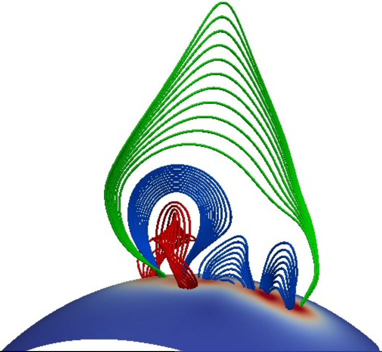
MHD model of the lift-off of magnetic flux ropes

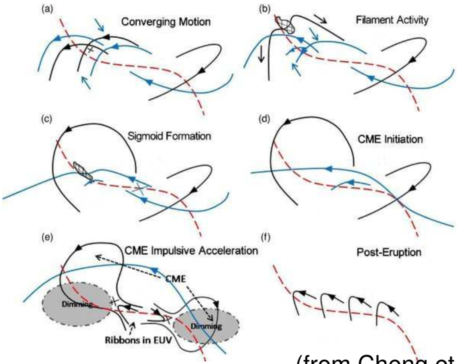
P. Pagano, D.H. Mackay
University of St Andrews
S. Poedts
KU Leuven



Eruption of Flux ropes

Flux-rope eruptions are the main progenitors of CMEs.
The eruption often consists of two phases:

- Formation of flux rope: accumulation of magnetic energy
- Flux rope eruption: release of energy



(from Cheng et al., 2010)

Goals

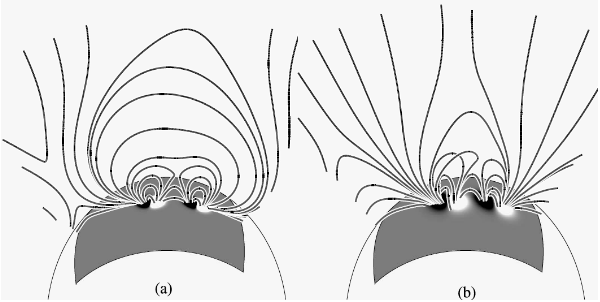
- bridging the build-up of the flux rope with the eruption
- model the dynamics of the eruption accounting for plasma effect

Method

We couple a Magnetofrictional model, suitable for the flux rope formation phase, with full MHD simulation suitable for the eruption phase.

Magnetofrictional MHD

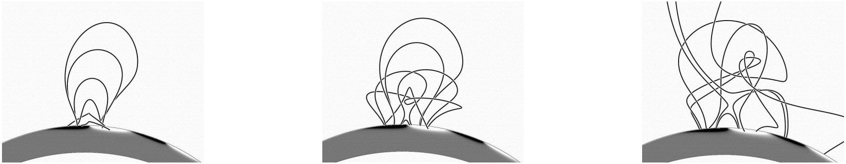
We model the slow evolution of the coronal field by means of a Magnetofrictional model (Mackay and van Ballegooijen, 2006)
Starting from a simple configuration that have two bipoles in the domain.
The evolution of the bipoles produces flux ropes.



Open questions

Eventually, in the MF simulation, the flux rope erupts, however:

- The time scales of the eruption are not realistic
- The role of Alfvén waves was neglected by the technique used



Coupling the models: complete the set of variables

Magnetofrictional Model variables $\Longrightarrow$

Induction Equation and velocity prescription

$\vec{v}$, $\vec{B}$

$\Longleftarrow$ MHD Simulation

MHD Equations

ρ, $\vec{v}$, p, $\vec{B}$

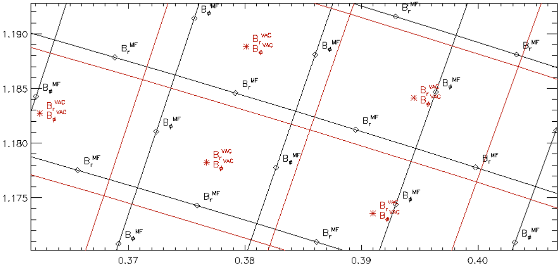
We assume that:

$\rho = \rho_0 \frac{B^2}{B_0^2} + \rho_{background}$

$p = cost$

$\vec{v} = 0$

Coupling the models: interpolate variables



Second-order 3D interpolation in spherical coordinates between two grids:

- Different number of points: $181 \times 176 \times 106 \longrightarrow 128 \times 128 \times 132$
- Different Spacing
- ”Face cell values” to ”Center cell values”

MHD Simulation

We model the evolution from a state of the MF by means of MHD Simulations: AMRVAC

MHD

$$\frac{\partial \rho}{\partial t} = -\vec{\nabla} \cdot (\rho \vec{v}) \tag{1}$$

$$\frac{\partial \rho \vec{v}}{\partial t} + \vec{\nabla} \cdot (\rho \vec{v} \vec{v}) = -\nabla p + \frac{(\vec{\nabla} \times \vec{B}) \times \vec{B}}{4\pi} \tag{2}$$

$$\frac{\partial \vec{B}}{\partial t} = \vec{\nabla} \times (\vec{v} \times \vec{B}) \tag{3}$$

$$\frac{\partial u}{\partial t} + \vec{\nabla} \cdot [(u + p)\vec{v}] = 0 \tag{4}$$

$$\nabla \cdot \vec{B} = 0 \tag{5}$$

$$u = \frac{1}{2}\rho v^2 + E \tag{6}$$

$$p = (\gamma - 1)E \tag{7}$$

Simulation

Simulation

- $128 \times 128 \times 128$ points
- fixed grid
- spherical geometry
- $\vec{B} = \vec{B}_0 + \vec{B}_1$

