Bulk and Loop Heating of the Solar Corona

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Three-dimensional numerical models of an active region, with coronal heating driven by boundary motions acting on an initially potential extrapolation from an MDI magnetogram, demonstrate that the solar corona is heated by braiding due to the photospheric velocity field.

Magnetic energy equation

$$\frac{\partial E_B}{\partial t} = -\nabla \cdot (\vec{E} \times \vec{B}) - \underline{u} \cdot (\vec{J} \times \vec{B}) - \vec{E}_\eta \cdot \vec{J}$$

Poynting flux | Lorentz work | Joule dissipation

- Poynting flux: energy input; e.g. boundary work
- Lorentz work: replenishes kinetic energy dissipation
- Joule dissipation: replenishes radiative losses

History

- Gold 1964
- Parker 1972
- Parker 1983
- van Ballegooijen 1986
- Hendrix et al 1996
- Galsgaard & Nordlund1996

The corona is probably heated by current dissipation.

History

- Gold 1964
- Parker 1972
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TOPOLOGICAL DISSIPATION

Continuous motions of field lines at a boundary inevitably leads to the creation of current sheets.

History

- Gold 1964
- Parker 1972
- Parker 1983

P = Poynting flux [per unit area]

Q = Heating [per unit volume]

L = Loop length

How large is the angle???

SCALING OF CORONAL HEATING:

$$P = Q\,L = \frac{B^2}{8\pi}\, v \tan\varphi$$

Field inclination

Magnetic energy density

Boundary velocity

History

- Gold 1964
- Parker 1972
- Parker 1983
- van Ballegooijen 1986

Correlation time

Diffusion

$\sim 100\ \mathrm{km^2 s^{-1}}$

$$P = Q\,L = \frac{B^2}{8\pi}\, v\, \frac{v\,\tau}{L} = \frac{B^2}{8\pi}\, \frac{D}{L}$$

Contested the notion that continuous field line motions could lead to mathematical discontinuities in a finite time.

But showed that current densities in gener[illegible] exponentially with time, so the consequenc[illegible] same as in Parker's picture:

How large is the angle???

$$P = Q\,L = \frac{B^2}{8\pi}\, v \tan\varphi$$

History

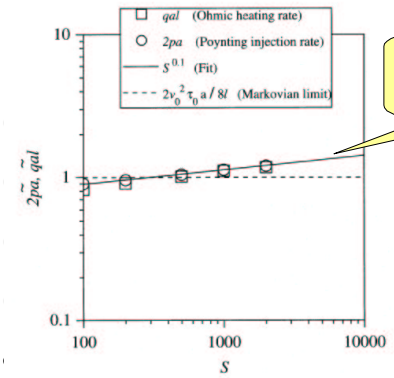
Note that van B predicted a logarithmic Rm dependence

$$Q \approx \frac{B^2 \ln R_m}{6\sqrt{2}\,\pi^{3/2}} \frac{D}{L^2} \approx \frac{0.11 B^2 D}{L^2}$$

- Gold 1964
- Parker 1972
- Parker 1983
- van Ballegooijen 1986

In the end, van Ballegooijen concluded, based on analytically estimated numerical factors, and an estimate of D from granulation buffeting of flux tubes, that the heating estimate fell short of the required one by a factor of about ten.

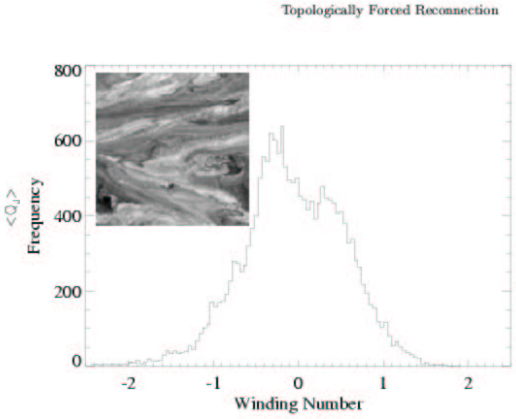
HENDRIX



Might as well be logarithmic

$$Q \propto \frac{B^2 v}{8\pi} \frac{\ell}{L^2} S^{0.1}$$

Assumed the memory of random motions to reach back only one step, so that the angle is $\approx \ell / L$. Demonstrated that the dependence of heating on magnetic Reynolds number (or Lundquist number S) is very weak (and positive!).



