Fully 3D Modeling of Prominence Formation by Plasma Evaporation and Condensation

Research Supported through NASA H-SR Grant NNX15AR13G

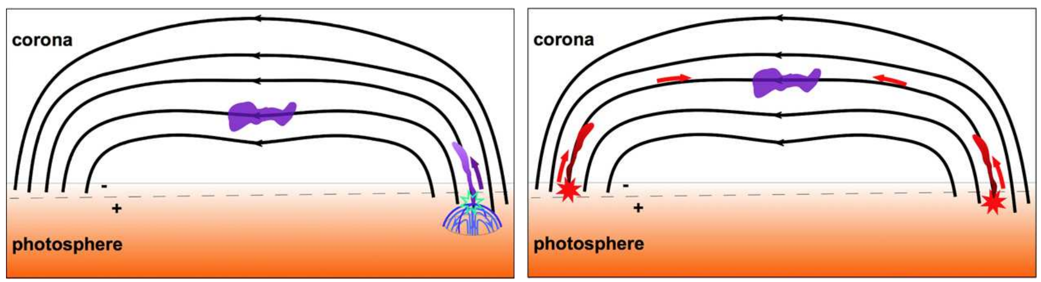
Roberto Lionello[1], Tibor Török[1], Cooper Downs[1],
Zoran Mikić[1], Jon A. Linker[1]

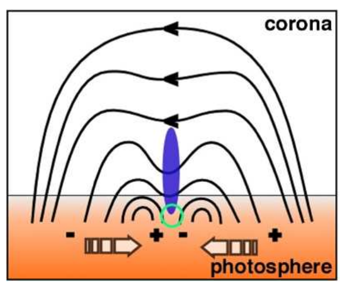
lionel@predsci.com

1 Predictive Science, Inc.

Introduction

- Prominences are cold an dense structures suspended by $\mathbf{B}$ in the corona; range from small, short-lived AR filaments to long-lived, huge polar-crown filaments.
- Formation mechanisms of coronal prominences are not well understood. We know mas has to come from chromosphere, since corona does not have enough mass. But how?
- Three possible mechanisms: injection, levitation, evaporation/condensation.

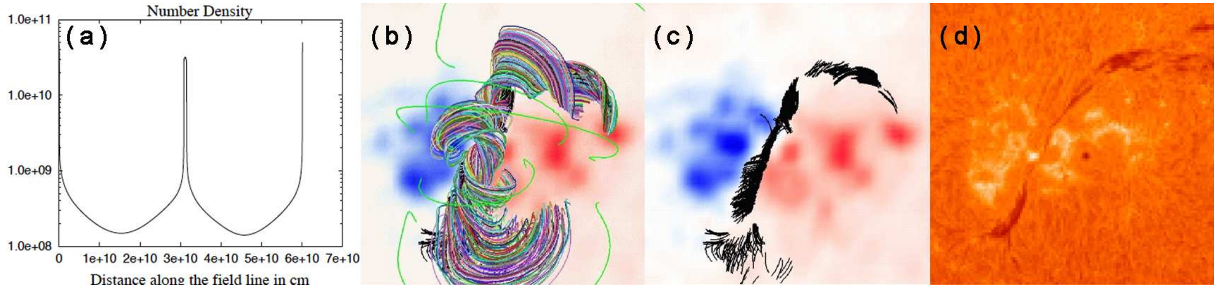


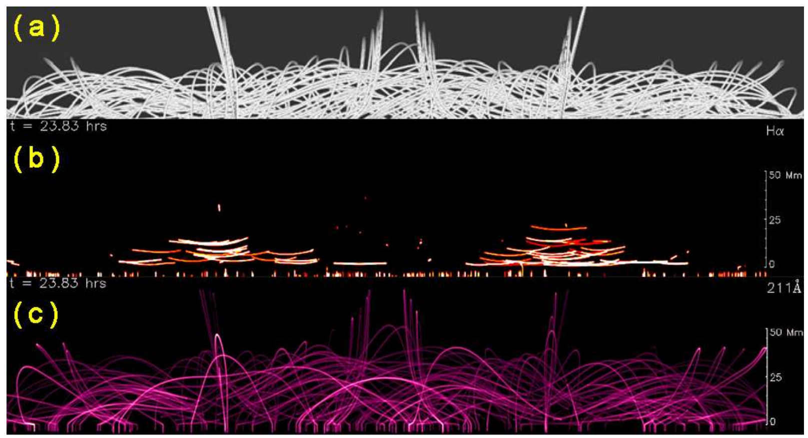


Cartoons of the three main scenarios for prominence formation (Mackay et al. 2010): chromospheric plasma injection by small-scale jets or spicules (top left); levitation by rising magnetic f elds (left); evaporation and subsequent condensation in the corona (top right).

