Generating CME’s with the Space Weather Modeling Framework

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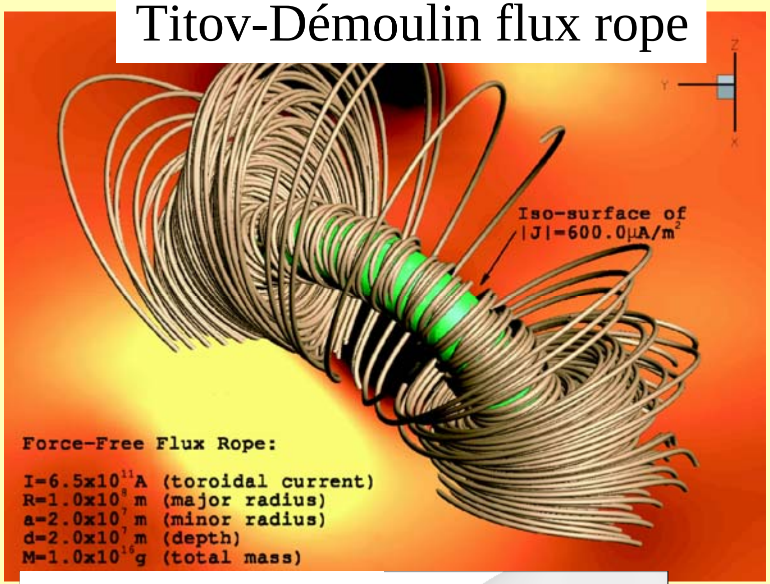
Outline

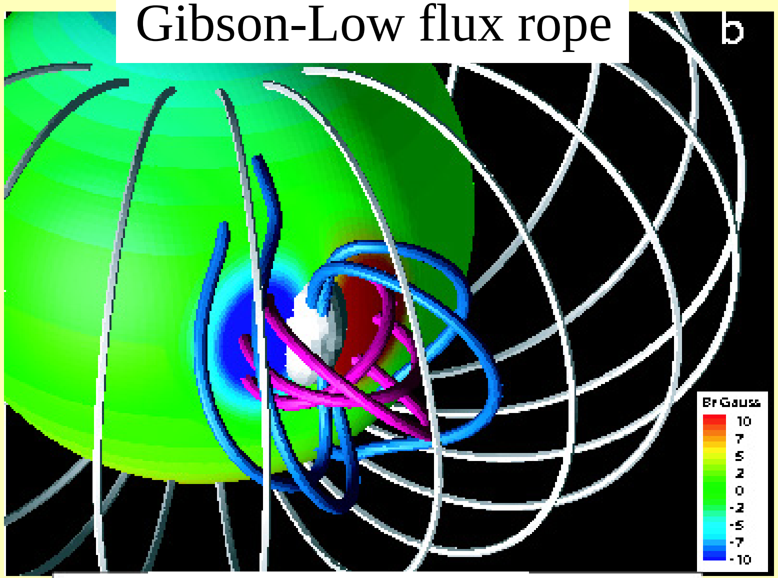
- **CME models in the Space Weather Modeling Framework**
- **The breakout CME**
- **Development of the emerging of magnetic flux ropes from convection zone into the global corona**
  - Radiation MHD in the SWMF
  - Outlook for flux emergence

