3D MHD simulations to model solar eruptive events

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- Modeling solar eruptions
- Recent results on solar jets and coronal mass ejection
- Scientific and computational prospective
Energy release through magnetic reconnection:

- Plasma heating and particle acceleration
- Magnetic reconfiguration
Understanding the causes of the eruptive activity e.g. the physical mechanisms triggering the eruptions

& the consequences: dynamics of the CME, bright ribbons, energetic particles

Modeling solar eruptions

Simulations

Constrain

Compare/interpret

Observations
Modeling solar eruptions

- Magneto-hydrodynamic formalism

  large scale modeling ( >1s and > 1m)
  no treatment of the particles
  auto-consistent simulations of solar eruptions

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{u}) = 0
\]
\[
\frac{\partial T}{\partial t} = -(\vec{u} \cdot \nabla)T - (\gamma - 1)T \left( \nabla \cdot \vec{u} \right)
\]
\[
\frac{\partial \rho \vec{u}}{\partial t} = -\nabla \left( \rho \vec{u} \cdot \vec{u} \right) - \nabla P + \mu^{-1} \left( \nabla \times \vec{B} \right) \times \vec{B} + \rho \vec{g}
\]
\[
\frac{\partial \vec{B}}{\partial t} - \nabla \times \left( \vec{u} \times \vec{B} \right) = 0
\]

- The solar corona

  - Ionized plasma \( n \approx 10^{14-16} \text{ m}^{-3} \) (Hydrogen, Helium & heavy ions)
  - Magnetized plasma: active regions with strong magnetic field \( \sim 1000 \text{ G} \)
    \[ \beta = \frac{P_{\text{kin}}}{P_{\text{mag}}} \ll 1 \] : structured by the magnetic field

  - Small electric resistivity \( R_m >> 1 \): Reconnection develops at small scales

Eclipse August 2017
Modeling solar eruptions

- Scale challenges

Reconnection site ~ m to the size of the CME ~ Rs

Reconnection timescale ~ seconds to CME propagation ~ hours (CME)
### 3D MHD Codes @ LESIA

#### ARMS Code
- DeVore 1991; DeVore & Antiochos, 2008
- Cartesian and spherical
- Flux Corrected Transport algorithm: strong gradients resolution (e.g. shock capture)
- \( \text{div} B = 0 \) => No Data-driven

#### OHM-MPI Code
- Aulanier et al., 2005
- Collaboration with the LUTH
- Cartesian
- high order scheme for derivatives
- Diffusive term to ensure the code stability
- \( \text{div} B \neq 0 \) => Data driven

<table>
<thead>
<tr>
<th>Adaptive Mesh refinement</th>
<th>Numerical resistivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Small &amp; Large scale MHD simulation</td>
<td></td>
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<tr>
<td>- No limitation of the size and resolution of the system</td>
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<td>- Structures at small scale (e.g. magnetic island)</td>
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<table>
<thead>
<tr>
<th>Non-uniform mesh</th>
<th>Physical resistivity</th>
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<tr>
<td>- Small scale (active region) MHD simulation</td>
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<tr>
<td>- structures at small scale: increase the spatial resolution (in progress)</td>
<td></td>
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<tr>
<td>- Control of each diffusive term</td>
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Choose the most appropriate code !!
Destabilize the system

Apply slow flows at the solar surface

line-tying $\Rightarrow$ inject magnetic stress and energy

Dynamics of the solar eruption

Current sheet formation

Magnetic reconnection: change of field lines connectivity
- Modeling solar eruptions
- Recent results on solar jets and coronal mass ejection
- Scientific and computational prospective
3D MHD simulations of solar eruptions

• Effect of the plasma-\(\beta\) on solar jet properties (ARMS)


• Solar jet model: magnetic reconnection between closed & twisted field and open field.