- We focus on the EC mechanism and model the formation and internal dynamics of prominences, using a fully 3D MHD treatment of the thermodynamics and time-dependent magnetic fields.

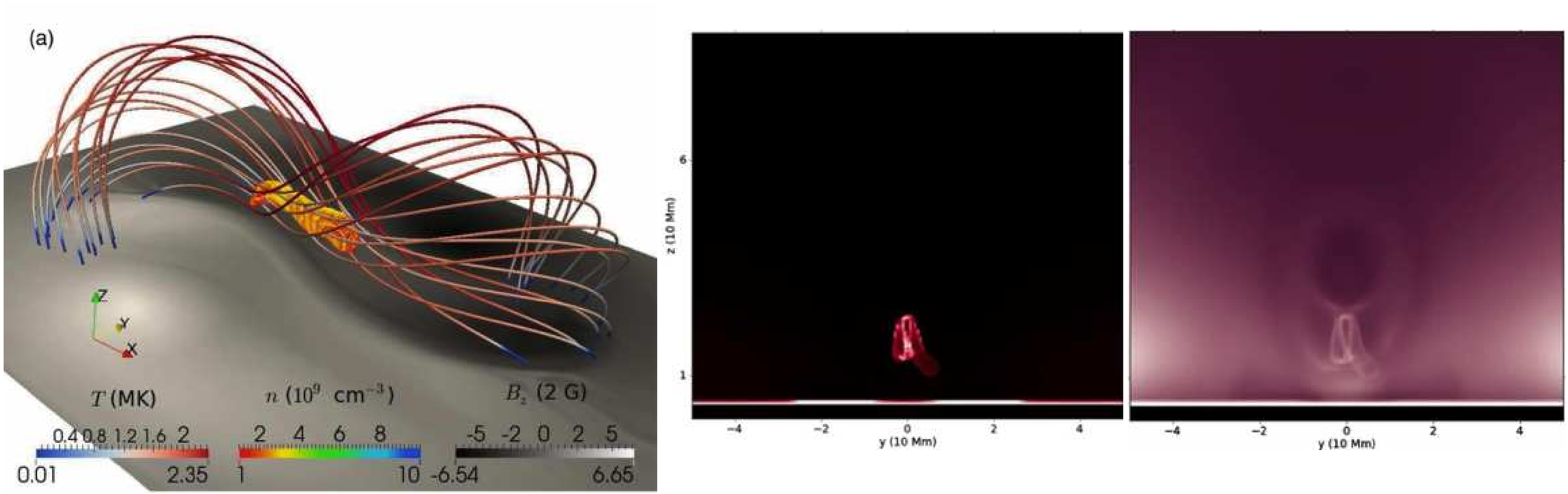
1D Simulations





- Top: 1D thermodynamic calculation (a) along a static field line of a 3D magnetic field configuration (b) from an observed magnetogram. Plasma condensation occurs in the dips. Black threads in (c) outline the locations of field line dips in the whole configuration, in agreement with observed filament (d). From Lionello et al. (2002).
- Bottom: 1D thermodynamic calculations along many flux tubes with varying cross-sectional area of an idealized sheared-arcade configuration (a). Synthetic emission images for an Hα proxy (b) and the SDO/AIA 211 Å (c). From Luna, Karpen, DeVore, (2012).

3D Simulations



- Fully 3D thermodynamic MHD simulation using an idealized, time-dependent magnetic field (from Xia et al. 2014). **Left:** the accumulation of dense and cold material in the center of a flux rope. **Center:** synthetic SDO/AIA 304 Å; **Right:** synthetic SDO/AIA 211 Å integrated along the flux rope axis, showing enhanced emission at the edge of the plasma sheet (the prominence-corona transition-region) and the presence of a barb on the right-hand side of the prominence. The 211 Å image shows a coronal cavity.