CME models in the SWMF

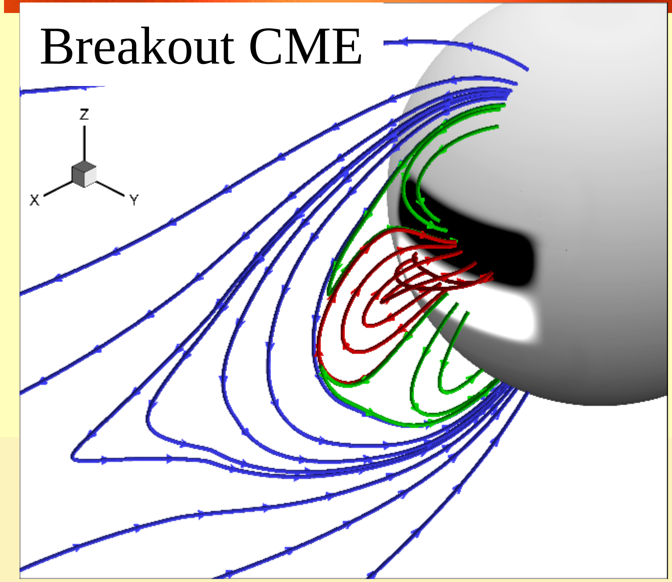
Titov-Démoulin flux rope



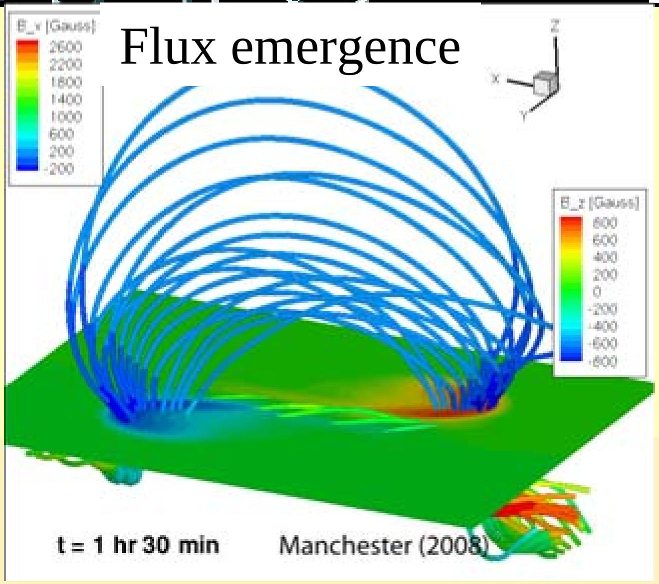
Gibson-Low flux rope



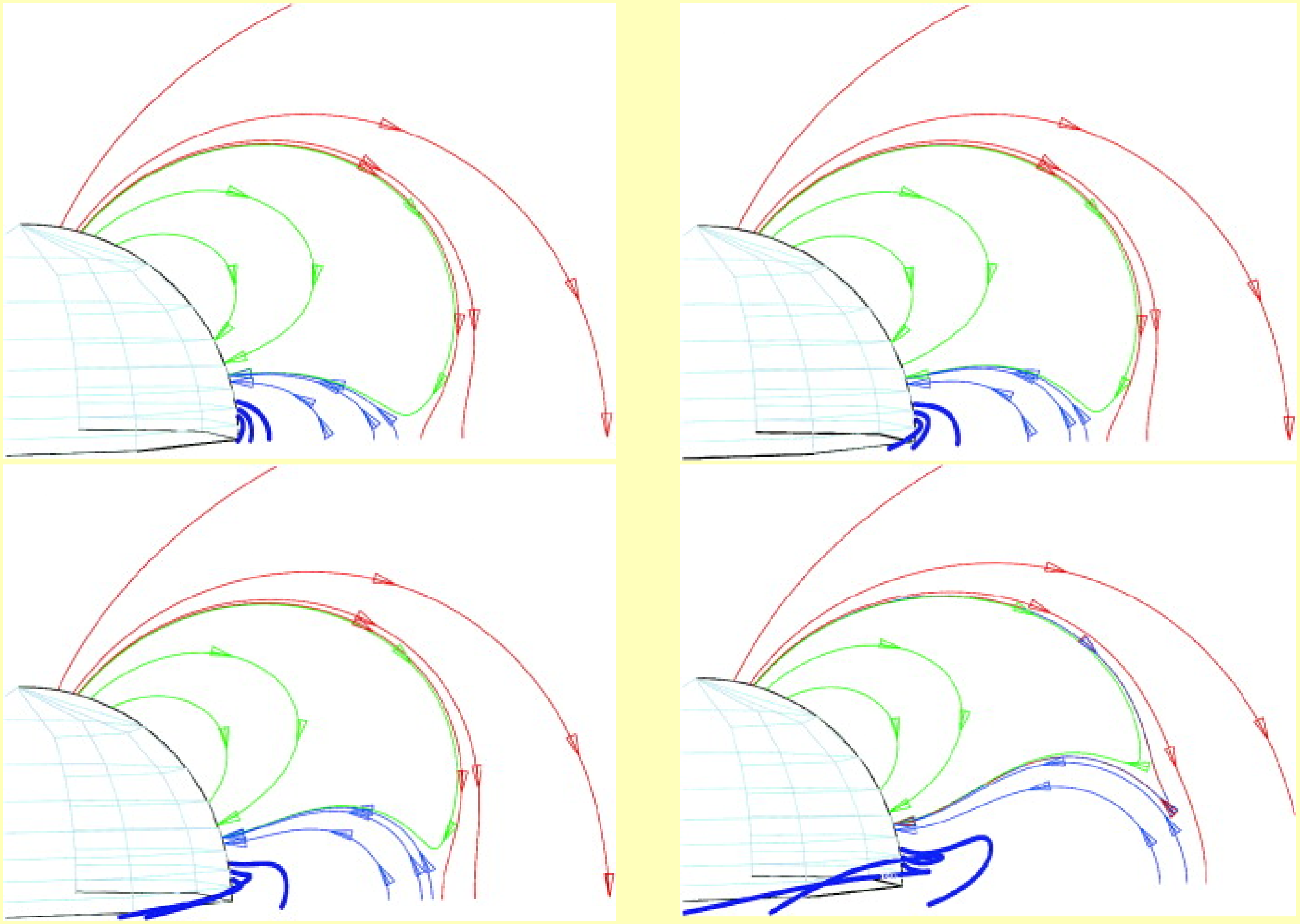
Breakout CME



Flux emergence

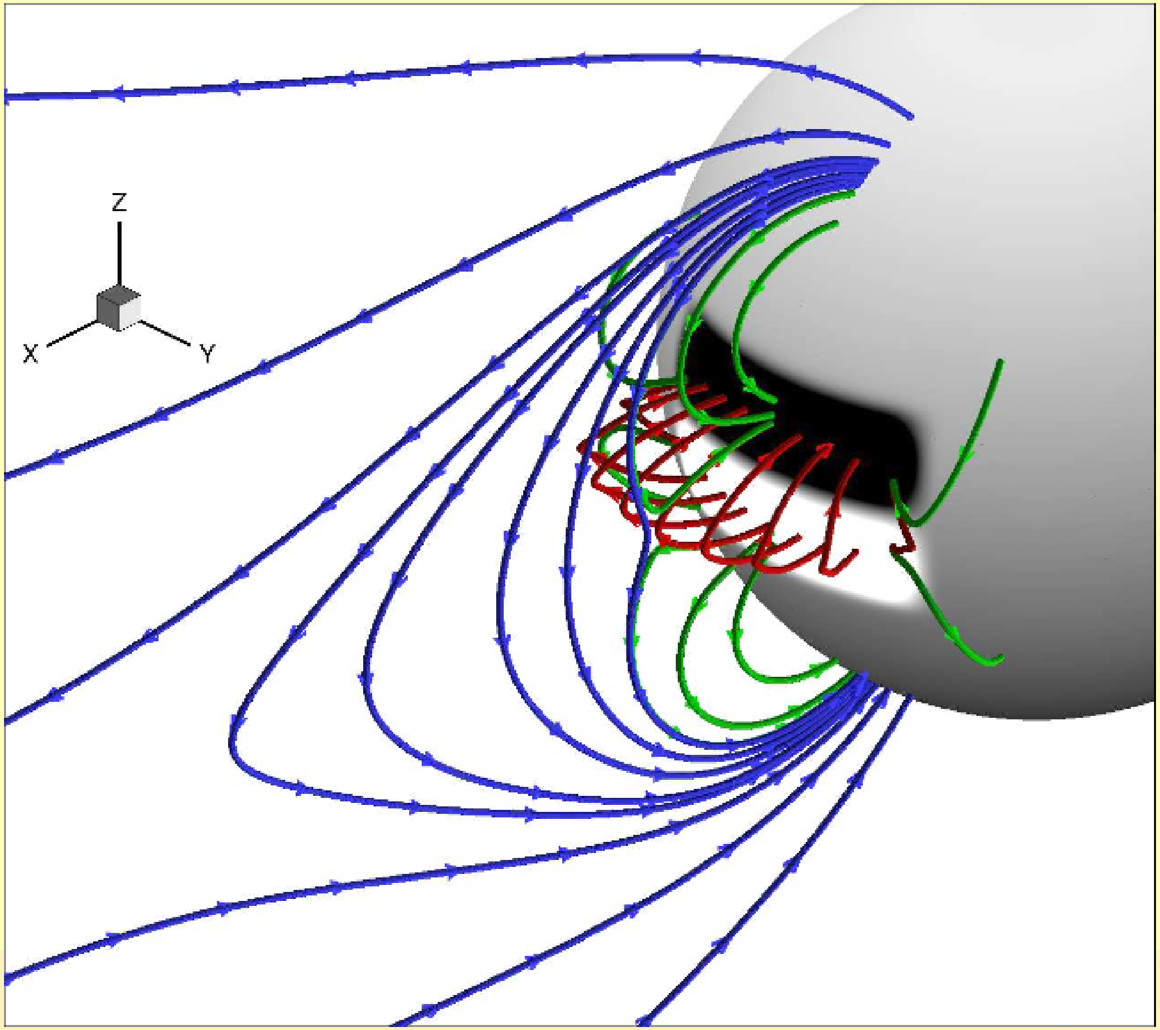


Breakout model
Antiochos, DeVore, and Klimchuck (1999)



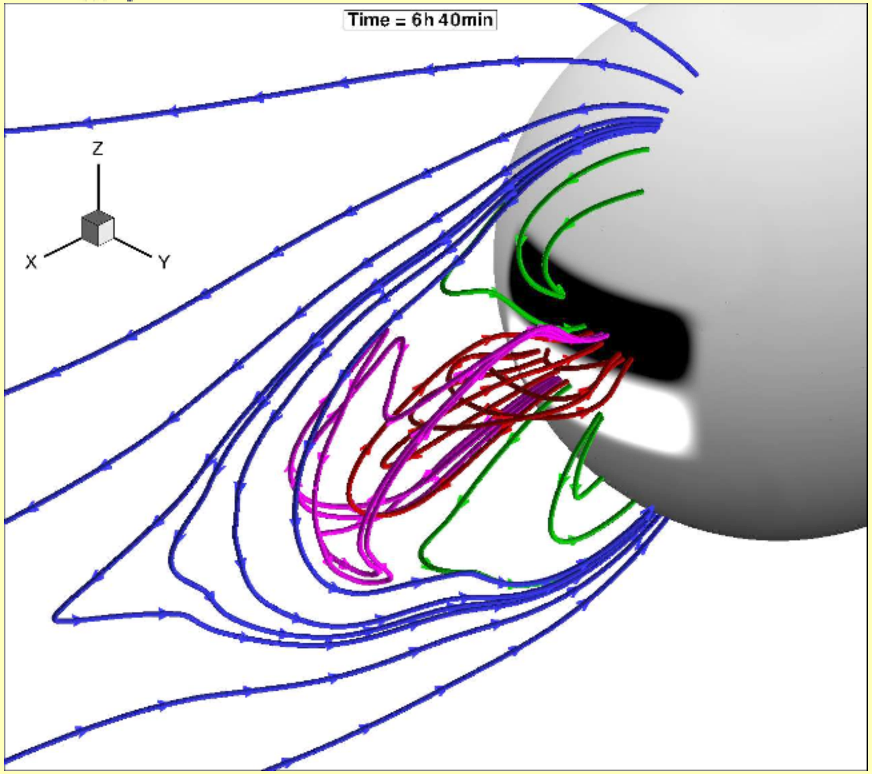
