MHD avalanches: heating the solar corona

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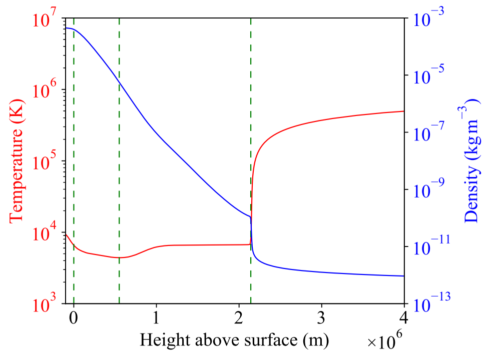
Coronal heating problem

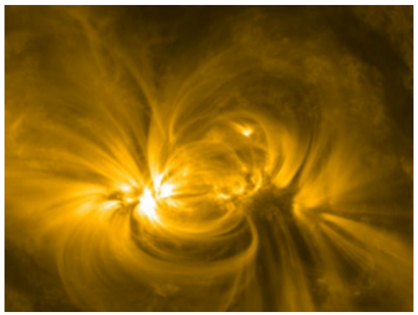
Intense nuclear fusion in the Sun's core produces the energy to heat and illuminate the solar system. From there, the interior temperature falls off with radius out to the surface, the photosphere, where it is a few thousand degrees; then, counter-intuitively, temperature rises with height into the upper atmosphere, the corona. Answering this coronal heating problem requires a way to transport energy into the upper corona, and there dissipate it, in order to maintain temperatures of many millions of degrees. Propagating waves can carry energy upwards, or slow stresses can store energy in the magnetic field. Physically, energy is released by viscosity acting on fluid flows, resistivity causing Ohmic dissipation of magnetic energy, or acceleration of particles by powerful electric fields.

Arcing coronal loops thread active regions, where heating is most intense. Visually, loops consist of several bright strands, where emission is very strong and which trace out the magnetic field.

Temperature rising with height above the surface.



Vast, multi-stranded coronal loops.



Self-organized criticality

- Bak et al. (1987) propose 'self-organized criticality':
  - Systems may be in minimally stable states, from which they are easily perturbed
  - Small, local disturbances propagate and grow by causing similar small disturbance around them: an *avalanche*
  - For example, a snowball could lead to an avalanche on a mountain, or a single grain cause sand to fall down the side of a sand-pile
- Parker (1988) argues that the solar corona is heated by the collective effect of uncountably many small, barely observable events: 'nanoflares'
- Hood et al. (2016)'s avalanche model suggests that a small, discrete instability in a confined region can trigger like events, provoking a chain reaction that generates great heat

Magnetohydrodynamics

Magnetohydrodynamics (MHD) marries hydrodynamic laws and Maxwell's electromagnetic equations; its equations govern plasma evolution:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0 \qquad \nabla \cdot \mathbf{B} = 0$$

$$\rho \frac{\mathrm{D}\mathbf{v}}{\mathrm{D}t} = -\nabla P + \mathbf{j} \times \mathbf{B} + \rho\, \mathbf{g} + \mathbf{F}_{\text{visc.}} \qquad \frac{\partial \mathbf{B}}{\partial t} = -\nabla \times \mathbf{E}$$

$$P = (n_i + n_e)\, k_B T \qquad \mathbf{j} = \frac{1}{\mu_0} \nabla \times \mathbf{B}$$

$$\frac{\mathrm{D}}{\mathrm{D}t}\left(\frac{P}{\gamma - 1}\right) = -\frac{\gamma P\, (\nabla \cdot \mathbf{v})}{\gamma - 1} - \nabla \cdot \mathbf{q} - \mathcal{L}_r + \frac{j^2}{\sigma} + Q \qquad \mathbf{E} + \mathbf{v} \times \mathbf{B} = \frac{1}{\sigma}\mathbf{j}$$

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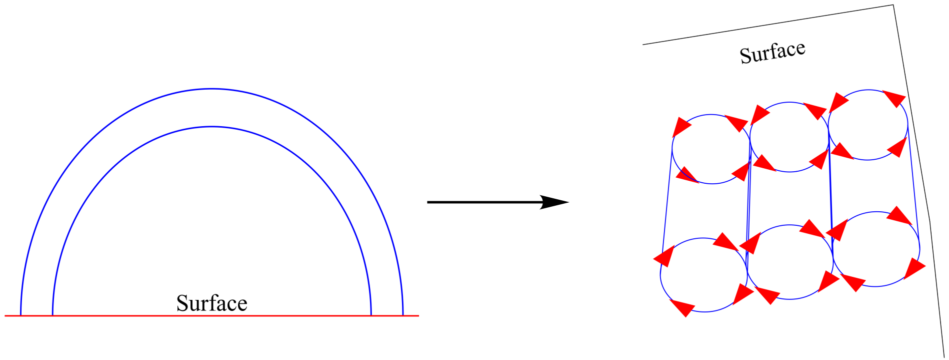
MHD model