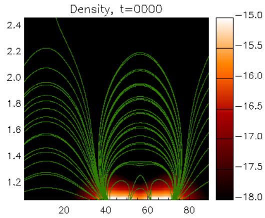
Domain

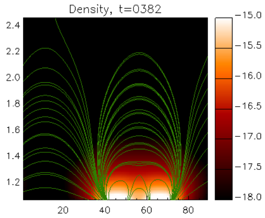
- nearly one octant of a sphere
- 1.5 $R_\odot$ tall

Boundary condition

- Fixed photosphere
- open outer corona
- periodic over ϕ
- no flux across θ boundaries

Equilibrium Test





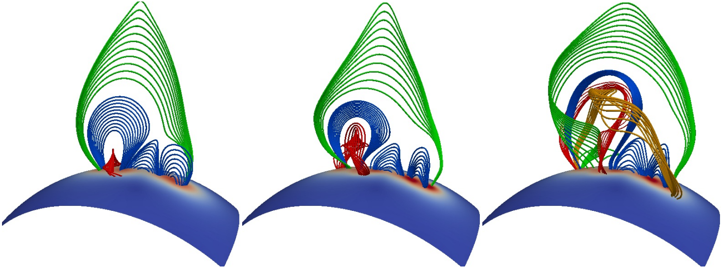
Initial Condition

- Force free field: two bipoles, $\vec{j} = 0$.

Evolution

- No change in the structure of the fields.
- Some slight change in density.
- Solution is static for more than 30 Alfvén crossing time over the whole domain

Eruption Simulation, Day 19: magnetic evolution



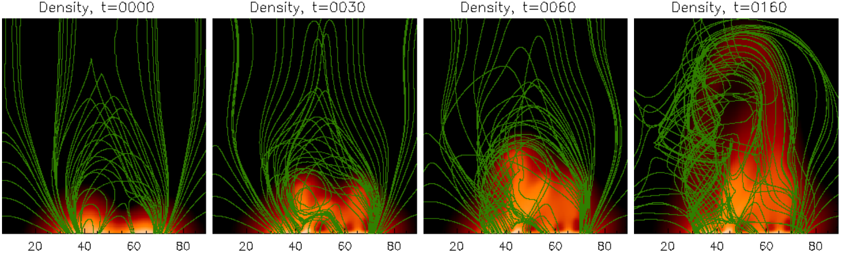
Initial Condition

- Day 19: pre-eruption configuration

Evolution

- The flux rope lifts due to Lorentz force initially direct upwards
- The flux rope fragments in two
- Full eruption takes place at, $\sim 100\ km/s$

Eruption Simulation, Day 19: plasma evolution



evolution

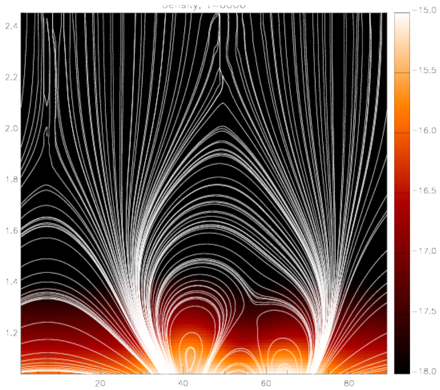
- Plasma is ejected outwards by the eruption
- The matter is better pushed where the field is twisted and the motion is perpendicular to $\vec{B}$
- A density front expands and follows the full eruption
- A dense structure is formed up in the corona and finds a stable position

Conclusions

- Eruption is triggered by the initial conditions
- The evolution takes place in $\sim$ hours ($\sim$ Alfvén time).
- The coupling of the Magneto-Frictional model with MHD simulation seems a promising tool.

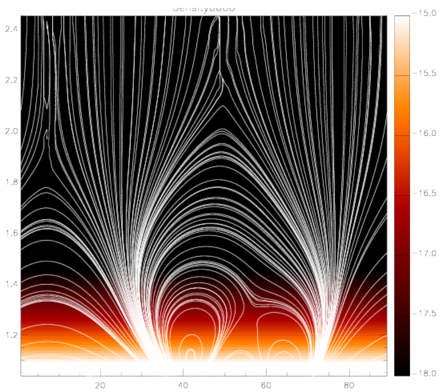
Future development

$$\rho = \rho_0 \frac{B^2}{B_0^2} + \rho_{background} + \rho_1 e^{\frac{\lambda}{r}}$$



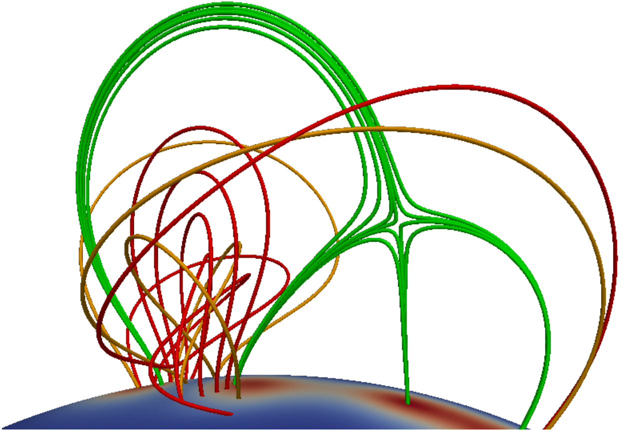
- Stratified atmosphere

Future development



- Add gravity in the model

Future development



- More developed initial condisitons: Day 21