- **How does the breakout CME propagate through the helmet streamer and solar wind?**

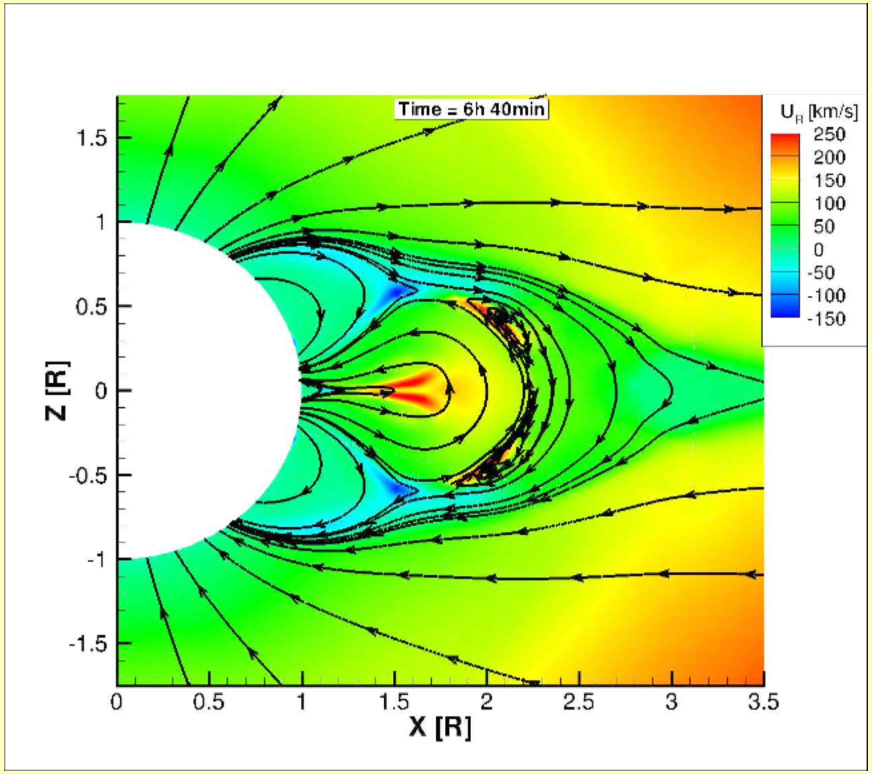
3D breakout CME in a solar wind



- 3D breakout model
- Triple arcade structure with overlying helmet streamer
- CME generating quiescent filament channel is 60° wide
- Maximum unsigned B_r is 14.3 Gauss
- Spherical grid, 8.6 million cells, AMR

