

1. Introduction

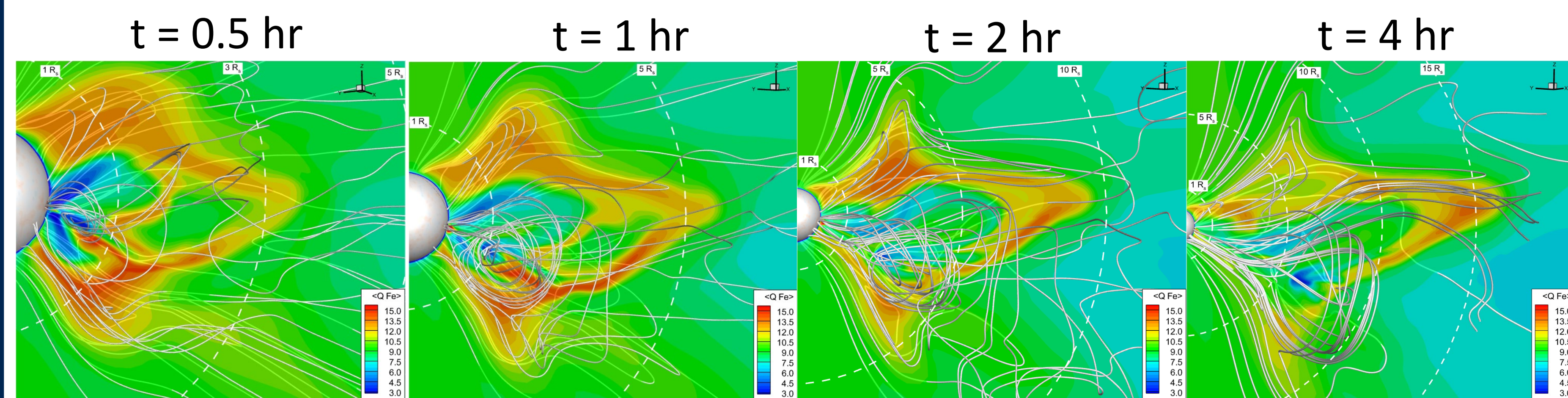
We simulated the 2008 April 9 CME with the **Alfvén Wave Solar atmosphere Model (AWSoM)** [van der Holst et al. 2014, 2022] of the solar corona and inner heliosphere. It includes:

- Low-frequency Alfvén wave turbulence
- Collisional and collisionless heat conduction
- Radiative cooling

Wraback et al. [2025] showed a <5% difference between the AWSoM simulated non-equilibrium ionization spectroscopic plasma diagnostics and actual *Hinode*/EIS observations at 1.1 Rs for this CME. **The good comparison with the observed thermodynamics motivates us to study the evolution of the energy budget in CMEs.** As a result of Wraback et al. [2025], we modified our flux rope parameters to prevent the overexpansion of the flux rope.

4. Charge State Evolution

Figure 3: Average Fe charge state ($\langle Q_{Fe} \rangle$) evolution at t=0.5, 1, 2, and 4 hr posteruption, as the material freezes in.