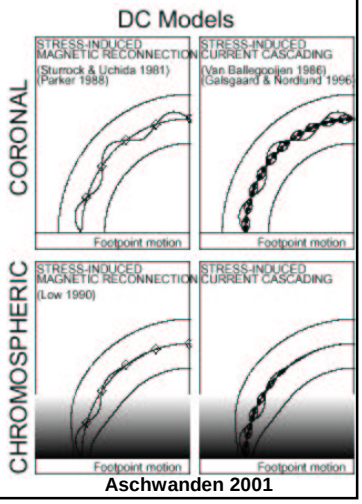
$$Q \propto \frac{B^2 v}{8\pi} \frac{\ell}{L^2}$$

- Galsgaard & Nordlund 1996

Settled the issue of the angle; the angle is determined by the winding number. A dissipating system is in a marginal state, where the winding number is of the order of unity. Larger values lead to rapid dissipation in a hierarchy of current sheets.

Modeling a generic active region

- Necessary to include the photosphere and chromosphere
  - Driving is well defined in the photosphere
  - The filling factor changes drastically through the chromosphere
- A generic active region
  - Realistic dimensions
  - Realistic physics



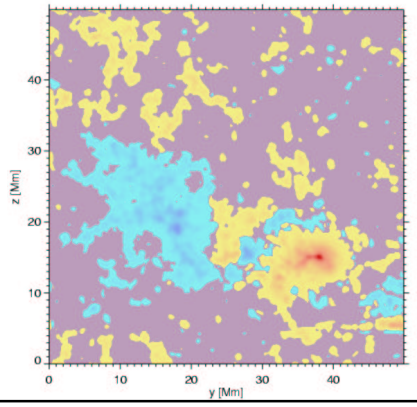
Aschwanden 2001

Numerical experiments

- 3-D magnetohydrodynamics
- Radiative cooling (Kahn 1976)
- Spitzer conductivity along B
- Conservative staggered mesh method
- Short time step, moderate resolution:
  - Time step ~ 20 ms, duration 15-30 min
  - Resolution = 100x100x100
  - Box = 30x50x50 Mm, periodic horizontally

Initial conditions

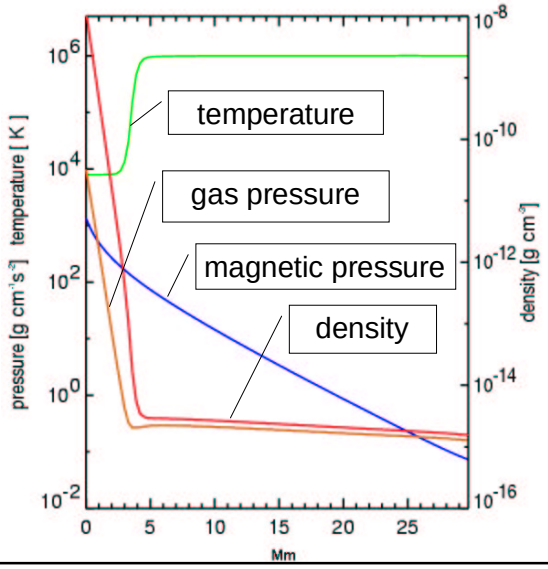
- Initial magnetic field from AR 9114
  - Potential extrapolation initially
  - Quickly evolves away from potential in corona
  - Hardly changes in the photosphere



Boundary conditions

- Boundary driving
  - Realistic power spectrum of horizontal velocities
  - Covers granulation, meso-granulation, super-granulation
    - **But remember life times: G: 5 min, MG: hour, SG: day**
    - **Takes that long to pick up the corresponding heating**
  - Marginally resolved, dx=0.3 Mm, dy=0.5 Mm
    - **Implies extra loss of power in the chromosphere**
    - **Renormalized V_{drive} to 5 km/s (true RMS ~ 3 km/s)**

Initial stratification

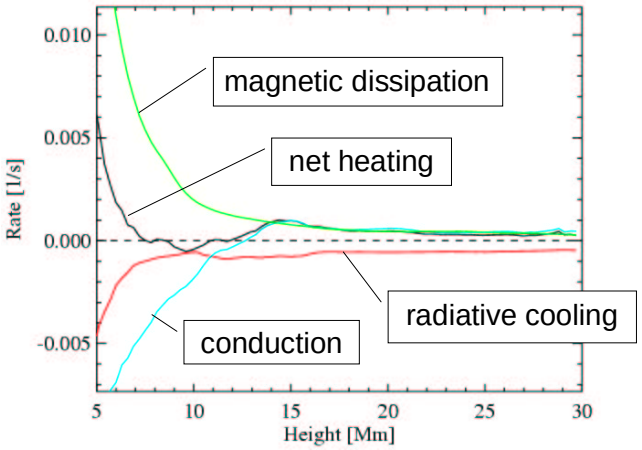


Startup phase

- No work can be done against the initially potential field
  - must first have time to tilt the field lines
- ~ 5 solar min startup phase
  - cooling and conduction turned off
- After startup phase
  - cooling and conduction turned on
  - quasi-static equilibrium after ~ 15 min