3D breakout CME in a solar wind

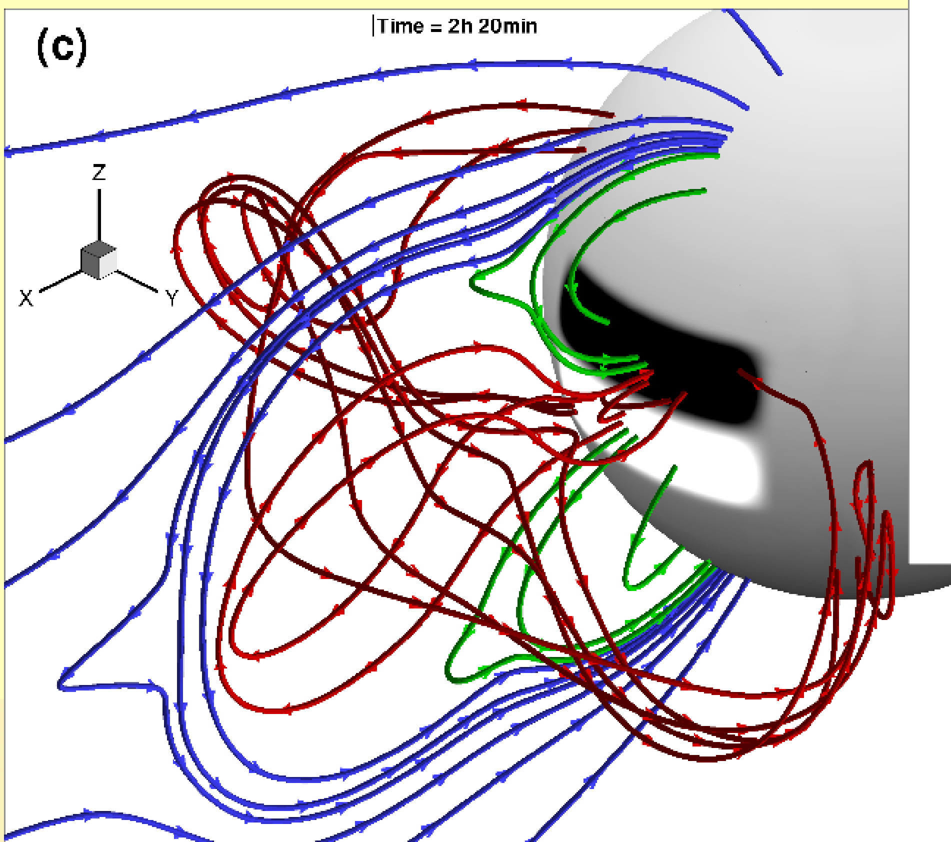


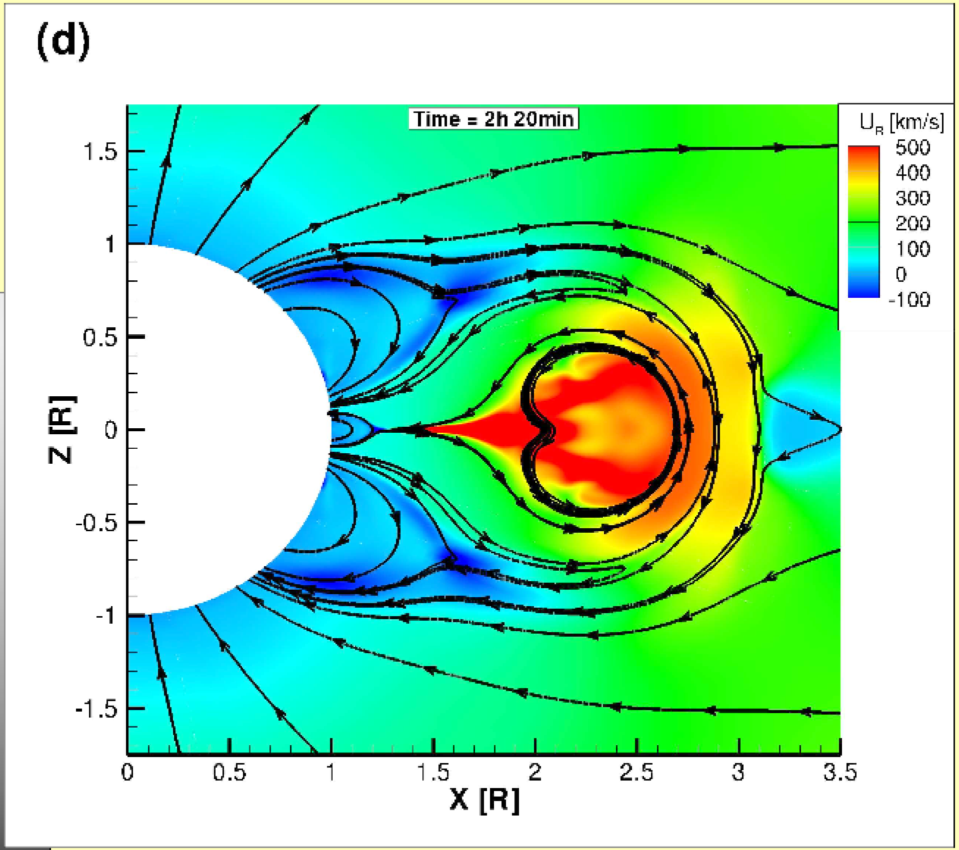


- Maximum shear velocity near PIL is 10 km/s (0.5% alfvén speed)
- Very slow rise of central arcade --> reconnection sets in on the sides --> breakout reconnection fails
- Ejection in mid-plane is favorable for breakout reconnection (more overlying field), but less so for side reconnection

3D breakout CME in a solar wind

- Applied flux conserving flow vortices: velocity near PIL is at most 40 km/s (2% of Alfvén speed)

