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Self-consistent nanoflare heating in model active regions: MHD avalanches in curved coronal arcades

J. Reid[1], **J. Threlfall**[2] **and A. W. Hood**[1]

[1]University of St Andrews, St Andrews, United Kingdom

[2]Abertay University, Dundee, United Kingdom

Abstract. MHD avalanches involve small, narrowly localized instabilities spreading across neighbouring areas in a magnetic field. Cumulatively, many small events release vast amounts of stored energy. Straight cylindrical flux tubes are easily modelled, between two parallel planes, and can support such an avalanche: one unstable flux tube causes instability to proliferate, via magnetic reconnection, and then an ongoing chain of like events. True coronal loops, however, are visibly curved, between footpoints on the same solar surface. With 3D MHD simulations, we verify the viability of MHD avalanches in the more physically realistic, curved geometry of a coronal arcade. MHD avalanches thus amplify instability across strong solar magnetic fields and disturb wide regions of plasma. Contrasting with the behaviour of straight cylindrical models, a modified ideal MHD kink mode occurs, more readily and preferentially upwards in the new, curved geometry. Instability spreads over a region far wider than the original flux tubes and than their footpoints. Consequently, sustained heating is produced in a series of 'nanoflares' collectively contributing substantially to coronal heating. Overwhelmingly, viscous heating dominates, generated in shocks and jets produced by individual small events. Reconnection is not the greatest contributor to heating, but is rather the facilitator of those processes that are. Localized and impulsive, heating shows no strong spatial preference, except a modest bias away from footpoints, towards the loop's apex. Remarkable evidence emerges of 'campfire' like events, with simultaneous, reconnection-induced nanoflares at separate sites along coronal strands, akin to recent results from Solar Orbiter. Effects of physically realistic plasma parameters, and the implications for thermodynamic models, with energetic transport, are discussed.

Keywords. Sun: corona, Sun: magnetic fields, magnetohydrodynamics, methods: numerical

1. Introduction

One of the most long-standing open questions in solar physics is the coronal heating problem, namely why the Sun's temperature should rise further away from its surface. Heating is greatest in coronal loops that visibly curve between footpoints on the photosphere. Several explanations are offered, including MHD 'avalanches'. Some natural systems, such as the coronal magnetic field, are posited to be self-organized and critical, such that one local event can dissipate a small amount of energy and trigger further such small events at stressed, yet stable, neighbouring sites. A chain reaction—an 'avalanche'—occurs, releasing great energy through the cumulative action of self-similar events. Convective motions inject energy into the coronal field. When sufficiently stressed, magnetic reconnection reconfigures, and releases energy from, the field (Lu & Hamilton 1991). At one extreme, these events trigger flares; at the other, they are scarcely detectable, giving weak, underlying heating: 'nanoflares' (Parker 1988).

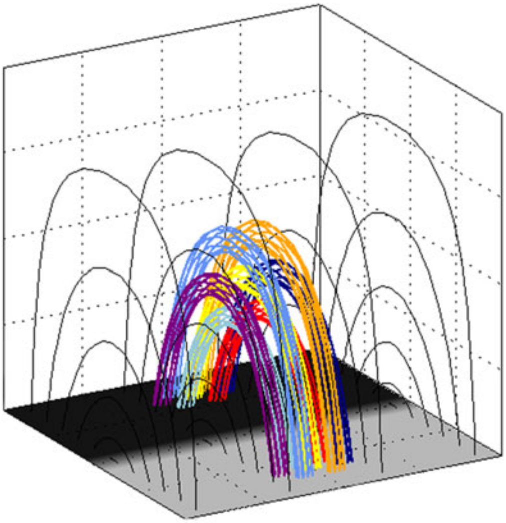

Figure 1. Initial arcade.

Loops are typically modelled as straightened cylinders, between two parallel planes, which are far simpler to conceive, study, and simulate. Recently, truly curved models have become more common. Can, therefore, the first type of model accurately reproduce the behaviour of the more realistic second? One can also compare the effect on heating.

2. Model

A curved magnetic field is modelled, with field lines anchored at footpoints on the same plane, as in bipolar arcades (Figure 1). Vortical motions twist these footpoints, creating seven magnetic flux tubes. *Lare3d* (Arber et al. 2001), an MHD code, advances the model in time. Shock heating mimics the physics of shocks, and background viscosity reflects the general viscous damping. Anomalous resistivity dissipates strong currents.

3. Results & conclusions

Twisting motions create helical current sheets. In the fastest-twisted central tube, this appears as a thin crescent in a cross-section, intense enough to cause an ideal MHD instability, which enables resistivity, starts an unstable, dissipative phase, and disrupts the first tube, which progressively disturbs each surrounding it. Substantial heating arises in a series of 'bursts' atop a fairly steady background (Figure 2). Each such event corresponds to a sharp fall in magnetic energy, growth in kinetic energy via fast outflows, and consequently higher thermal energy from viscosity and Ohmic dissipation.

Total heating mostly consists of shock heating and viscosity, with little Ohmic heating (Figure 2). In one heating event, disruption begins with strong currents causing a magnetic instability and thereby reconnection in a small diffusion region, yielding Ohmic heating, which thus precedes other forms. Strong outflows and jets are then accelerated, which may form shocks and contribute to turbulence in the plasma. Viscous heating then surpasses Ohmic. Spatial distributions of heating and current show the same property. Currents are strong in fine, field-aligned layers, but heating is smoother and more diffuse, generated by fluid and plasma processes, such as shocks, jets, and turbulence, around narrow reconnection regions.

MHD avalanches are shown equally viable in curved and straightened models, vindicating the simplified models. Heating in a curved arcade is dispersed, highly localized,

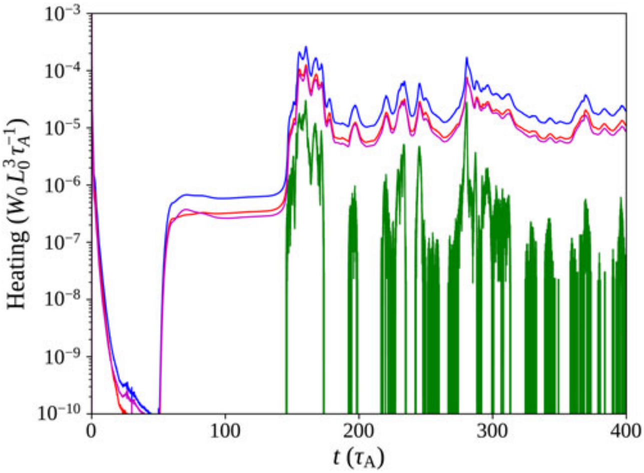

Figure 2. Total heating (blue) composed of shock (red), viscous (magenta), and Ohmic (green).

and lacking spatial preference. Magnetic reconnection is not itself a major source heating, but rather facilitates the processes, such as shocks, jets, and turbulence, that are.

Enhanced computational resources and refined numerical methods are now enabling a more detailed study of the aftermath and effect of the heating. Thermodynamic properties, even around the steep gradients in temperature in the transition region, will be resolvable in MHD, and thus the thermal response of the plasma to heating within reach.

References

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