MHD modeling the heating of a twisted coronal loop

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Outline

• Introduction: coronal loop issues
• Loop modeling
• 3D MHD loop modeling:
  – Uniform resistivity: monolithic loops
  – Switch-on resistivity: structured loops
Solar corona
Coronal loops
Coronal loops issues

- Out-of-equilibrium (e.g. overdensity)
- Multi-thermal structure
- Fine structure
- Flows
- Hot plasma (6-8 MK)
- Dynamic heating? Heating frequency?

Warren et al 2011
Dynamic heating? Very hot plasma (6-8 MK) in non-flaring active region cores

(pink, e.g. Reale+ 2011, Testa & Reale 2012, Petralia+ 2014)
Loop modeling

- Plasma confined in flux tubes moves and transports energy along the magnetic field lines
- Hydrodynamic modeling w/ empirical heating function
- Flares, loop ignition

Peres et al. 1987
Reale et al. 2000
Next step: Multi-strand loop modeling

- Random combination of single loop outputs

Warren+ 2002

Warren+ 2003
Next step: Multi-strand loop modeling

- Random combination of single strand evolution to reconstruct spatial aspect
Toward self-consistent loop modeling

• 3D MHD numerical experiments
  – nonlinear phase of an ideal kink instability, where magnetic reconnection leads to relaxation to a state of minimum magnetic energy (e.g. Hood+ 2009).
  – self-consistent heating mechanism based on the braiding of magnetic field lines rooted in the convective photosphere (e.g. Bingert & Peter 2011).
Twisting
(e.g. Depontieu+, Science, 2014)
MHD modeling of twisted coronal loops

- Progressive twisting of coronal loop field lines
- Driven by rotation of footpoints (Rosner+ 1978, Golub+ 1980)

Rosner, Golub, Coppi, Vaiana 1978
Rationale

- Extension of hydrodynamic loop modeling to MHD loop modeling:
  - magnetic field to release energy, change of beta, non-uniform (expanding) field
  - Include chromosphere and TR
- Towards self-consistent modeling
- Keep it simple:
  - Magnetic twisting (not random braiding)
  - Simple resistivity
- Targets:
  - Typical loop structure
  - Dynamic heating
  - Fine structure
HPC PRACE project

(PRACE n°2011050755)
The way to heating the solar corona: finely-resolved twisting of magnetic loops

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Simulations: 3D MHD (resistivity; thermal cond.; radiative cooling; gravity)

Numerical code: PLUTO 4 (Mignone+ 2007)

Resources: ~ 31 Mhours on BlueGene/P FERMI/CINECA (storage ~ 10 TB)

Project schedule: October 2012/April 2013+Fall 2013
Initial conditions
The 3D MHD model

Three-dimensional cylindrical coordinates: $r$, $\phi$, $z$

One quarter domain: $0 < \phi < \pi/2$, $r_0 = 0.07 \times 10^9$ cm

The equations:

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho u) = 0 ,
\]

\[
\frac{\partial \rho u}{\partial t} + \nabla \cdot (\rho uu - BB + IP_t) = \rho g ,
\]

\[
\frac{\partial \rho E}{\partial t} + \nabla \cdot [u(\rho E + P_t) - B(u \cdot B)] =
\]

\[
- \nabla \cdot [(\eta \cdot J) \times B] + \rho u \cdot g - \nabla \cdot F_c - n_e n_H \Lambda(T)
\]

\[
\frac{\partial B}{\partial t} + \nabla \cdot (uB - Bu) = -\nabla \times (\eta \cdot J) ,
\]

where

\[
P_t = P + \frac{B \cdot B}{2} ,
\]

\[
E = \epsilon + \frac{u \cdot u}{2} + \frac{B \cdot B}{2\rho} ,
\]

\[
F_c = \frac{F_{sat}}{F_{sat} + |F_{class}|} F_{class}
\]
Initial atmosphere (Guarrasi+ 2014)

- **Loop atmosphere:**
  - Hydrostatic: gravity of a curved loop
  - Tenuous and cool:
    - $2L = 5 \times 10^9$ cm
    - $T_0 = 7 \times 10^5$ K
    - $n_0 = 10^8$ cm$^{-3}$
  - Background heating in the corona

- **Magnetic field:**
  - Loop expansion in the TR
  - $B \sim 10$ G in the corona ($B \sim 300$ G in the chromosphere close to the central axis)

- Relaxed to equilibrium before twisting is switched on
The chromosphere

- Simplified:
  - Isothermal: $T = 10^4 \text{ K}$
  - Gravitationally stratified
  - No heating, no radiative losses
- No resistivity at all times
Two main simulations