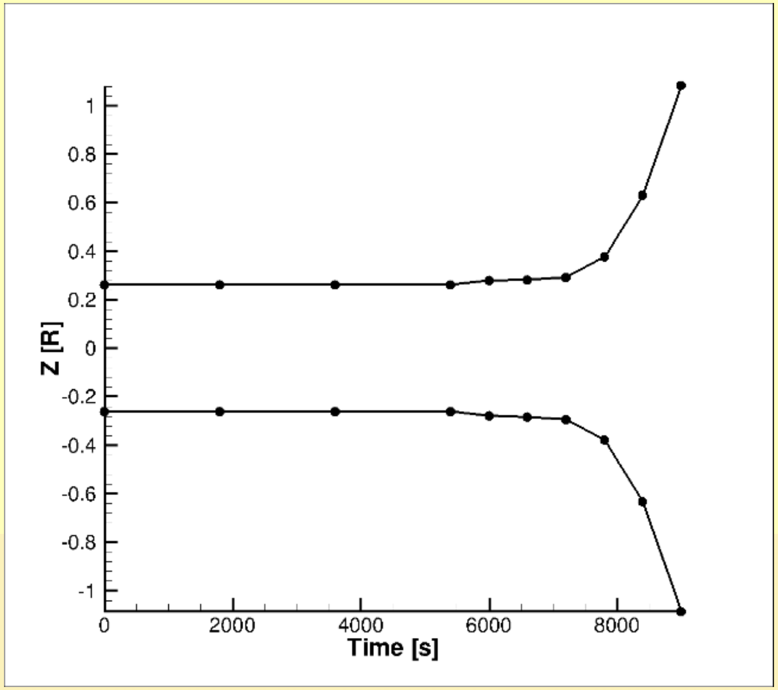


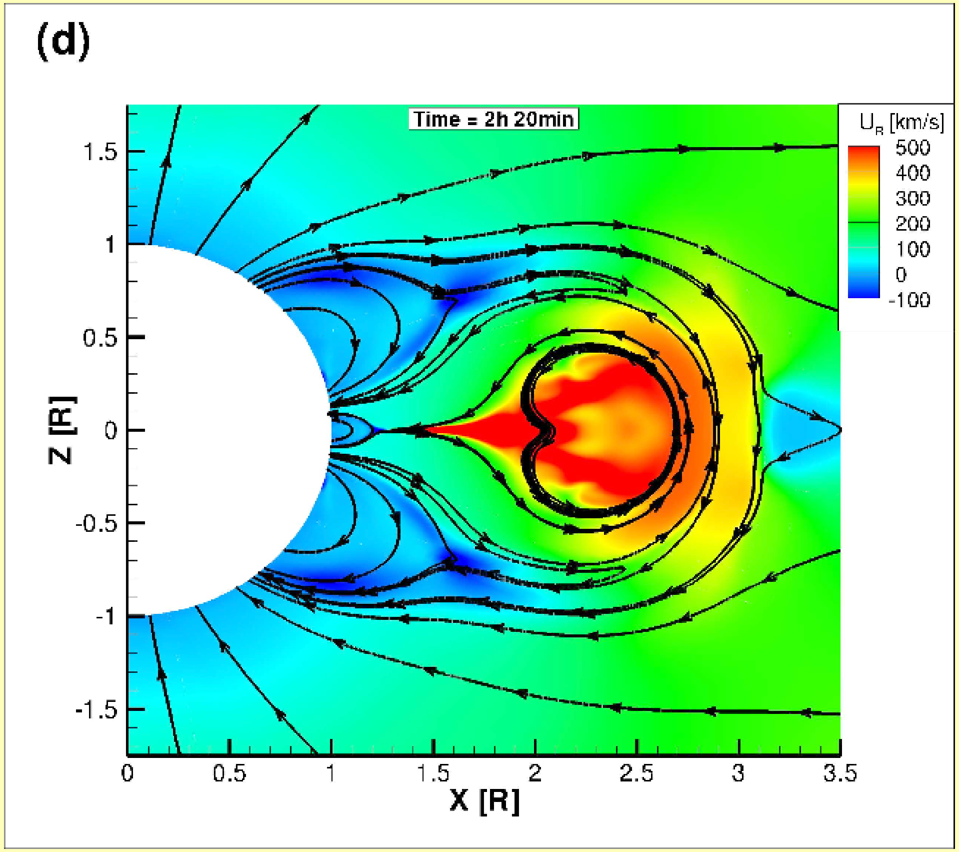


- No side reconnections
- Breakout reconnection succeeds
- Flare reconnection

3D breakout CME in a solar wind

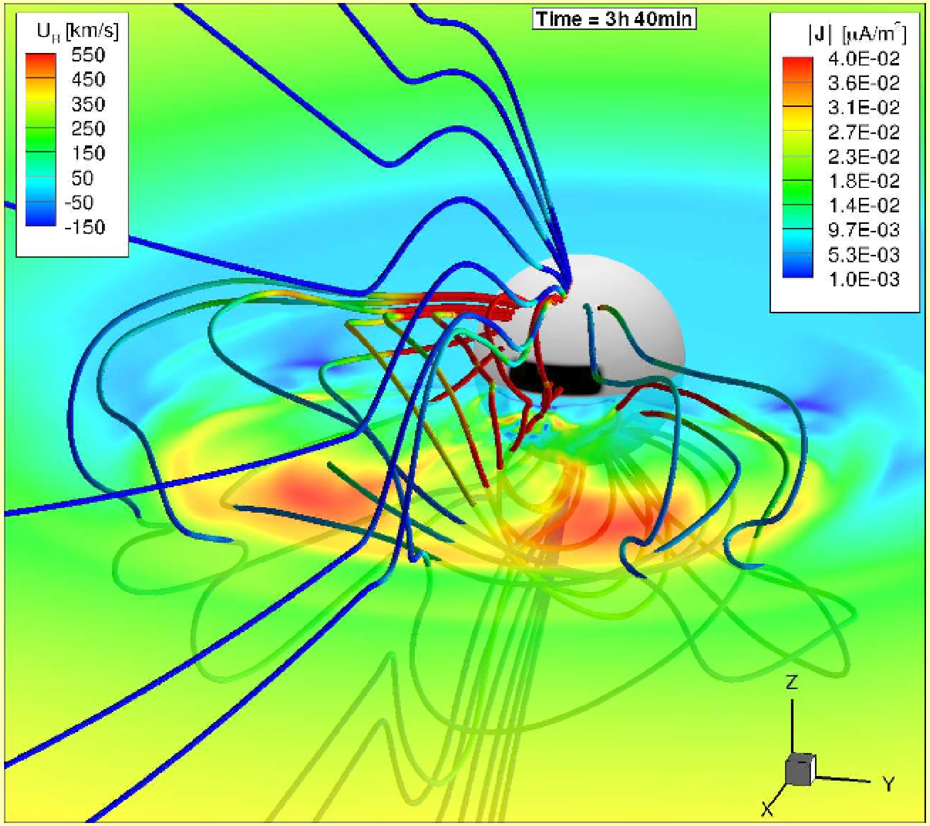
- **Note swept up plasma ahead of the breakout flux rope (snow plowing effect)**
  - =>pre-event swelling of streamer
  - =>facilitates breakout reconnection