Energy budget & balance

- Fluctuation time scales ~ 1000 sec



Distribution of $J^2/\langle B^2\rangle_{horiz}$

Nearly flat distribution of J/B in the corona

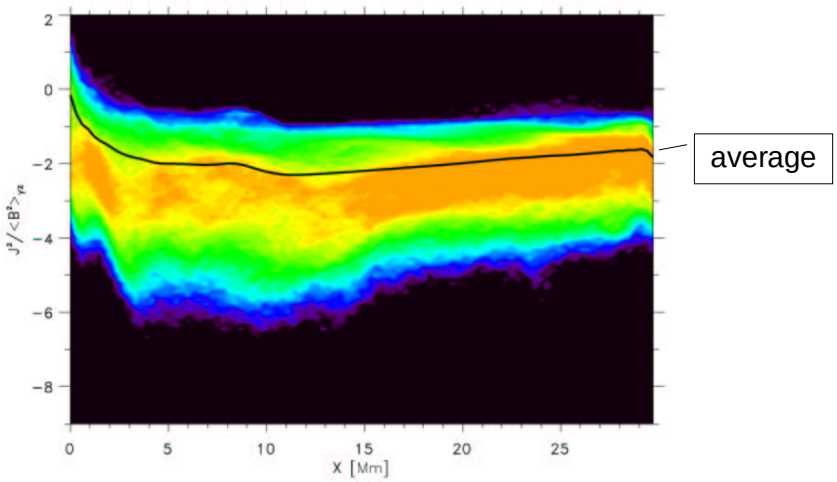
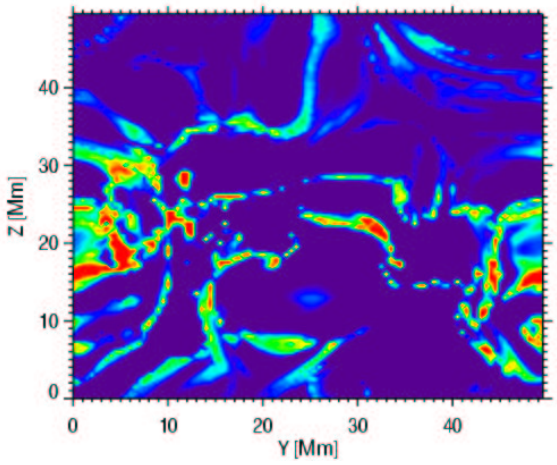
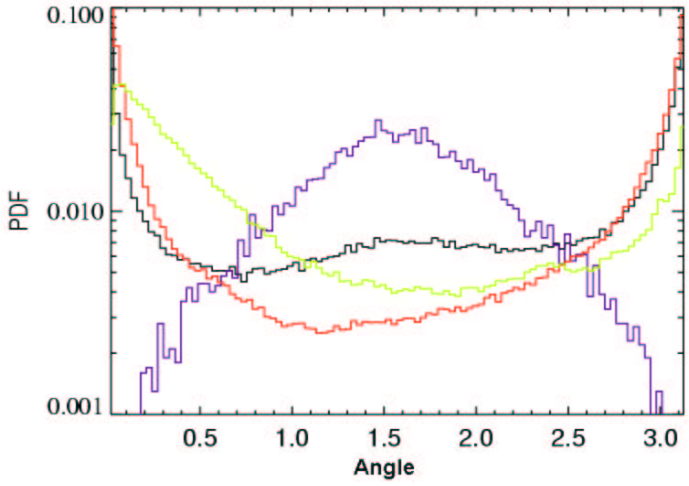


