MHD avalanches in magnetized solar plasma: proliferation and heating in coronal arcades

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Introduction

Among the several open questions in solar physics, one of the most long-standing is the coronal heating problem, namely the question as to why, despite its heat, light, and energy emanating from nuclear fusion in its core, the Sun's temperature should rise further away from its surface. Temperature-sensitive emission is observed to be strongest in regions of similarly stronger magnetic fields, underlining the importance of the magnetic field in this phenomena. Indeed, the greatest concentrations of heating are in coronal loops, magnetic flux tubes that thread the solar atmosphere, and visibly curve between footpoints on different parts of the solar surface. Several mechanisms are posited to explain how the magnetic field transports energy into the corona, and there dissipates it, to give the elevated temperatures.

One such mechanism is an MHD 'avalanche'. Self-organized criticality is a theory contending that natural systems can exist in minimally stable states, wherein they are liable to perturbation by external driving. When so disturbed, a local event occurs, which dissipates a small amount of energy and whose aftermath triggers further such small events in stressed, yet stable, neighbouring states. In consequence, a scale-free chain reaction—an 'avalanche'—occurs in which significant energy is released through the cumulative action of these self-similar events. As this paradigm is applied to the solar corona, photospheric motions constitute the external driving, injecting energy into the magnetic field. When sufficiently stressed, a locality in the magnetic field undergoes an instability, releasing energy and triggering like events in neighbouring, similarly stressed parts of the field. On the largest scales, these events originate solar flares; on the smallest, they are analogously constituted, but barely detectable, with commensurately weaker heating: 'nanoflares'.

Commonly, coronal loops are modelled with curvature neglected, as straightened cylinders, fixed between two parallel planes, representing different parts of the same photosphere. Conceptually, analytically, and computationally, these are far more straightforward to handle. Recently, curved models of coronal loops have increasingly been studied. Naturally, the question arises as to whether the first type of model and can accurately reproduce the behaviour seen in the second.

Moreover, one can investigate the effect of curvature, particularly upon the heating produced.

Model

Addressing these points, a curved, initially potential magnetic field is created. Field lines curve between footpoints spanning a polarity inversion line (PIL), reflecting the structure of bipoles seen in active regions (Figure 1).

To such a field, vortical motions are applied at footpoints, twisting the magnetic field, and thereby creating and stressing flux tubes. Motions are arranged on the photosphere such that seven constituents strands are created.

In order to follow the evolution of the model, the governing MHD equations are solved in three-dimensional numerical simulations using the Lagrangian remap code, *Lare3d*. Especially pertinent for the later study of heating are the inclusion of shock and uniform, background viscosities, respectively in order to handle the physical dissipation occurring at shocks and to reflect ubiquitous physical damping of flows, and an anomalous resistivity, which dissipates especially strong currents. In particular, the resistivity is active on currents exceeding a critical threshold on a parameter ζ, analogous to twist, which accounts for variable field strength in the arcade, and consequently varying strength of current.

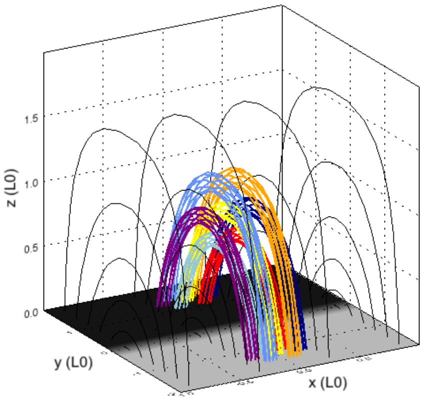


Figure 1: Initial magnetic field, with seven-stranded loop.

Instability

Rotations within the seven flux tubes, that of the central one being fastest, stress the magnetic field and form currents. Particularly strong in the central flux tube, a helical current sheet arises from each such rotation. Within the plane above the inversion line, a cross-section of the flux tube, this current sheet forms a crescentic layer, of current sufficiently intense, measured in terms of parameter ζ, to cause an ideal MHD instability and thus to trigger resistivity, thereby bringing about dissipation and disrupting the flux tube.

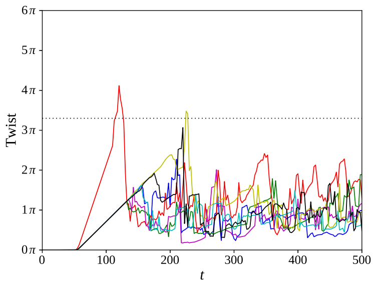
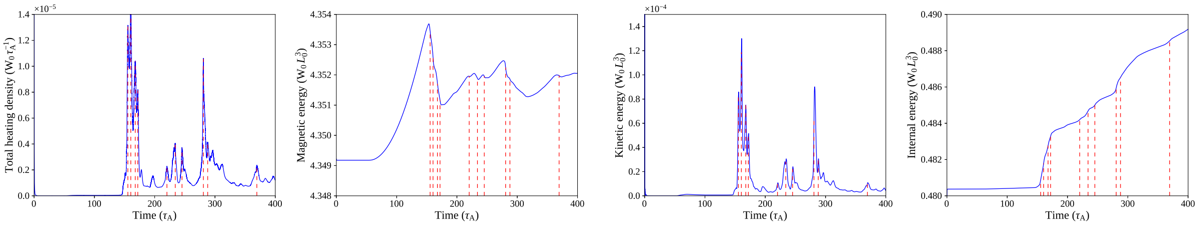


Figure 2: Twist in each flux tube (each in a different colour; red for the central), over time.