• Jets are observed over a broad spatial range:
  - small scale chromospheric jets
  - large scale coronal jets

Varying the plasma-\(\beta\) to interpret the observations of the observed jet-like events:

Common property: Helicoidal structures
3D MHD simulations of solar eruptions

• Effect of the plasma-\(\beta\) on solar jet properties (ARMS)

3D MHD simulations of solar eruptions

- Effect of the plasma-$\beta$ on solar jet properties (ARMS)

**Chromospheric-like jets**

**Bulk flow**

**Density**

**Vertical speed**

**Lorentz force**

**One flow**

$v_{\text{flow}} < C_A = 0.26$

**Magnetically driven**

3D MHD simulations of solar eruptions

• Effect of the plasma-\( \beta \) on solar jet properties (ARMS)

**chromospheric-like jets**
- Bulk flow
- One flow
  - \( v_{\text{flow}} < C_A \)
  - Magnetically driven

**coronal-like jets**
- Fast untwisting Alfvén waves
- + Slow bulk flow

• Triggering mechanism of coronal mass ejections (OHM-MPI)

Torus instability = When the filament reaches the height at which the external B field decreases $\propto R^{-n}$

Does the critical decay index vary with respect to the property in the filament?


Apply 4 different photospheric forcing => Build up the filament with different properties

- convergence
- stretching
- outer dispersal
- full dispersal

3D MHD simulations of solar eruptions
3D MHD simulations of solar eruptions

- Triggering mechanism of coronal mass ejections (OHM-MPI)

To determine the onset of the eruption: Stop the forcing earlier

Flux rope axis reaches the height \((nc = 1.5)\)

\(\Rightarrow\) erupts

4 different forcing:

The critical index \(\sim 1.4 - 1.5\)

Universal condition for eruptivity

3D MHD simulations of solar eruptions

- CME eruption into a more realistic environment (ARMS)

**Large scale background B field:**
- Magnetic dipole at the Sun center + Isothermal solar wind
  - Define the open/closed field domain

**Dipolar active region**
- More realistic – large scale magnetic configuration

**Realistic atmosphere:**

- \(\beta \ll 1\)
- \(\beta \approx 1\)
- \(V_{SW}^{max} = 420 \text{ km s}^{-1}\)
• CME eruption into a more realistic environment (ARMS)  

Magnetic reconnection with the surrounding field

• At least 4 reconnection sites/episodes versus 1 in the small scale simulation.
  → corona reconfiguration
  → particle acceleration

• Coupling the filament and the open IMF
  → Injection of particles into the IMF
3D MHD simulations of solar eruptions

• CME eruption into a more realistic environment (ARMS)

Masson, DeVore & Antiochos, submitted

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Fast auto-consistent filament eruption into an interplanetary field structured by the solar wind
- Modeling solar eruptions

- Recent results on solar jets and coronal mass ejection

- Scientific and computational prospectives
Scientific & computational prospectives

• Going to smaller scales

3D MHD simulations: reproduce the global dynamics of the eruption, but it is too slow compared to the reality

Include some small scale MHD processes!!

- Multi-reconnection sites in the current sheet
- Petscheck reconnection regime

Reconnection rate increase

• Plasmoids’ role in reconnection and flares

Plasmoids in simulation (ARMS)

How do islands form and evolve in 3D flare current sheet?

How does it affect the eruption characteristic (dynamics radiative signatures,...)?
• Increase the spatial and temporal resolution

To identify magnetic islands and study their dynamics

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<td>non-uniform mesh</td>
<td>Using the adaptive mesh refinement</td>
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<td>~8 GB / output file (1 vector)</td>
<td>~3 GB / output file (3 vectors &amp; 4 scalar)</td>
</tr>
<tr>
<td>+ output files every ( t &lt; t_A ) over a long period of time (&gt;20 tA)</td>
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• **OHM-MPI allows us to control the resistivity in the system ≠ ARMS has a numerical resistivity**

  → **OHM-MPI needs a fine-tuning of parameters during the simulation**

  → **test several parameters within a day : need to decrease the time spending in the queue**

• Use ‘homemade’ softs tailored to analyse solar eruption simulations :

  **Size of high resolution runs → Difficult to analyse the results locally**

  **Help to parallelize & export the visualisation softs to analyse the results on clusters**
Scientific & computational prospectives

• Including particles

How those particles are accelerated during the eruptions?

precipitate toward the solar surface → EUV bright ribbons / X-rays

Compare the radiative signature with simulations including particles → new constrain on the model

Test particles in a dynamic B resulting from 3D MHD simulation → Shape & dynamics of the radiative signatures

Masson et al., 2009

Large scale simulations (ARMS)

Developp the particle code

Run the MHD & the particle codes in parallel

Rosdahl & Galsgaard, 2010