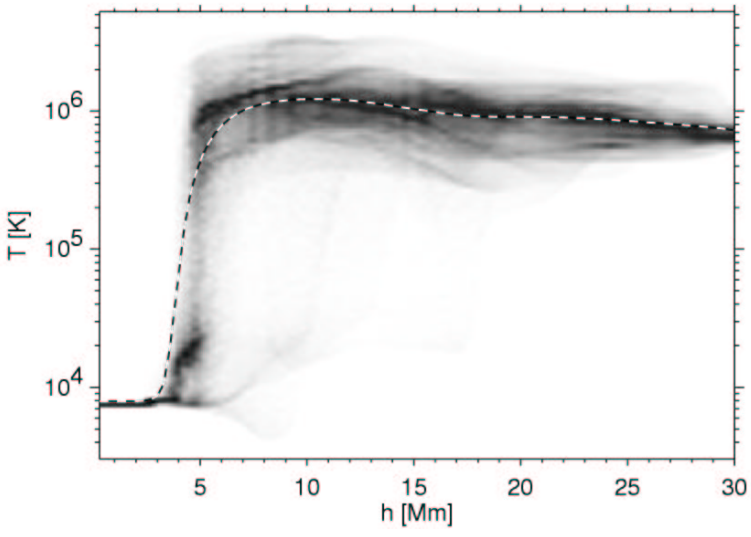
Image of alpha



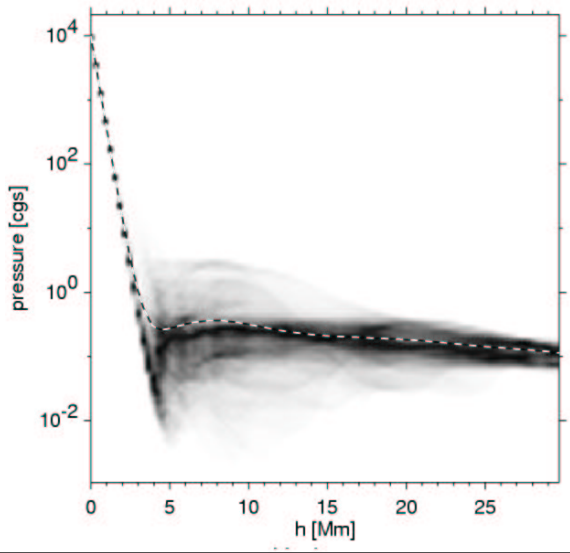
J x B angle distribution



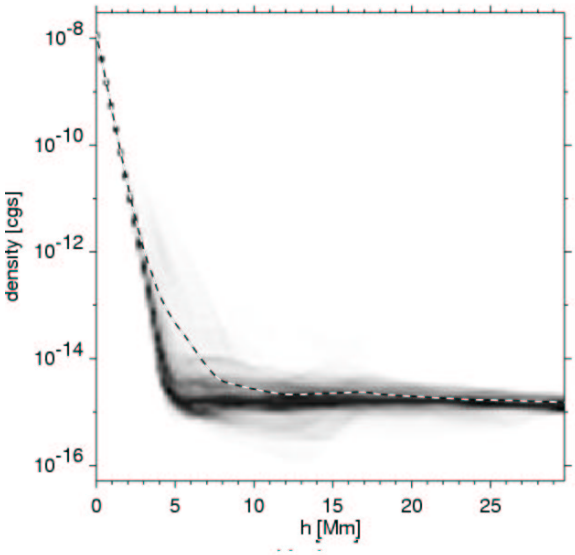
Temperature distribution



Pressure distribution



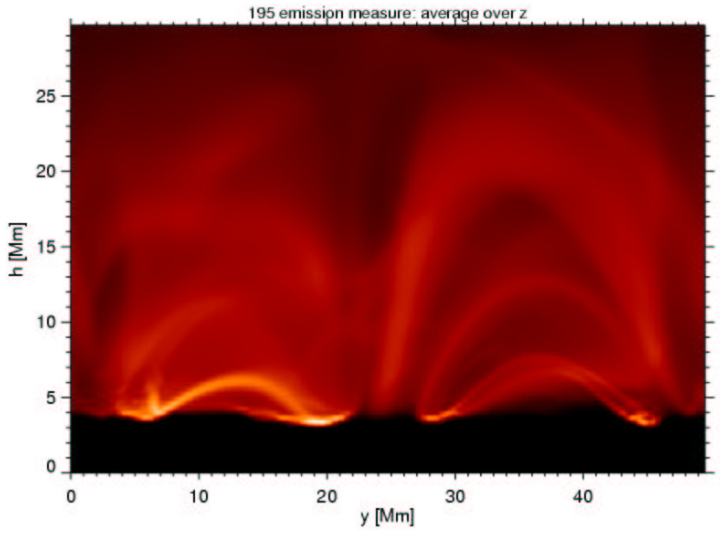
Density distribution



Emission measures

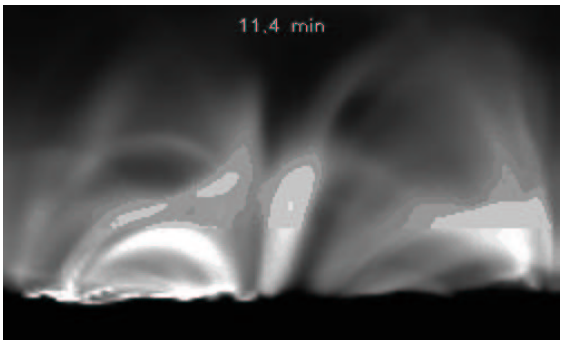
- TRACE 171
  - Centered at 0.9 MK, width ~ 0.3 MK
- TRACE 195
  - Centered at 1.4 MK, width ~ 0.35 MK
- Any other filter may be synthesized
