From DC current heating to 3D reconnection - the modes of magnetic energy conversion in chromosphere and corona - Numerical simulations based on Hinode observations

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XRT and SOT observations

XRT- X-ray images taken between 23:00 UT and 23:56 UT on December 12, 2006 as well as SOT photospheric B-fields from [Kotoku et al., 2007] -> What causes the brightening?
LOS photospheric B-field around the observed Xray-BP (23:00 UT)

Basic 8 spatial modes of the photospheric B-fields (LOS)

The potential B field shows strong connection changes

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2nd Hinode Science Meeting, Boulder, 30.9.08
LCT -> Patterns of photospheric plasma motion change with time

Corresponding boundary conditions for simulation
Equilibrium plasma conditions:
density and temperature stratification

Plasma density, temperature, pressure in the solar gravitation

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Set of RMHD equations, solved

\[
\begin{align*}
\frac{\partial \rho}{\partial t} &= -\vec{\nabla} \cdot \rho \vec{u} - \mu(\rho) \\
\frac{\partial \rho \vec{u}}{\partial t} &= -\vec{\nabla} \cdot \rho \vec{u} \vec{u} - \vec{\nabla} p + \vec{j} \times \vec{B} - \nu \rho (\vec{u} - \vec{u}_0) \\
&= -\vec{\nabla} \cdot \left[ \rho \vec{u} \vec{u} + \left( p + \frac{B^2}{2\mu_0} \right) 1 - \frac{\vec{B} \vec{B}}{\mu_0} \right] - \nu \rho (\vec{u} - \vec{u}_0) \\
\frac{\partial \vec{B}}{\partial t} &= \vec{\nabla} \times (\vec{u} \times \vec{B} - \eta \vec{j}) \\
\frac{\partial p}{\partial t} &= -\vec{\nabla} \cdot p \vec{u} - (\gamma - 1)p \vec{\nabla} \cdot \vec{u} + (\gamma - 1)\eta j^2 - \kappa n k_B (T - T_0)
\end{align*}
\]

\[
\begin{align*}
\vec{E} &= -\vec{u} \times \vec{B} + \eta \vec{j} \\
\vec{\nabla} \times \vec{B} &= \mu_0 \vec{j} \\
p &= 2n k_B T
\end{align*}
\]

\[
\hat{\eta}^* = \begin{cases} 
\eta^*_a \left( \frac{|v_{dr}|}{v_{thr}} - 1 \right); & |v_{dr}| \geq v_{thr}, \\
0; & |v_{dr}| < v_{thr}.
\end{cases}
\]
RMHD simulation results

• Simulated heating is maximum at BPs position

• The heating is robust, does not depend on the details of the photospheric plasma motion.

• Most important for heating are geometrical features of the magnetic field, in particular strong changes in the B-field connectivity

• A consequence of connectivity changes if footpoint motion applies: current generation

To understand current dissipation:

-> kinetic theories have to be applied
Current dissipation

If the resistivity is parametrized by an „effective collision frequency“ as

\[ \eta = \frac{\nu}{\epsilon_0 \omega_{pe}^2} \]

then in the chromosphere binary particle collisions dissipate currents [Spitzer–Härm]:

\[ \nu_{coll} \approx \frac{\omega_{pe}}{n \lambda_D^3} \]

However, in the transition region and corona -> binary collisions become inefficient-->micro-turbulent dissipation:

Threshold: current carrier velocity or gradients > critical

Quasi-linear estimate [Sagdeev et al.]

\[ \nu_S \approx 0.01 \omega_{pe} \frac{T_e}{T_i} \frac{u_D}{\nu_{te}} \]

Nonlinear->kinetic simulations needed for solar conditions [Büchner & Elkina]

– higher beta -> IA / double layers
– lower beta -> LH turbulence

\[ \nu_C \approx \frac{\omega_{pi}}{2\pi} \]
\[ \nu_C \approx \Omega_{LH} \]
Results of simulations diagnosed in a vertical plane through the Bmax
Initial situation

Density \((n)\)

Temperature \((T)\)
(\(\text{Red} = 10^6\) K)
Turbulent current dissipation

\[ \frac{J}{n_e} \]

represents the current carrier velocity.
Results of 5-minute runs

(Red = $1.3 \times 10^6$ K)
Results of 5-minute runs

(Red = $1.4 \times 10^6$ K)
Above the chromosphere:
3D reconnection („slipping“)
Conclusions

• An observed Hinode X-ray Bright Point location
  – coincides well with the sites of strong B-field connectivity changes, and
  – do not depend much on the exact form of the plasma motion in the photosphere below

• Strong B-field connectivity changes + some plasma motion across the footpoints
  -> currents, both parallel and perpendicular to B

• While in the chromosphere binary collisions dominate the current dissipation, causing Ohmic heating,

• In the transition region / lower corona main dissipation microturbulence-induced 3D „slipping“ reconnection
Outline

• Unprecedented high resolution Hinode observations
• But: Still open, what causes the formation of X-ray and EUV Bright Points
  – coincides well with the sites of strong B-field connectivity changes, and
  – do not depend much on the exact form of the plasma motion in the photosphere below
• Strong B-field connectivity changes + some plasma motion accross the footpoints
  -> currents, both parallel and perpendicular to B
• While in the chromosphere binary collisions dominate the current dissipation, causing Ohmic heating,
• In the transition region / lower corona main dissipation microturbulence-induced 3D „slipping“ reconnection