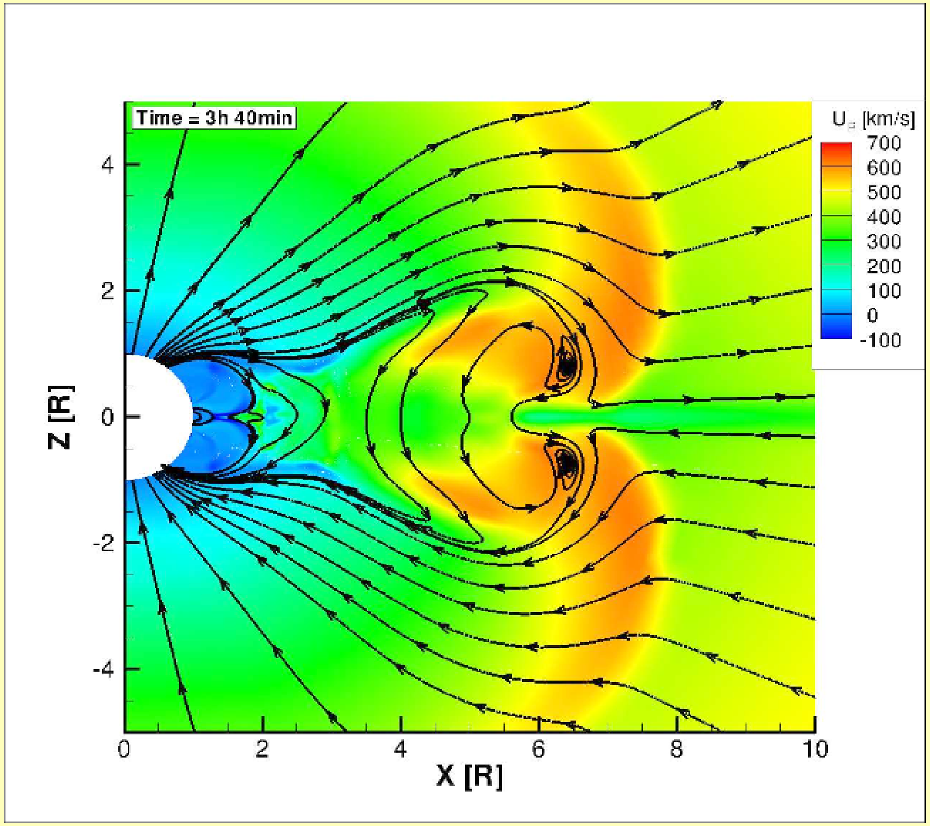




- **Width of helmet streamer at given height increases in time (Bugle pattern, Hundhausen)**

3D breakout CME in a solar wind



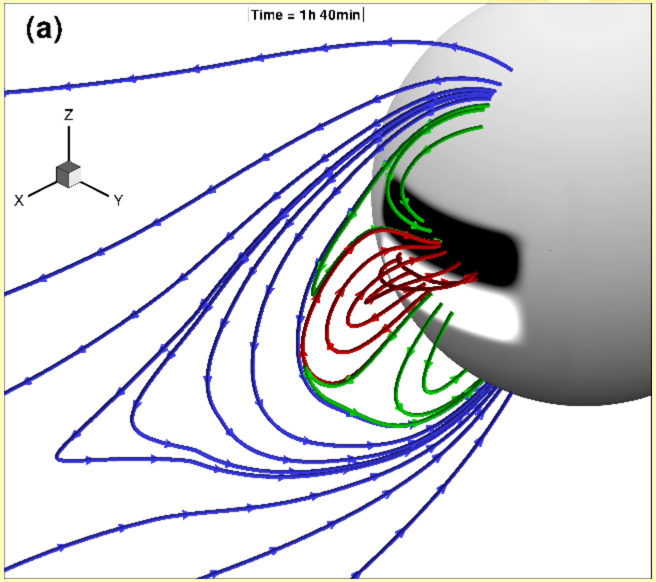


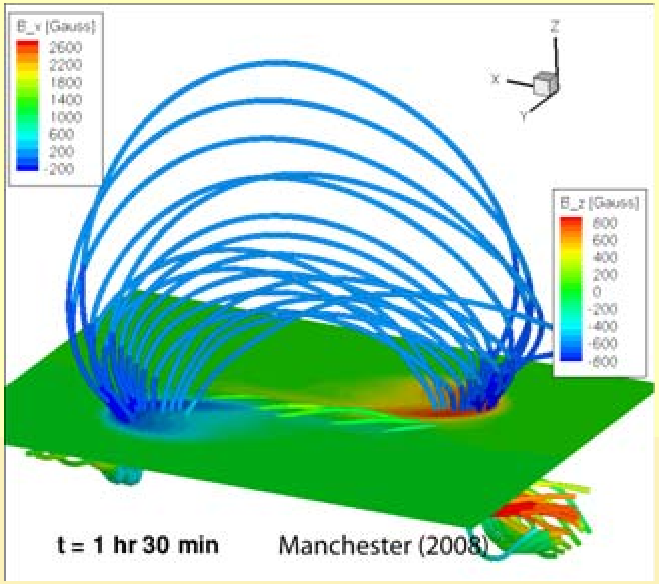
- Maximum velocity of CME is 620 km/s
- Restructuring of helmet streamer

Eruptive Event Generator

- **Empirical: EEE**
  - Titov-Demoulin flux rope (Roussev)
  - Gibson-Low flux rope (Manchester)
  - breakout CME

- **Physics based: EE**
  - Standalone BATS-R-US in a 3D box
  - In progress: model the emergence of a flux rope from the convection zone into the corona
  - To do: coupling with the global coronal model





