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Heating the hot and super-hot corona in solar active regions: Insights from MURaM

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What physical mechanisms heat the outer solar or stellar atmosphere to million-kelvin temperatures is a fundamental but long-standing open question. In particular, differential emission measure (DEM) analyses show that, the corona in solar active region cores has high temperatures that peak around 3–4 MK, with a non-negligible super-hot portion around 10 MK. The scaling law suggests that the required heating flux varies dramatically with coronal temperature, which implies that different heating mechanisms may dominate in different thermal components. In this talk, we will present self-consistent, hot and super-hot coronal heating models spanning from the near-surface convective zone to the solar corona in different active region configurations, based on three-dimensional radiative magnetohydrodynamics simulations with MURaM code.

We start from a simple, bipolar, non-emerging active region[1] (Fig. 1), where magneto-convection is the main driver for magnetic free energy accumulation. This simulation well reproduces the observational features including realistic interweaving coronal loops, periodic coronal rain, and periodic intensity pulsations, with two periods of 3.0 hr and 3.7 hr identified within one loop system. More importantly, as the driver of the mass circulation, the self-consistent coronal heating rate is considerably complex in time and space, with hour-level variations in one order of magnitude, minute-level bursts, and varying asymmetry reaching ten times between footpoints. This provides an instructive template for *ad hoc* heating functions and further enhances our understanding of the coronal heating process.

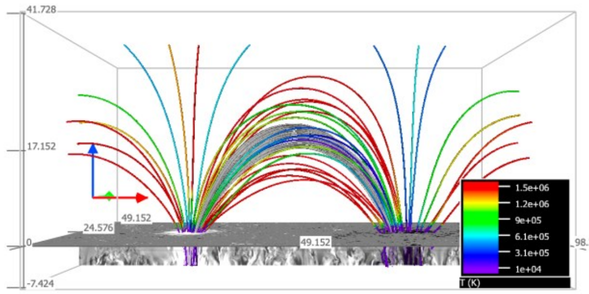

Figure 1. A 3D overview of the bipolar active region simulation, where the colored tubes represent magnetic field lines, with colors indicating the temperature. The grayscale slices at the bottom display the z-direction magnetic field component in the photosphere and of the convective zone.

We then investigate a complex, emerging active region[2] (Fig. 2), which is coupled with a global-scale dynamo simulation at the bottom boundary. We find that the continuous emergence of magnetic flux keeps driving magnetic reconnections that release energy impulsively but are persistent over time on average. As a result, numerous substructures are heated to 10 MK and then evolve independently; these strands collectively form the long-lived and stable coronal loops that have been observed. This flux-emergence-driven model provides a heating flux of $1.9 \times 10^6\ \mathrm{W\,m^{-2}}$, which is one order of magnitude higher than the convection-driven magnetic braiding scenario, and specifically explains the origin of super-hot corona in emerging solar active regions.

References
[1] Lu, Zekun *et al.*, ApJL, 973, L1 (2024)
[2] Lu, Zekun *et al.*, NatAs, 8, 706 (2024)

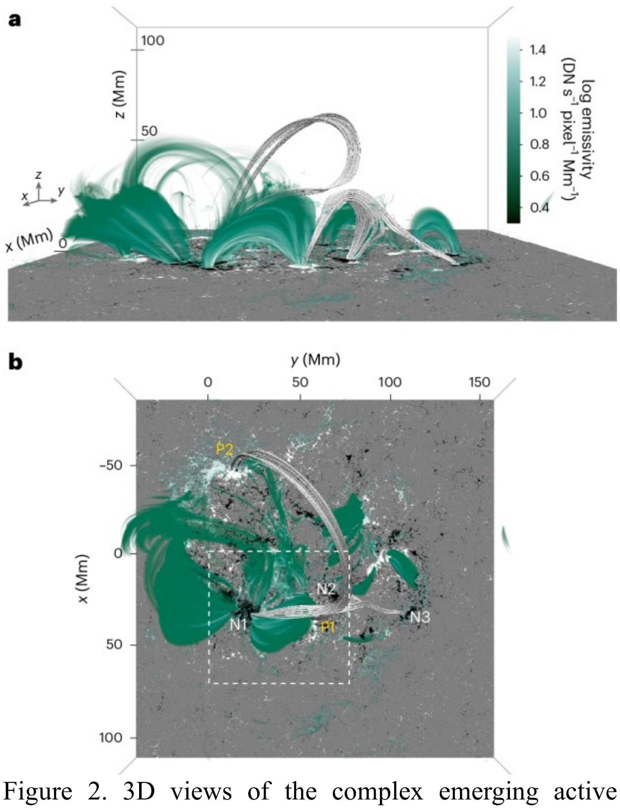

Figure 2. 3D views of the complex emerging active region simulation from (a) x and (b) z directions, where the synthetic emission in AIA 94 Å is shown in green. The white solid tubes represent magnetic field lines, and the bottom surface is the photospheric magnetogram.