Evolution of the magnetic topology due to reconnection in a 3D MHD corona above an active region
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Overview:
* Time-evolution of magnetic field (and plasma bulk motion)
* Reconnection in the corona (and photospheric flux emergence)
* Electric fields in an MHD model...?
* Proton and Electron acceleration from electric fields in the corona
Coronal 3D MHD model

Observationally driven forward model ("field-line braiding"):

- Photospheric granulation advects small-scale magnetic fields
- Stress is induced into the magnetic field
- Braiding (or bending) of the field in the corona
- Currents are induced and dissipated to heat the corona

Model setup

3D-MHD simulation:
- Large box: 235*235*156 Mm³
- High resolution grid: 1024*1024*256
  - Horizontal: 230 km, matches observation
  - Vertical resolution: 100 – 800 km, sufficient to describe coronal heat conduction and evaporation into the corona

The Pencil Code:

- High-performance computing:
What is needed to solve the coronal heating problem...?

- General self-consistent model description on the observable scales
  - Photospheric driving mechanism for coronal energy input of ~ 0.1-1 kW/m²
Driving the simulation

Hinode/SOT observation (14<sup>th</sup> November 2007, 15:00-17:00 UTC)
What is needed to solve the coronal heating problem...?

- General self-consistent model description on the observable scales
- Photospheric driving mechanism for coronal energy input of \( \sim 0.1-1 \text{ kW/m}^2 \)
- Heat conduction that leads to chromospheric evaporation
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- General self-consistent model description on the observable scales
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  - Heat conduction that leads to chromospheric evaporation
  - Compressible resistive MHD
Compressible resistive magneto-hydrodynamics (MHD):

- Continuum equation: \[ \frac{D \ln \rho}{Dt} = -\nabla \cdot \mathbf{u} \]

- Equation of motion: \[ \frac{D \mathbf{u}}{Dt} = -c_s^2 \nabla \left\{ \frac{s}{c_p} + \ln \rho \right\} - \nabla \Phi_{\text{Grav}} + \frac{1}{\rho} \mathbf{j} \times \mathbf{B} \]
  \[ + \nu \left\{ \nabla^2 \mathbf{u} + \frac{1}{3} \nabla \nabla \mathbf{u} + 2 \mathbf{S} + \nabla \ln \rho \right\} + \zeta \left| \nabla \nabla \cdot \mathbf{u} \right| \]

- Induction equation: \[ \frac{\partial \mathbf{A}}{\partial t} = \mathbf{u} \times \mathbf{B} - \mu_0 \eta \mathbf{j} \]

- Energy balance: \[ \rho T \frac{Ds}{Dt} = \mu_0 \eta \mathbf{j}^2 + \nabla \cdot q_{\text{Spizer}} - L_{\text{rad}} + 2 \rho \nu \mathbf{S} \odot \mathbf{S} + \zeta \rho \left| \nabla \cdot \mathbf{u} \right|^2 \]
Compressible resistive magneto-hydrodynamics (MHD):

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- Energy balance: \( \rho T \frac{Ds}{Dt} = \mu_0 \eta j^2 + \nabla \cdot q_{\text{Spitzer}} - L_{\text{rad}} + 2 \rho \nu S \otimes S + \zeta \rho \left| \nabla \cdot u \right|^2 \)

=> Radiative losses: \( L_{\text{rad}}(\rho, T) \) \hspace{1cm} \text{(Cook et al., 1982)}

=> Heat conduction: \( q_{\text{Spitzer}} \sim \kappa T^{5/2} \nabla T \) \hspace{1cm} \text{(Spitzer, 1962)}
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  - Heat conduction that leads to chromospheric evaporation
  - Compressible resistive MHD
  - Resolve strong gradients in density and temperature

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- Heat conduction that leads to chromospheric evaporation
- Compressible resistive MHD
- Resolve strong gradients in density and temperature
- Avoid switching-on effects

Synthesized emission (CHIANTI)

hot loops in AR core

(Bourdin et al., PASJ 66/S7, 1–8, 2014)
Comparing to observations
Comparing to observations (Hinode EIS/SOT)

Model fieldlines follow observed loops

Fe XV ~1.5 MK

Hinode EIS observation

Hinode SOT magnetogram

(Bourdin et al., A&A 555, A123, 2013)
Comparing to observations (STEREO A/B)