Radiation models

- **The Center for Radiative Shock Hydrodynamics (CRASH) at the University of Michigan is advancing predictive science of radiation hydrodynamics.**
- **Three radiation models that are (to be) developed in the SWMF as part of the CRASH project**
  - Discrete ordinates radiation transfer describing the evolution of the spectral radiation intensity $I_\nu(x,t;\Omega,\nu)$ accounting for emission, absorption, and scattering.
  - Multi-group flux limited diffusion
  - Non-equilibrium gray radiation diffusion
- **The Gray-Diffusion will soon be used for the deeper layers of the convection zone**

Gray-Diffusion radiation model in SWMF

- (Near) conservation of mass, momentum, energy, radiation energy (magnetic field not shown)

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0,$$

$$\frac{\partial \rho \mathbf{u}}{\partial t} + \nabla \cdot [\rho \mathbf{u}\mathbf{u} + p\mathbf{I}] + \nabla p_{\mathrm{rad}} = 0,$$

pressure force

$$\frac{\partial E}{\partial t} + \nabla \cdot [(E + p)\mathbf{u}] + \mathbf{u} \cdot \nabla p_{\mathrm{rad}} = \kappa_{\mathrm{P}} c (E_{\mathrm{rad}} - a T_{\mathrm{e}}^4),$$

Advection and compression

energy exchange

diffusion

$$\frac{\partial E_{\mathrm{rad}}}{\partial t} + \nabla \cdot [E_{\mathrm{rad}} \mathbf{u}] + p_{\mathrm{rad}} \nabla \cdot \mathbf{u} = -\kappa_{\mathrm{P}} c (E_{\mathrm{rad}} - a T_{\mathrm{e}}^4) + \nabla \cdot [\frac{c}{3\kappa_{\mathrm{R}}} \nabla E_{\mathrm{rad}}],$$

- **Isotropic:** $p_{\mathrm{rad}} = \frac{E_{\mathrm{rad}}}{3}$
- **Planck mean opacity:** $\kappa_{\mathrm{P}} = \kappa_{\mathrm{P}}(\rho, T_{\mathrm{e}})$
- **Rosseland mean opacity:** $\kappa_{\mathrm{R}} = \kappa_{\mathrm{R}}(\rho, T_{\mathrm{e}})$

Radiation flux limiter

- **Diffusion theory shows too rapid energy transport when photon mean free path is comparable to length scales in the flow.**
- **Introduce radiation flux limiter to restrict energy transport to physically allowable values (of the free streaming limit).**
- **The Rosseland mean opacity is modified by including gradient of radiation energy:**

$$\kappa_{\mathrm{R}} = \kappa_{\mathrm{R}}(\rho, T_{\mathrm{e}}, \|\nabla E_{\mathrm{rad}}\| / E_{\mathrm{rad}})$$

- **This fix is convenient but lacks the accuracy and consistency of the full transport equation.**

Operator-split, semi-implicit

- **During the *explicit* hydro step we solve the hydro equation including advection, compression, and pressure force of radiation**
- **Numerical schemes that are stabilized by numerical diffusion proportional to the wave speeds, need to include radiation for stability:**

$$c_{\mathrm{sound}} = \sqrt{\frac{\gamma p + \gamma_{\mathrm{rel}} p_{\mathrm{rad}}}{\rho}}, \quad \gamma_{\mathrm{rel}} = 4/3$$

Operator-split, semi-implicit

- After explicit hydro step, solve radiation diffusion and energy exchange ***implicitly***:

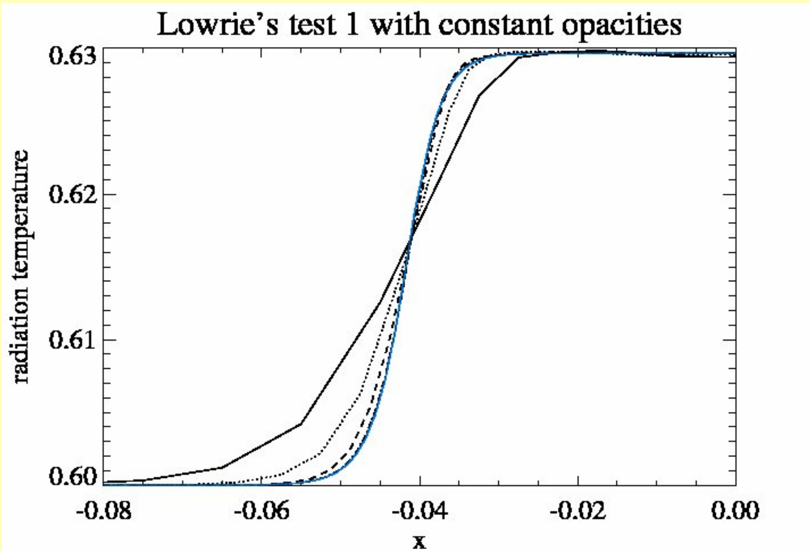
$$\frac{\partial E}{\partial t} = \kappa_\mathrm{P} c (E_\mathrm{rad} - aT_\mathrm{e}^4),$$

$$\frac{\partial E_\mathrm{rad}}{\partial t} = -\kappa_\mathrm{P} c (E_\mathrm{rad} - aT_\mathrm{e}^4) + \nabla \cdot [\frac{c}{3\kappa_\mathrm{R}} \nabla E_\mathrm{rad}],$$

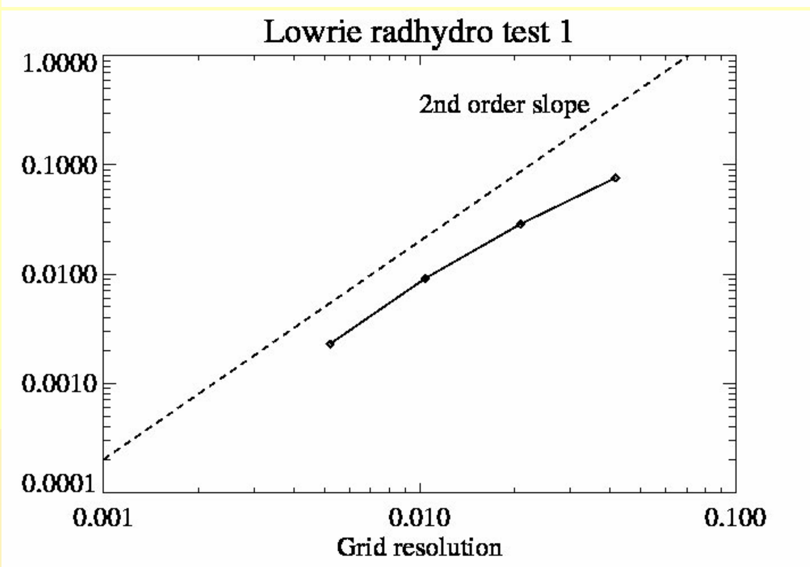
- Linearize in terms of $B=aT_e^4$ and E_{rad}
- This introduces "specific heat": $C_\mathrm{e} = \partial E / \partial B$
- Employ principle of frozen coefficients during linear solve.
- Linear problem has symmetric and positive definite matrix and is solved using preconditioned conjugate gradient.