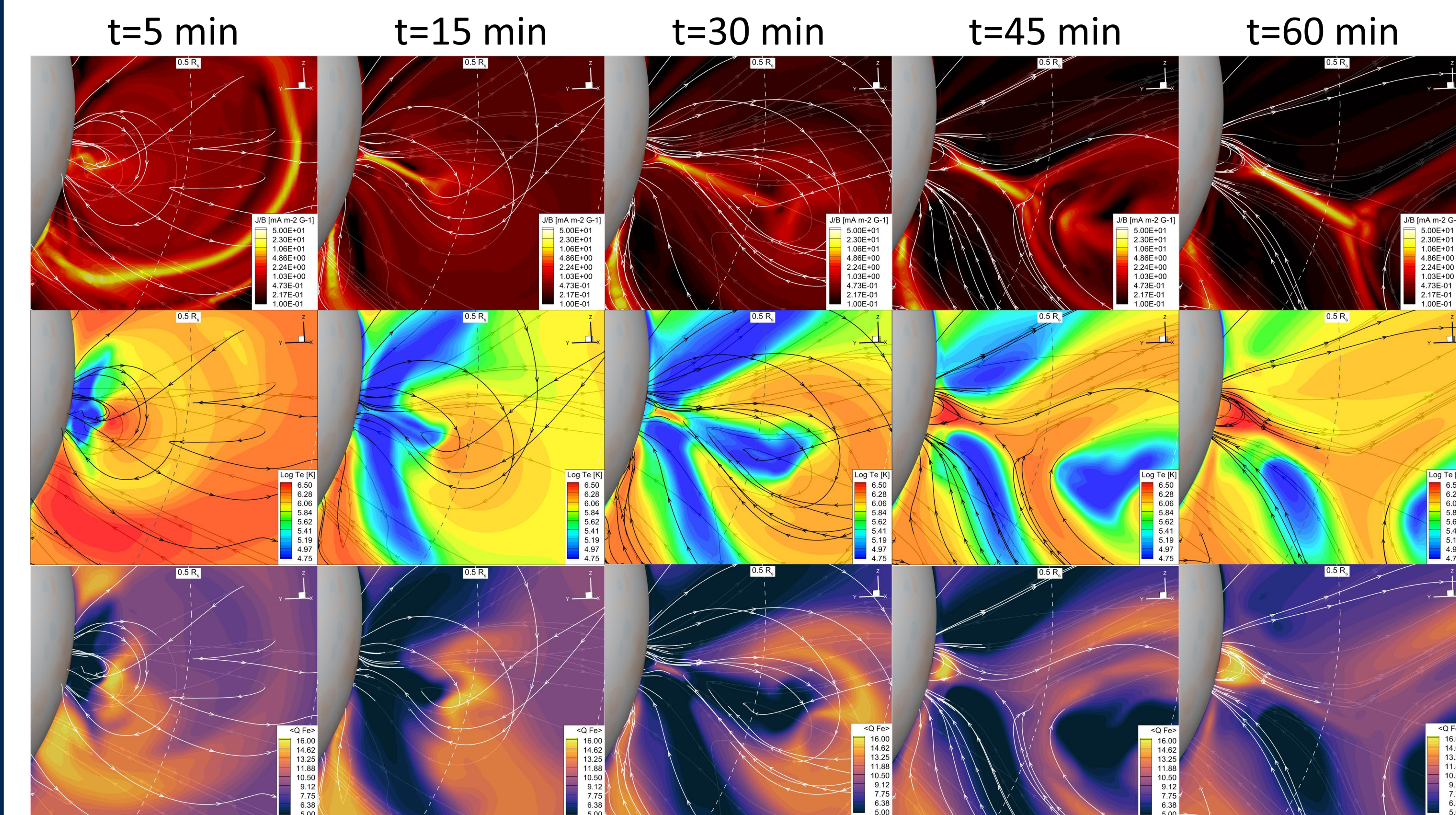


The enhanced temperature and density at the front increases the ionization rate, which causes $\langle Q_{Fe} \rangle \approx 12$ in the sheath. In the CME cavity, the low densities inhibit ionization, leaving the material $\langle Q_{Fe} \rangle \approx 9 - 10$.

The prominence remaining cold, inhibiting ionization, keeping $\langle Q_{Fe} \rangle \approx 3 - 5$ even out to 10 R_s . As the CME expands, the prominence also expands and moves towards the center of the magnetic cloud.

5. Reconnection Heating

Figure 4: A slice through the CME, zoomed in on the reconnection region, showing the current sheet (J/B), electron temperature, and average Fe charge state ($\langle Q_{Fe} \rangle$).



As the CME detaches, a clear current sheet forms. The energy from the reconnection heats the protons and then the electrons, through collisions. **The increased temperature along the legs of the CME, which increases the efficiency of ionization and $\langle Q_{Fe} \rangle \approx 10 - 11$.**