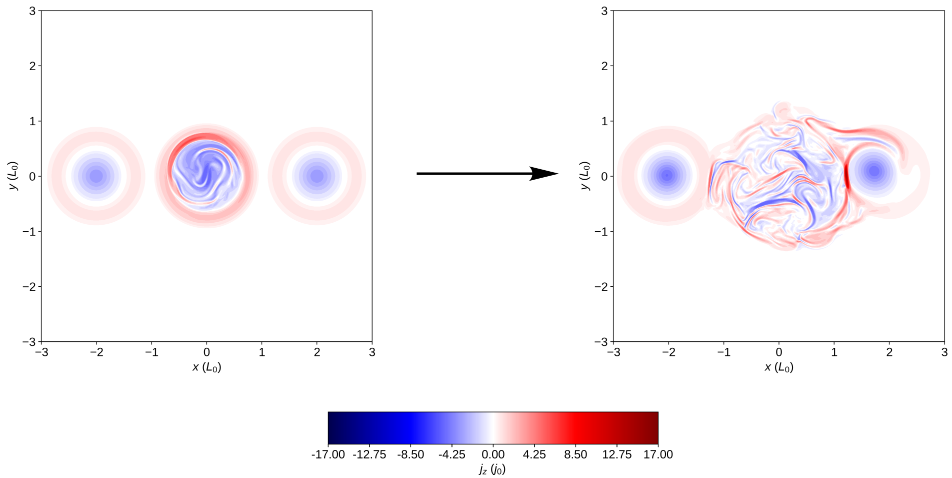
Curved coronal loop represented by straight strands between two planes.



- Coronal loops are curved over the Sun's surface, and composed of several strands
- For simplicity, we treat three model strands, between two boundary planes that represent the photosphere
- In opposing directions, the ends of these are vortically driven
  - Fastest in the central thread, slower in the outer two
- Continuously driving these threads, they should become unstable
  - We are interested in the 'avalanche': how a local instability in one spreads to, and affects, the others
- Thermodynamics—heat flux and radiation—are too difficult to model in three dimensions, so, for simplicity, we neglect them for now
- We use a numerical simulation code, *Lare3d* (Arber et al. 2001), to solve the MHD equations and evolve the model through time

Instability begins

- An ideal MHD instability—the kink mode—takes places in the central thread when it is sufficiently stressed
  - One of its hallmarks is a helical current through the tube, which appears as a crescent in a cut through one plane
- Strong currents enhance electrical resistivity, causing magnetic reconnection
  - Thereby, magnetic field lines break and are rejoined
  - Stress is released, as the field moves to a lower-energy state
- Reconnection enables the disruption to spread further
- Complex, interconnected arrangements of current are formed
- By ongoing photospheric motions, the resultant, highly braided magnetic field is constantly being further stressed



Current: helical current sheet (left), leading to fragmentary currents (right).

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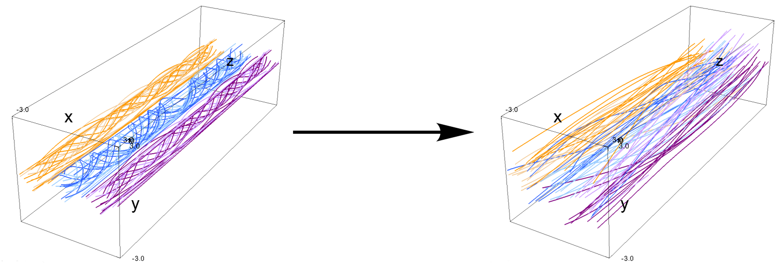
Avalanche: instability spreads

- A thread becomes unstable, fragmenting into a network of tiny currents
- Symmetry breaks and neighbouring tubes interact: the avalanche spreads



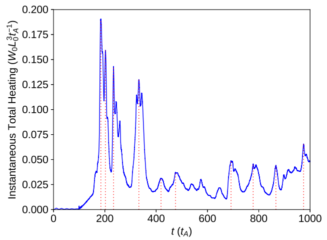
Magnetic field lines becoming entangled by instability.

