9th Asia-Pacific Conference on Plasma Physics, 21-26 Sep, 2025 at Fukuoka

Mathematics for coronal rain: the hydrodynamic thermal continuum

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The solar corona is structured in myriads of magnetic loops and contains rarified plasma at million degrees Kelvin. However, observations reveal how spontaneous in-situ condensations show up nearly everywhere. In the strong coronal magnetic field, this cold (10000 K) and dense blobs are then guided to rain down curved loops, such that an essentially hydrodynamic evolution along a 1D loop suffices to explain the physics. These coronal rain condensations are manifestations of an energy exchange between the plasma and the radiation field, where optically thin radiative losses preferentially act as a sink for internal energy. This makes the loop plasma liable to a runaway linear thermal instability, originally postulated by the late Eugene Parker [1]. In this talk, I will present an overview of state-of-the-art numerical simulations that have progressed from 1D hydrodynamic loop models to multi-dimensional [2] and full 3D radiative magnetohydrodynamic setups [3], which rival in resolution with our observations. All these confirm the essential role played by thermal instability to instigate rain formation. A rigorous mathematical analysis of the linearized non-adiabatic hydrodynamic equations reveals the presence of a thermal continuum in the essential spectrum of eigenmodes of a stratified loop. We will show the intricate links with spectral theory in stratified atmospheres, where p- and g-modes get modified by radiative losses, and where the entropy mode turns into a continuous range of eigenfrequencies with ultra-localized (singular) eigenfunctions. This insight connects and clarifies findings on thermal non-equilibrium states, waves affected by thermal misbalance, and the present confusion on the role of isochoric versus isobaric thermal instabilities.

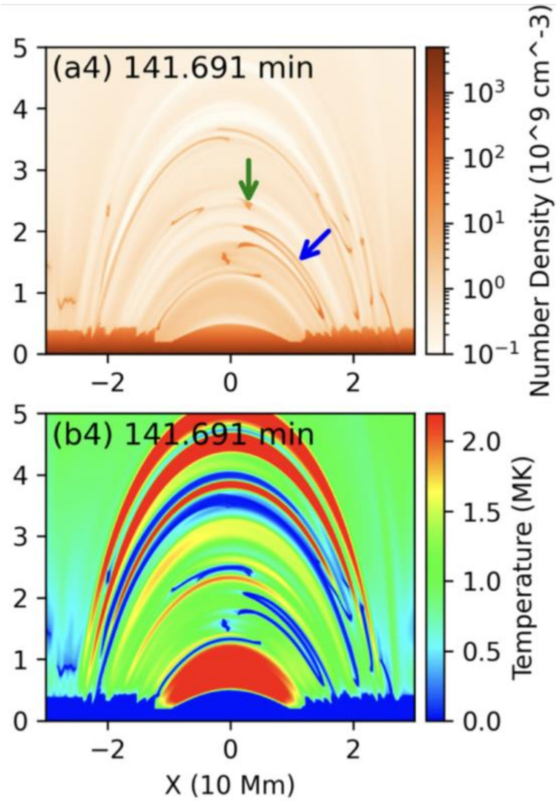

Figure 1: From Li et al. [2], a density and temperature view on a randomly heated arcade, demonstrating coronal rain.

References

[1] ApJ 117, 431, 1953

[2] A&A 688, A145, 2024; ApJ 926, 216, 2022; ApJ 807, 142, 2015

[3] ApJ 973, L1, 2024