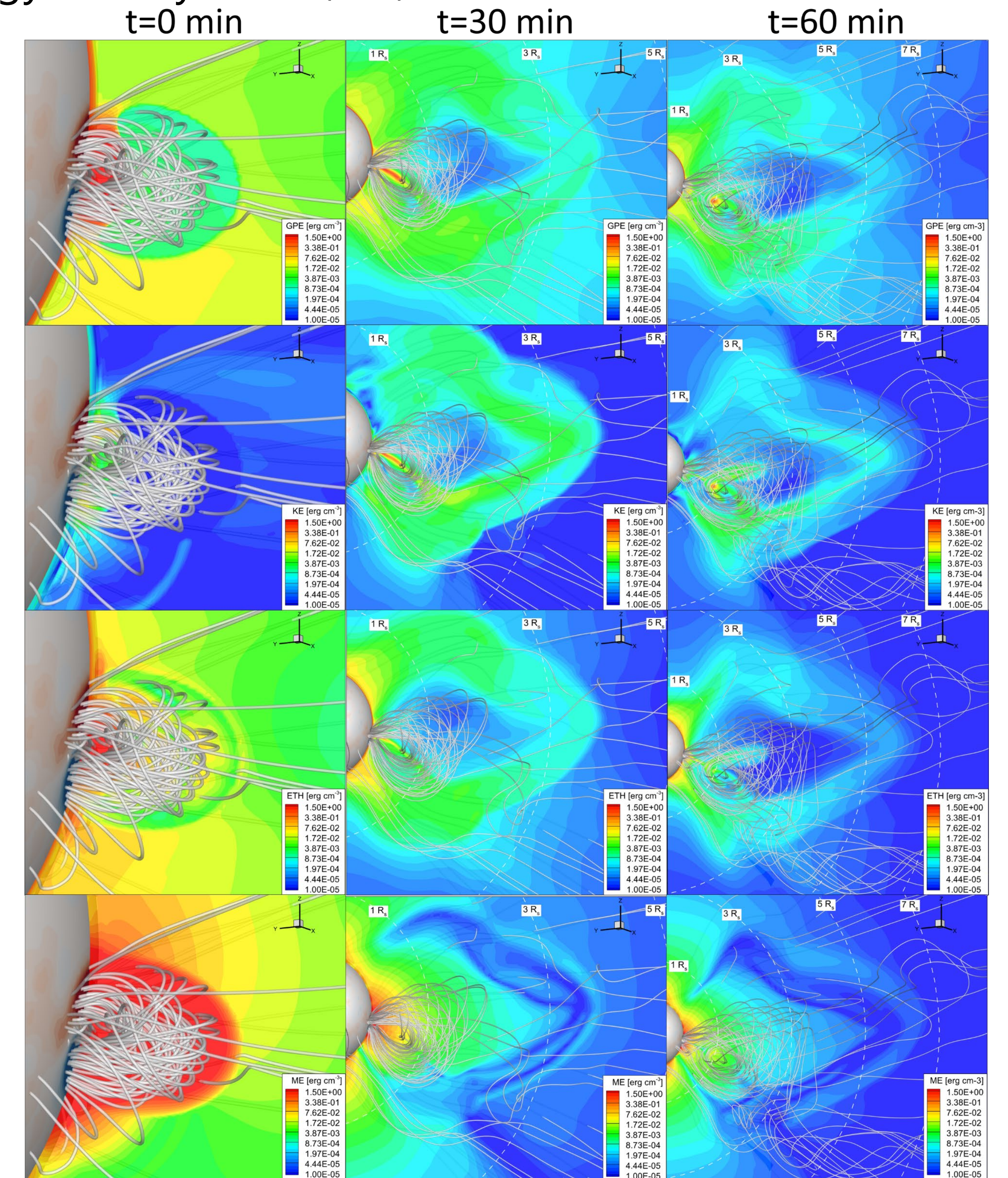
6. Conclusions

We simulated the Cartwheel CME with AWSoM to study the energy budget, in detail, and connect it to charge state evolution.

- Sheaths, with elevated densities and temperatures, due to wave heating, increase the efficiency of ionization, causing $\langle Q_{Fe} \rangle \approx 12$
- Radiative cooling keeps the prominence material cold and inhibits ionization, keeping $\langle Q_{Fe} \rangle$ small out to 10 R_s
- Reconnection heats the backside of the CME, increasing the ionization state relative to the cavity