- Uniform anomalous resistivity, smooth footpoint rotation
- Switch-on resistivity, perturbed footpoint rotation
Uniform anomalous resistivity

- **Anomalous resistivity** (Bingert & Peter 2011):
  - $\eta = 10^{13}$ cm$^2$/s
  - $R_m = v L/\eta \sim 1$ for $v \sim 10$ km/s, $L \sim 100$ km
  - Chromosphere: $\eta = 0$
The smooth twisting (red line)

- **Footpoint rotation (z-boundaries):**
  - Profile: constant angular speed $\omega$
  - Maximum: 5 km/s (both footpoints)
  - Radius: $r = 3000$ km
  - Linear reduction:
    $\omega \rightarrow 0$: $3000 < r < 6000$ km

- B-field dragged by footpoint rotation ($\beta \gg 1$): twisting!

- The twisting begins at $t=0$
Uniform resistivity

- The domain is one quarter of the whole space: $0 < \phi < \pi/2$

- Non-uniform (fixed) grid: maximum resolution $\sim 20$ km (in TR)

- Box: $[r, \phi, z] = [384, 256, 768]$ pts

- Time: $t = 0 – 2600$ s
- Twisting: $\sim 2 \pi$

- CPU time: 5 million hours
Basic modeling: uniform resistivity

- Cross-section+field lines
- Temperature rises uniformly
- Density from the chromosphere
- Uniform monolithic structure
Uniform resistivity: Loop evolution along $z$

- Spaced every 200 s
- From blue ($t=0$) to red ($t=1800$ s)
- Gradual heating, gradual evolution
- Moderate evaporation speed
Uniform resistivity: Max T, DEM, Heating
Uniform resistivity

• Loop heating
• Multi-thermal
• Slow flows
• No fine structure
• No hot plasma
Switch-on resistivity

• “Switch-on” anomalous resistivity (Hood+ 2009, eq.7):
  - $\eta = 0$ for $J < J_{cr}$
  - $\eta = 10^{14}$ cm$^2$/s for $J > J_{cr}$
  - Threshold:
    - $J_{cr} = 75$ A/cm$^2 = 3.16 \times 10^{-8}$ esu cm$^{-2}$ s$^{-1}$
      (from test simulations)
  - Minimum heating:
    - $H = \eta J_{cr}^2 \approx 10^{-2}$ erg cm$^{-3}$ s$^{-1}$
  - Chromosphere: $\eta = 0$
The perturbed twisting (black line)

- **Footpoint rotation (z-boundaries):**
  - Profile: constant angular speed $\omega$
  - Maximum: 5 km/s (both footpoints)
  - Radius: $r = 3000$ km
  - Linear reduction:
    $\omega \to 0$: $3000 < r < 6000$ km
  - **RANDOMLY PERTURBED VELOCITY AT THE FOOTPOINTS**
The main simulation

- Non-uniform (fixed) grid: maximum resolution ~ 20 km (in TR)

- Box: \([r, \phi, z]=[384, 256, 768]\) pts

- Time: \(t = 0 \rightarrow 1870\) s
- Twisting: \(\sim 1.5\ \pi\)

- CPU time: 5 million hours, 32000 cores
Current density (+ field lines)

- Only above threshold shown, i.e. heating marker
- The blue surface is the boundary where the density is $10^9$ cm$^{-3}$
- Most current sheets:
  - Close to axis
  - Close to footpoints
  - Lasting few frames: <1 min
Temperature [MK] (+ field lines)

- Max T ~ 4 MK
- Fine structure
Density
(+ field lines)

- Units: $10^9$ cm$^{-3}$
- Evaporation along field lines
Loop evolution along z

- Spaced every 200 s
- From blue (t=0) to red (t=1800 s)
The maximum temperature shows a "turbulent" evolution.

Temperature vs time

Max T

Avg T (>1 MK)
Heating rate vs time

Maximum rate

Average rate

Total energy (integrated over 10 s bins)

Total heated volume

12/05/15 ISSI workshop
Total loop DEM

![Graph showing Log EM vs Log Temperature at time = 220 s.](image)
MHD loop modeling

Uniform resistivity
- Loop heating
- Multi-thermal
- Slow flows
- No fine structure
- No hot plasma

Switch-on resistivity
- Loop heating
- Multi-thermal
- Faster flows
- Fine structure
- Hot plasma
- Good as DEM/spectral diagnostics testing ground
Issues

- *Twisting and resistivity* -> typical loop evolution, including evaporation
- *Perturbed rotation* -> fine structure
- *Switch-on resistivity* -> hot component
- *Status* -> Paper I (uniform resistivity) to be submitted, Paper II in preparation
- *For diagnostics* -> density, temperature 3D map at $t = 1800$ s -> *you know the 3D truth, but not a trivial one*