- 3D structure and height of model loops realistic
- Model fieldlines follow observed loops

3D reconstruction Fe XV emission model fieldline

Hinode SOT magnetogram

(Bourdin et al., A&A 555, A123, 2013)
Comparison of intensity

- Alignment accurate to 3 arcsec

Small loops SL 1-3 at same position

Hinode EIS observation

model emission

Fe XV ~1.5 MK

(Bourdin et al., A&A 555, A123, 2013)
Comparing to observations (Hinode EIS)

Comparison of Doppler-shifts:

- Dynamics match!
- Loop top rises: 2 km/s (Solanki, 2003)

Fe XII ~1.1 MK

Hinode EIS observation

model Doppler-shift

(Bourdin et al., A&A 555, A123, 2013)
Statistical Doppler-shift analysis

<table>
<thead>
<tr>
<th>Intensity:</th>
<th>Doppler shift:</th>
<th>Line formation Temperature:</th>
</tr>
</thead>
<tbody>
<tr>
<td>C IV</td>
<td></td>
<td>~ 100'000 K</td>
</tr>
<tr>
<td>Ne VIII</td>
<td></td>
<td>~ 700'000 K</td>
</tr>
<tr>
<td>Fe XV</td>
<td></td>
<td>~ 1'500'000 K</td>
</tr>
</tbody>
</table>
Statistical Doppler-shift analysis
Statistical Doppler-shift analysis

Gaussian fit of local maximum
Moment of total spectrum
Thresholded spatial average

Average Doppler shift [km/s]

Line formation temperature [K]

Elements:
- Si II (1533 Å)
- C II (1336 Å)
- C III (977 Å)
- Si IV (1394 Å)
- C IV (1548 Å)
- O IV (1401 Å)
- O V (1032 Å)
- Ne VII (1604 Å)
- Ne VIII (1079 Å)
- Ne IX (275 Å)
- Ne VII (465 Å)
- Ne VIII (770 Å)
- Fe IX (171 Å)
- Fe X (175 Å)
- Mg X (625 Å)
- Fe XII (195 Å)
- Fe XIII (202 Å)
- Fe XV (284 Å)
Statistical Doppler-shift analysis

Blue-shifts in the corona

Stronger Red-shifts above the AR as compared to QS (as observed)
Field topology
Field topology

Temperature: (horizontal cut) (height: 11.2 Mm) (black: 1.25 MK)

- Magnetic field quite parallel in the corona
- Braided field only in the lower atmosphere
Field topology

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Testing scaling laws with field-line ensemble

**RTV temperature:**

\[ T = c_T \cdot c_H^{-2/7} \cdot F_H^{2/7} L^{2/7} \]

**RTV density:**

\[ n_e = \frac{1}{2k_B} c_H^{-4/7} c_T^{-1} \cdot F_H^{4/7} L^{-3/7} \]
Temporal evolution of field lines (and bulk plasma motion)
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Temperature:
(white: 1.2 MK)

- Bulk plasma rising together with field line
- Material draining then to the both sides of the loop

(steady flow of “coronal rain”?)
Reconnection and B-parallel electric fields
Reconnection and B-parallel electric fields

**E\_parallel:**
(saturation level: ± 0.5 V)

- Loop in strong reconnection region (red)
- \(E\_parallel\) rather uniform along loop
Particle acceleration from electric fields
Particle acceleration from electric fields
Particle acceleration from electric fields

(a) Initial particle grid and high $E_\parallel$ regions

(b) Moderate and high $E_\parallel$ regions
Statistical study: Evolution of particle power spectra

Electrons:

Protons:
**Summary:**

- First observationally driven 3D MHD “1:1” model of a full Active Region.

  - Matches observation (3D structure of loop system in hot AR core & plasma flow dynamics).
  - Ohmic (DC) heating from field-line braiding main contributor to the coronal heat input.
    - (rather slow “magnetic diffusion” than fast “nanoflares”)
  - Model sufficiently describes the coronal heating mechanism
to explain a broad variety of coronal observations on the “real Sun”.
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More specific...?

=> Magnetic topology largely dominated by bipolar field, no sudden outbreaks or changes.
=> Heating and steady magnetic reconfiguration by “slow reconnection”.
=> Bulk plasma motion follows the raising field and leads to draining loop legs.
=> Particle acceleration by strong B-parallel electric fields yields up to MeV electrons.

“Dankeschön!”