded FFTs), each compution of ***A_p*** and ***P*** takes 3.6 seconds. Using NVIDIA's Tesla C1060 GPU and the CUFFT routines, the same computation takes 0.3 seconds, which corresponds to a 12x speed-up. For a problem with twice the number of grid cells in each cartesian direction (translating to 512x512 FFTs performed 1280 times), the GPU speed-up is ~30x (59 seconds on the CPU compared to 2 seconds on the Tesla).

Magnetic Field Line Connectivity Maps

To determine the different domains of magnetic connectivity

- we traced fields lines from each position at the bottom boundary, which gives the mapping (x,y)->(X,Y) and the associated Jacobian matrix *J*.

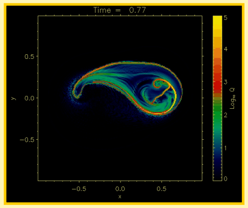


$$J = \begin{bmatrix} a & b \\ c & d \end{bmatrix} = \begin{bmatrix} \frac{\partial X}{\partial x} & \frac{\partial X}{\partial y} \\ \frac{\partial Y}{\partial x} & \frac{\partial Y}{\partial y} \end{bmatrix}$$

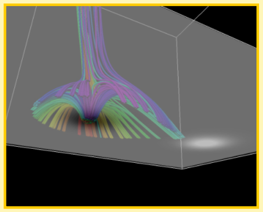
The Squashing Factor Q (Titov, Demoulin & Hornig 1999; Titov & Hornig 2002; Titov, Hornig & Demoulin 2002) is defined as:

$$Q = \frac{a^2 + b^2 + c^2 + d^2}{|ad - bc|}$$

In essence, large values of Q correspond to locations at the photosphere (bottom boundary) where neighbouring field lines map to conjugate locations that are far apart.



Above: Q as function of (x,y) at z=0 for the simultion of a twisted bundle reconnecting with the background vertical field during emergence.



Above: Field lines traced from points with large Q values envelope a coronal null point, which is a favourable location for magnetic reconnection to occur.

To calculate maps of the Q distribution, 512^2 field lines were traced for each snapshot. To accelerate these computations, we wrote CUDA kernels such that each thread performs a single field-line integration. The C routines of libtricubic (Lekien & Coulliette 2003) were also adapted into CUDA kernels to allow for tricubic interpolation of the magnetic field values inside gridcells. Using NVIDIA's Tesla C1060 GPU with 240 cores gave a 40x speed-up (6 mins vs 4 hours) compared using to IDL on a Linux machine with an Intel 3 GHz Core Duo CPU.

References

- *Berger, Geophys. and Astrophys.Fluid Dynamics, vol. 30, p. 79-104, 1984.*
- *Berger & Field, J. of Fluid Mech., 147, 133-148, 1984.*
- *Finn & Antonsen, Comments on Plasma Physics and Controlled Fusion, vol. 9, 3, pp. 111-126, 1985.*
- *Lekien & Coulliette 2003, http://www.lekien.com/~francois/software/tricubic/*
- *Titov, Demoulin & Hornig, 9th European Meeting on Solar Physics, ESA SP-448, 1999.*
- *Titov & Hornig, Advances in Space Research, Volume 29, Issue 7, p. 1087-1092, 2002.*
- *Titov, Hornig & Demouin, J. of Geophysical Research, vol 107, A8, pp. SSH 3-1, 2002.*

Acknowledgements

This work is supported by grant NNX08BB02G of NASA's Living With a Star Targeted Research & Technology program. K. Yang is a Gunn High School senior working as an intern at LMSAL.