  - See temperature sweep animation below

TRACE 195 Emission



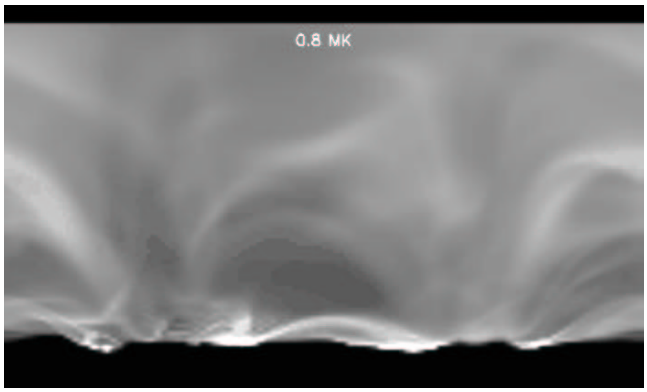
TRACE 171 animation

(click the image to run the animation)



Temperature scan

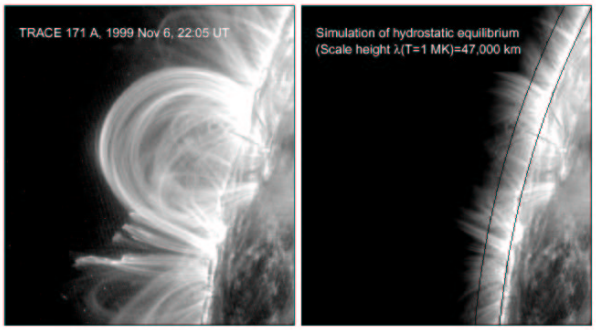
(click the image to run the animation)



Loop properties

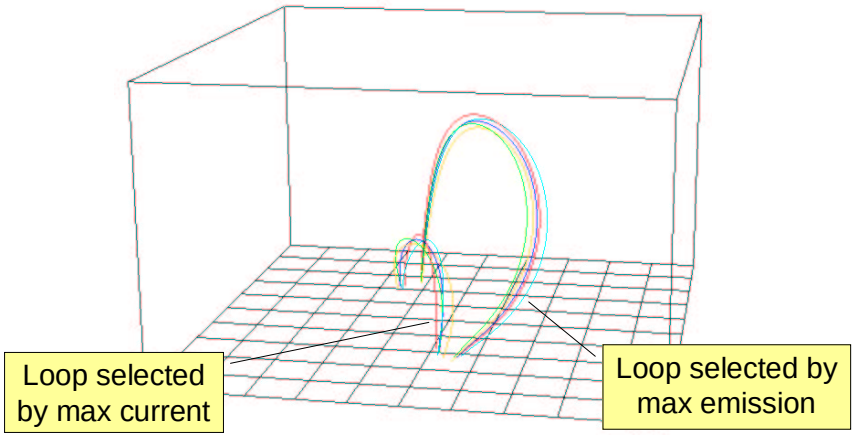
- Loops are often not in equilibrium
  - Neither thermal nor pressure:

The Astrophysical Journal, 550:1036–1050, 2001 April 1
Markus J. Aschwanden,[1] Carolus J. Schrijver, and David Alexander