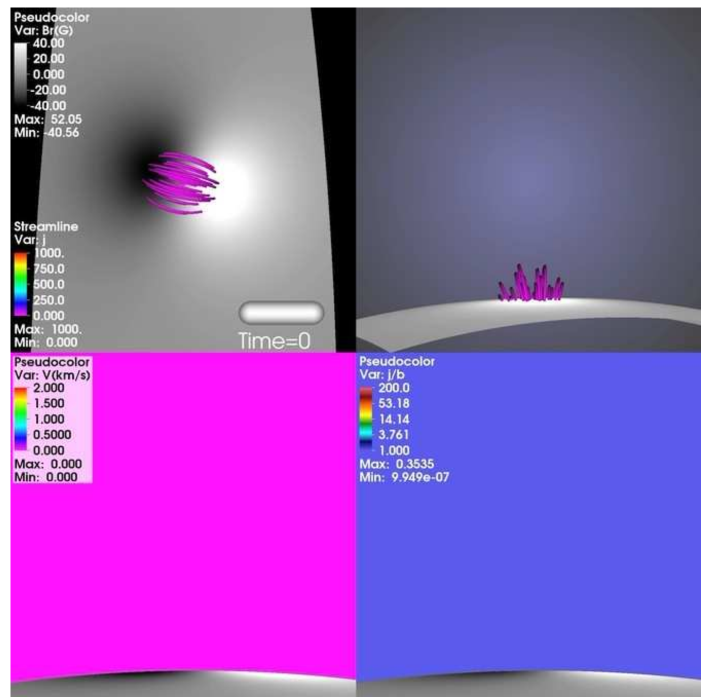
The Thermodynamic MHD Model

$$
\begin{aligned}
\nabla \times \mathbf{A} &= \mathbf{B}, \\
\frac{\partial \mathbf{A}}{\partial t} &= \mathbf{v} \times \mathbf{B} - \frac{c^2 \eta}{4\pi} \nabla \times \mathbf{B}, \\
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) &= 0, \\
\frac{1}{\gamma - 1} \left(\frac{\partial T}{\partial t} + \mathbf{v} \cdot \nabla T \right) &= -T \nabla \cdot \mathbf{v} \\
&\quad - \frac{m}{k\rho} (\nabla \cdot \mathbf{q} + n_e n_p Q(T) - H_{\mathrm{ch}}), \\
\rho \left(\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \cdot \nabla \mathbf{v} \right) &= \frac{\nabla \times \mathbf{B} \times \mathbf{B}}{4\pi} - \nabla p + \rho \mathbf{g} + \nabla \cdot (\nu \rho \nabla \mathbf{v}), \\
\gamma &= 5/3.
\end{aligned}
$$