Kink modes have been conjectured, studied, and verified as the cause of such instability in straightened cylindrical flux tubes. In the curved arcade, the twist present in each flux tube is calculated (Figure 2). By the time of the first instability,



(a) Total heating. (b) Magnetic energy. (c) Kinetic energy. (d) Internal energy.

Figure 4: Evolution of energies over time.

that present in the central flux tube does breach the approximate, theoretical critical threshold, consistent with the kink mode being the cause. However, instead of an arbitrary direction as in the straightened case, the instability is modified to occur preferentially upwards. Other flux tubes have measurable, but sub-critical, twist, showing that they are affected by another process, namely the spread of the avalanche. Following the introduction of curvature, the torus instability becomes a new possible mechanism for instigating the first instability; it affects curved flux tubes in magnetic fields whose strength decays with height. Variation of decay index n with height (Figure 3) measures liability to the torus instability, and the value measured within the central flux tube is consistent with instability, being within the range of situation-dependent critical thresholds. However, lack of strong net axial current and the fact that the slow rise of the flux tube does not continue and accelerate into eruption make a torus instability less likely.

Whichever precise mechanism be responsible, the ideal MHD instability serves to enable the transition from linear, stable growth, to non-linear, unstable evolution. Consequently, the surrounding flux tubes are perturbed, in turn, by the central one, constituting the spread of the avalanche.

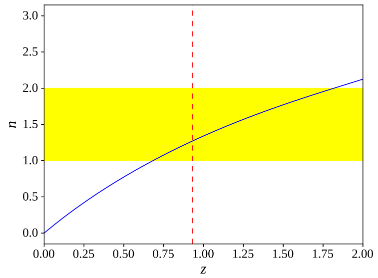


Figure 3: Toroidal decay index n against height when instability occurs. Red marks the axial height of the central flux tube.

Heating

During the avalanche, substantial heating is produced, in the form of a series of 'bursts' atop a fairly steady background (Figure 4(a)). Each event or burst corresponds to a sharp fall in magnetic energy (Figure 4(b)), growth in kinetic energy (Figure 4(c)) via fast outflows, and a commensurate rise in internal energy (Figure 4(d)) through viscous damping of flows and Ohmic dissipation of current.

Decomposing total heating according to the three MHD heating processes (Figure 5), shock heating and viscosity are responsible for a much larger proportion than Ohmic heating. In a single event, the process of disruption begins with an instability in the magnetic field, triggered by exceptionally strong currents, facilitating magnetic reconnection in a very small diffusion region, and releasing energy through Ohmic dissipation. Thus, Ohmic heating precedes other forms. Thereafter, strong outflows and jets are accelerated around this event, which may form shocks, and contribute to turbulence in the plasma. Viscous heating later grows, overwhelming Ohmic (Figure 6). Here, the role of magnetic reconnection is manifest, not as itself a major contributor of thermal energy, but rather as facilitating the more widespread, consequent plasma processes that contribute more substantially to heating.

Qualitatively, the same effect is seen by comparing heating along the loop with current. Strong currents arise in narrow, largely field-aligned layers. Contrastingly, heating is more diffuse, coming through fluid and plasma behaviours, such as shocks, jets, and turbulence, surrounding isolated reconnection regions.

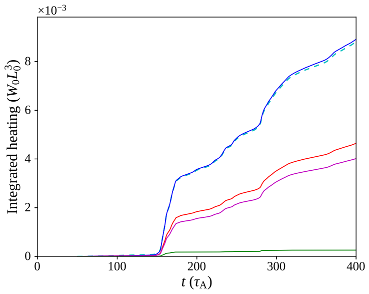


Figure 5: Shock (red), viscous (magenta), and Ohmic (green) components of total heating (blue), plotted over time.

Conclusions

By introducing a curved geometry and magnetic field to existing paradigms for MHD avalanches, it is shown that they are equally viable in curved and straightened models, vindicating the latter simplification. Within such a curved arcade, heating is found to be highly localized and dispersed, but without any obvious spatial preference. Magnetic reconnection facilitates instability and heating, but makes only a minor energetic contribution: shocks, jets, and turbulence contribute far more substantially.

In the near future, advances in computational power and refinement in numerical techniques will enable a more detailed study of the consequences of the heating. In particular, one will be able to study the thermal response to the plasma, by taking into account energetic transport, through heat flux and optically thin radiative losses.

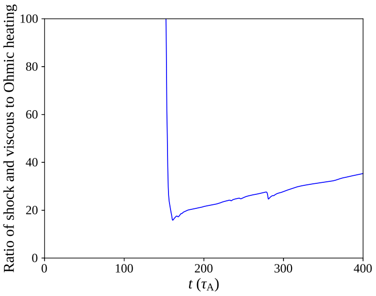


Figure 6: Ratio of time-integrated shock and viscous to Ohmic heating, over time.

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