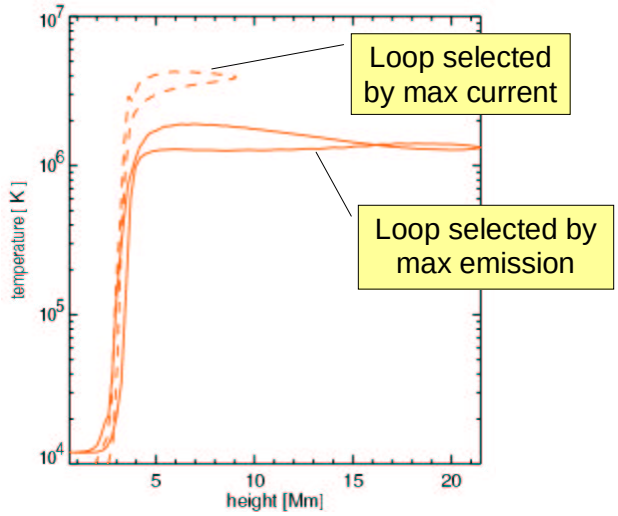


Tracing the magnetic field

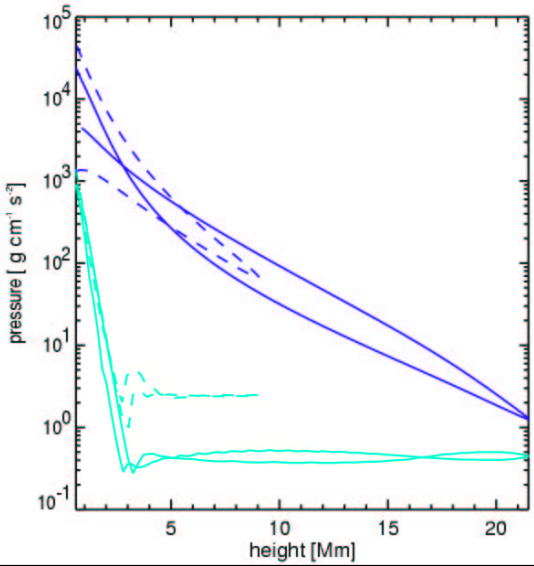
(click on the image for VRML rendering)



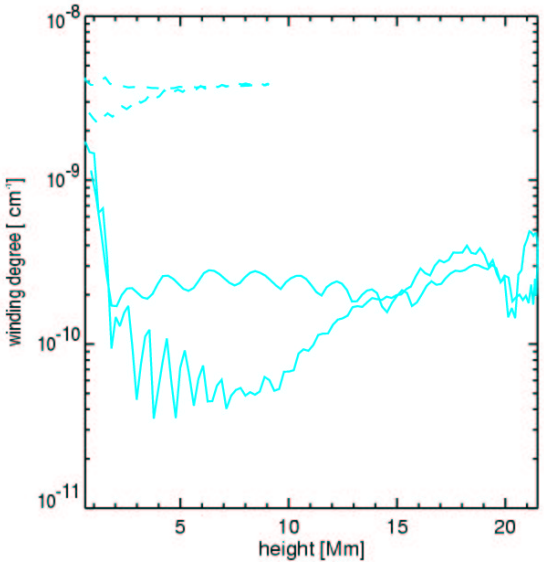
Temperature along loops



Pressure along loops



Alpha along loops



Summary

- History and summary of the braiding mechanism; now well understood
- Realistic numerical models of generic active regions are now possible
- Energy budget
  - The corona is maintained at MK temperatures
  - About 10^7 erg cm^{-2} s^{-1} net coronal heating over AR
    - Much more goes into chromospheric heating!
- Loops
  - Emission measures similar to observed ARs
  - Loop-like features, densities of the order 10^9 cm^{-3}

Robust results

- The photospheric magnetic field distribution is taken from a magnetogram
- The statistical properties of the boundary velocity field are well known
  - RMS from spectral line widths
- The Poynting flux scaling is well established from generic scenarios, theoretically and numerically
  - Galsgaard & Nordlund 1996
  - Hendrix, van Hoven, Mikic & Schnack 1996
- If there is any magnetic Reynolds number dependence, it is weak (logarithmic) and …
  - If anything increasing with Rm.
- The heating estimates obtained after the AR system settles down to a quasi-stationary state are thus robust
  - The heating is sufficient – not much room left for other mechanisms!

Overall conclusions

Three-dimensional numerical models of a generic active region, driven by photospheric motions, and with an MDI magnetogram as initial boundary condition, demonstrate that braiding due to the photospheric velocity field is sufficient to heat the corona.

Emerging flux clearly reprents a comparable, and more localized source of Poynting flux, and must be an additional source of heating and flaring activity.

Future

- Flares
  - Inject emerging flux at boundary
  - Large scale shear
- Filaments
  - Choose an AR that developed a filament in a sufficiently short time
  - Use velocity field from correlation tracking