2. Energetic Quantities

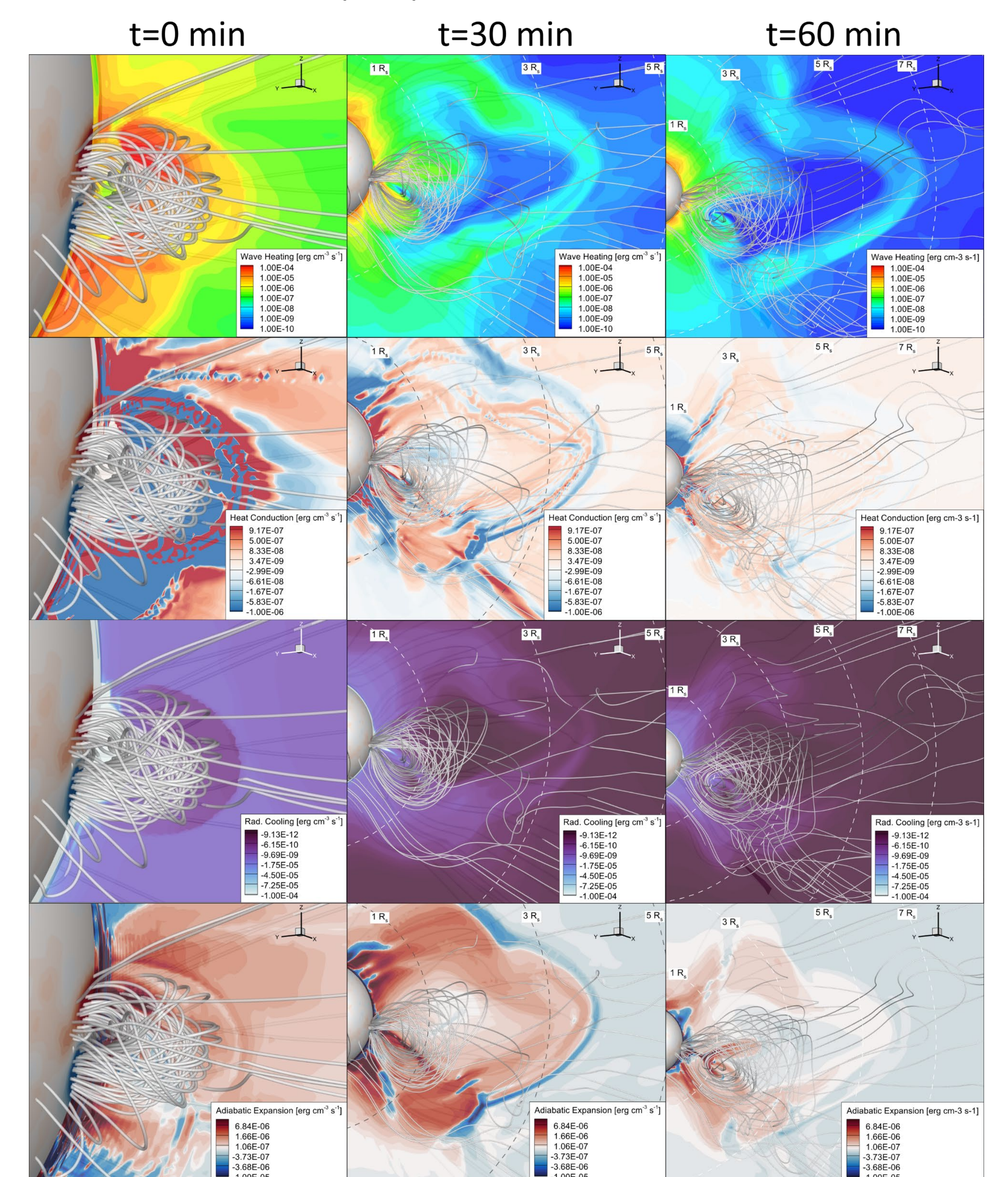
Figure 1: A slice through the CME showing the gravitational potential (GPE), kinetic (KE), thermal (ETH), and magnetic (ME) energy density at t=0, 30, and 60 min.



In the flux rope, the magnetic energy dominates. At the CME-driven compression, there is enhanced density increasing the energy densities. The high density in the prominence dominates its energetic evolution.

3. Heating/Cooling Rates

Figure 2: A slice through the CME showing the Alfvén wave heating, heat conduction, radiative cooling, and adiabatic expansion rates at t=0, 30, and 60 min.



The adiabatic expansion of the CME dominates the cooling of the flux rope. The enhanced density at the CME-driven compression increases the Alfvén wave heating rate. The prominence remains cold due to the radiative cooling rate staying large.

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