Heating

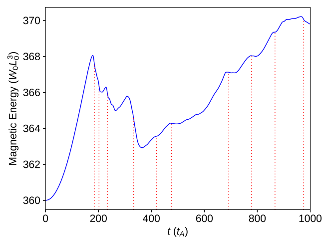
- ‘Bursty’ heating: recurring series of impulsive ‘events’, where:
  - magnetic energy falls, as it is released
  - kinetic energy grows, through fast outflow jets around events
  - temperature rises
- Beneath these is a stable, persistent background heating

Heating events (in red), where magnetic energy falls and is converted to kinetic.

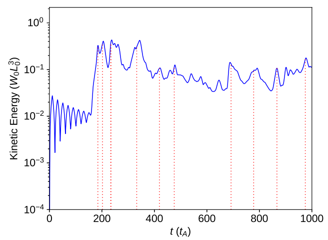
Total heating.



Magnetic energy.

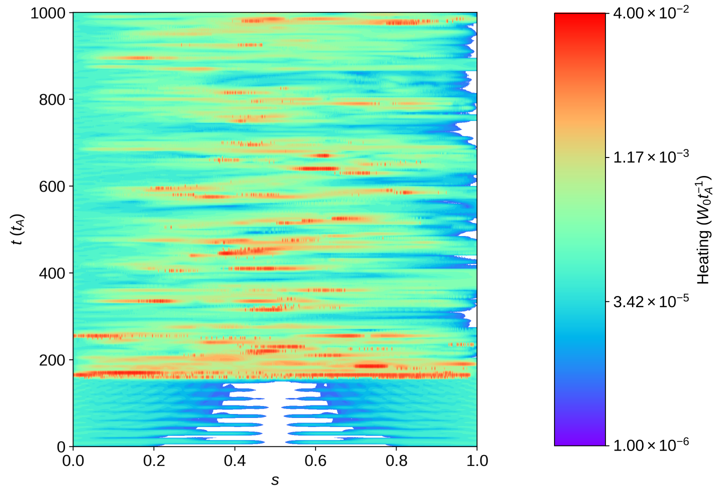


Kinetic energy.



Field-aligned heating

- Spitzer (1962): heat flux is almost entirely parallel to the magnetic field
  - the distribution of heating is most important along field lines
- Field lines are traced, and local heating along them calculated as a function of time and space



Heating along a field line as a function of space (on the horizontal axis) and time (on the vertical axis).

- Two physical mechanisms contribute heating in MHD:
  Ohmic heating reduces magnetic energy when reconnection takes place,
  viscous damping retards plasma flows and converts kinetic energy
- Tiny pockets of intense Ohmic heating arise in a sea of viscous damping

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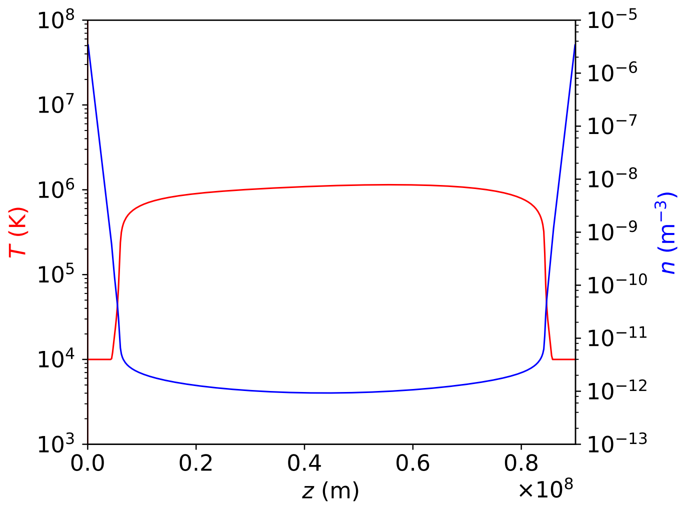
Coronal equilibrium

- Thermodynamic properties—heat flux and radiation—are too difficult to model in three dimensions, but can be modelled in one
- One-dimensionally, a thermo-hydrodynamic model, following the magnetic field along a loop, is constructed
- A physically motivated and realistic atmosphere is treated
- Field-aligned heating profiles are derived from the MHD model and injected into this simulation
- Loops attain steady, realistic coronal values:

$$T \approx 1.71 \times 10^6 \text{ K} \qquad n \approx 6.26 \times 10^{14} \text{ m}^{-3}$$

Temperature (red) and density (blue).



Conclusions

- MHD avalanches are shown to be viable, and the conjecture of Hood et al. (2016) verified
- Here, a feasible mechanism to store and release energy, dynamically and impulsively, is shown
- Remarkably, a chaotic and braided magnetic field emerges from very simple and smooth rotating motions
- A fairly stable background heating level persists
- In addition to this, there is a recurring series of events
- We have verified that these heating profiles can sustain loops and maintain coronal atmospheres

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