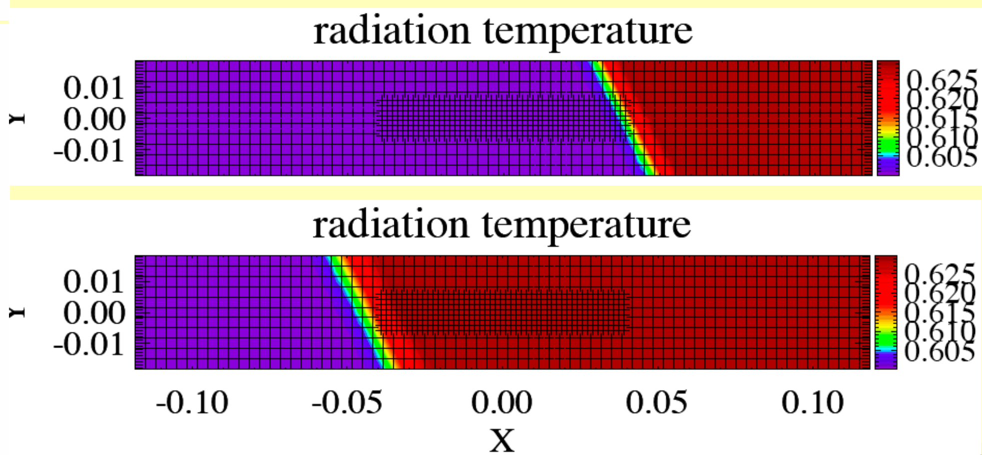
- Once the temperature is updated, the conservative energy is updated by: $E^{n+1} = E^n + C_\mathrm{e}(B^{n+1} - B^n)$
- Point implicitly solve Planck term if no heat conduction

Mach 1.05 RadHydro verification

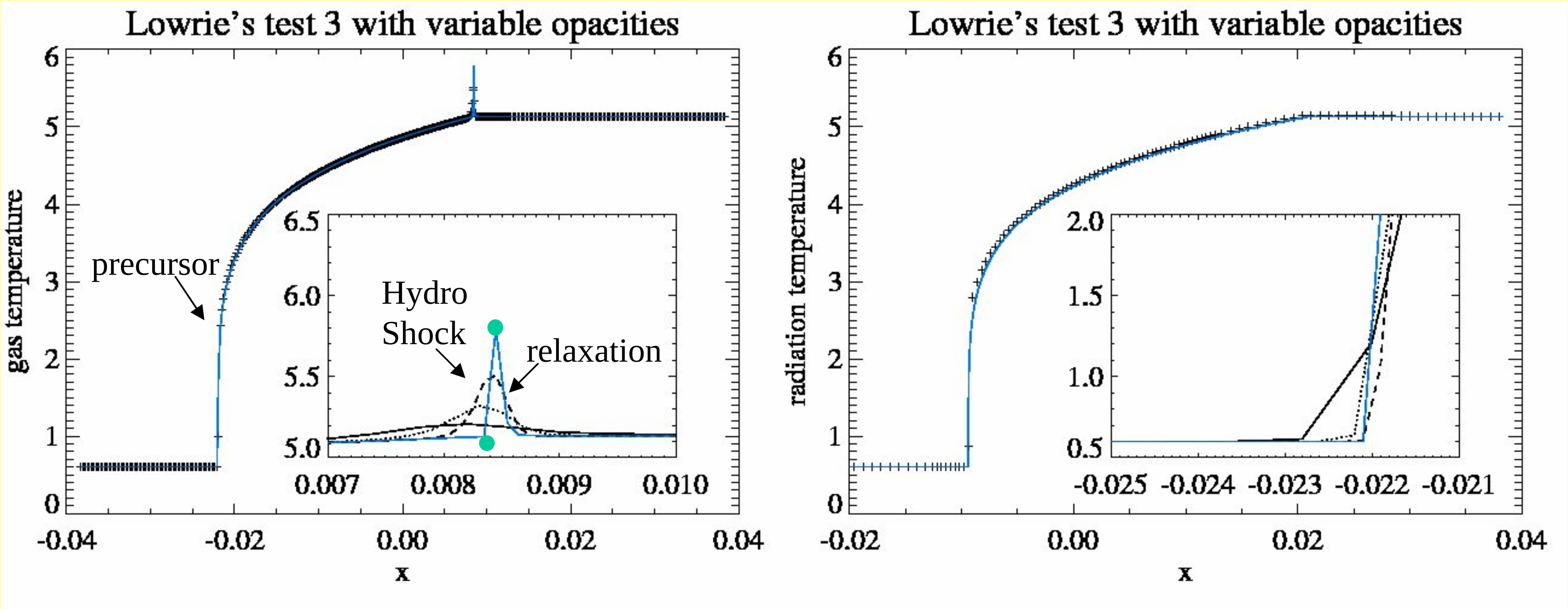


- Initial condition is the semi-analytical constant opacity, mach 1.05 solution of R. Lowrie
- Solution is advected with mach 1.05 on a rotated non-uniform grid





Mach 5 RadHydro verification



- **Initial condition is the semi-analytical mach 5 solution using Kramer's formula for the opacities** $\kappa = \kappa_0 \rho T^{-3.5}$
- **Solution is advected orthogonal to shock front with mach 5 on a rotated non-uniform grid**

Outlook

- Radiation MHD is being adapted to treat the convection zone and coronal base (Eruptive Event generator). Will then be coupled to the global solar corona.