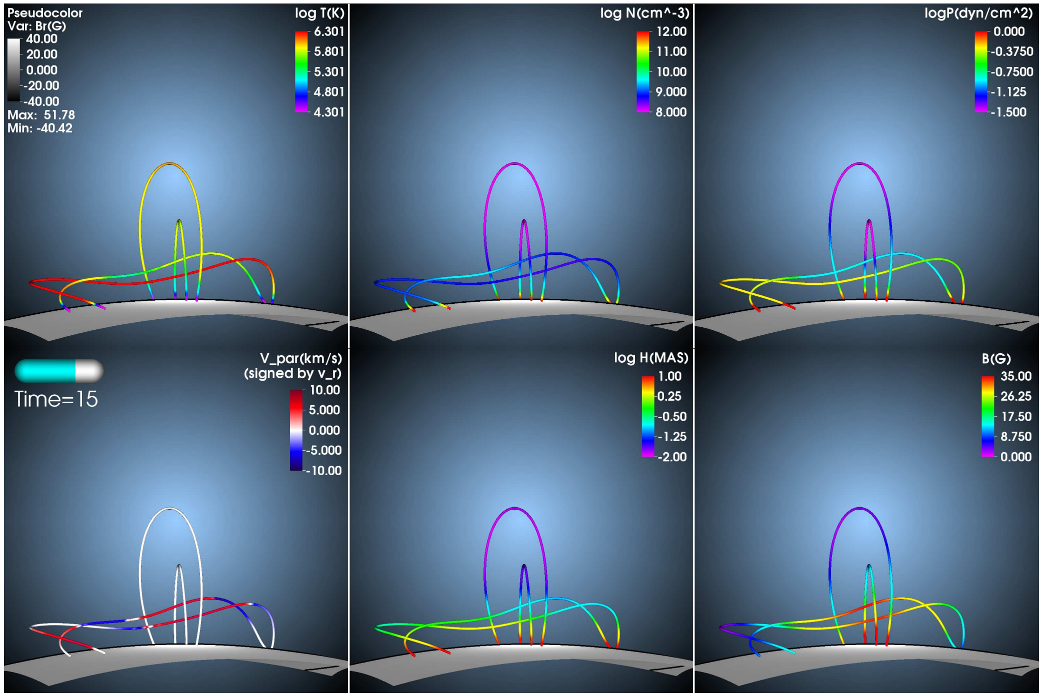
3D Flux Rope With Selected 1D Solutions

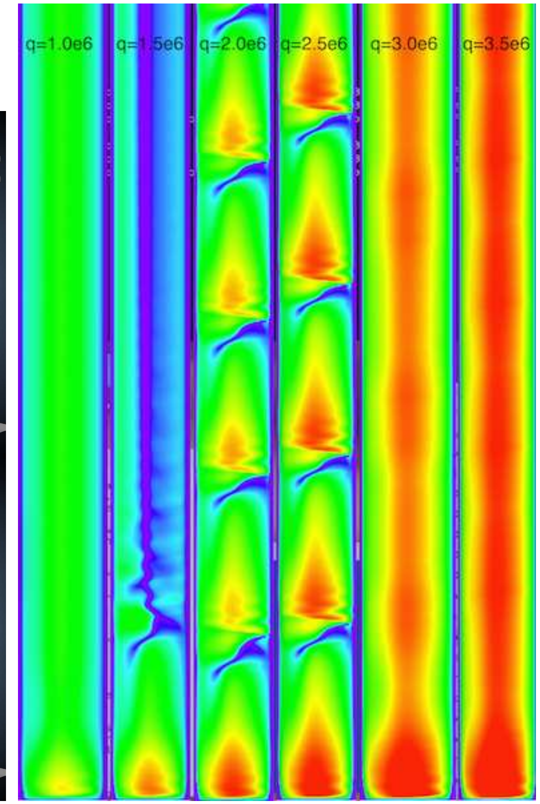
- We construct a bipolar region.
- We impose (emerge) axial field along the PIL at the lower boundary and form a sheared arcade.
- We apply converging flows towards PIL (flux cancellation), transforming the arcade into a flux rope.
- We stop the flows before flux rope would erupt and relax for a while (all this is done in zero beta).

- We extract the flux rope and insert into 1D SW-solution background, switch on thermodynamics (no solar wind is used; $\mathbf{v}$ at upper boundary is zero).
- Heating used so far: combination of two exponentials, one with short scale-length (for flux rope) and one with large scale-length (for corona).



1D Solutions

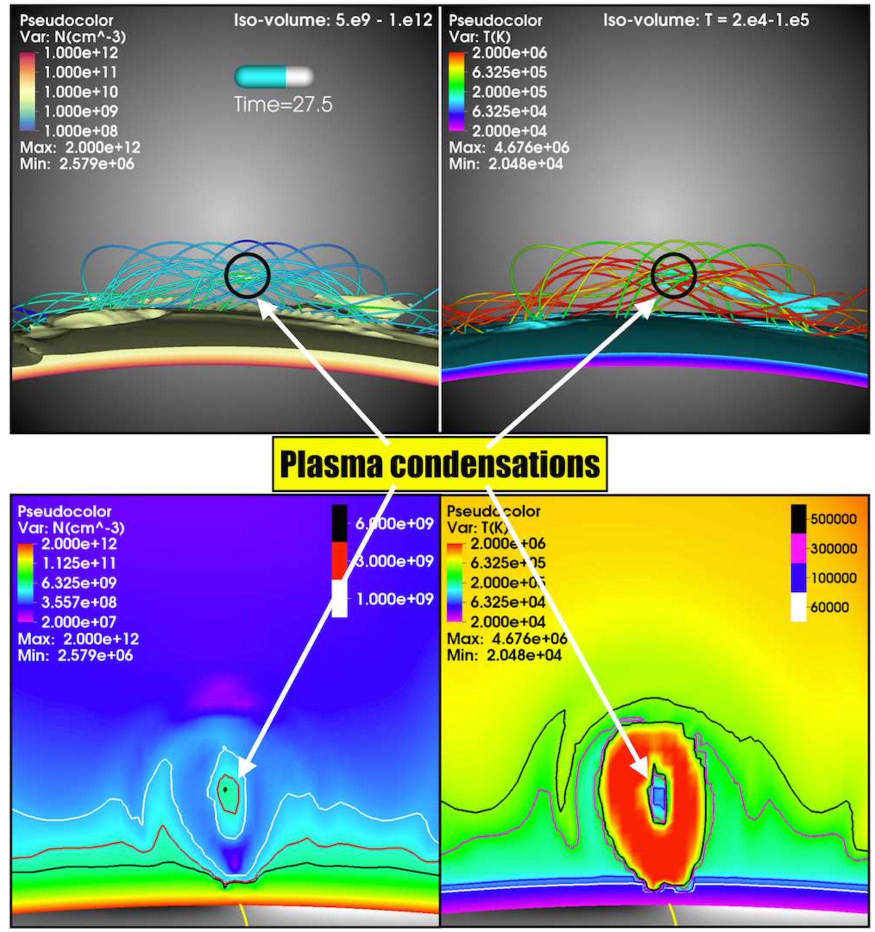




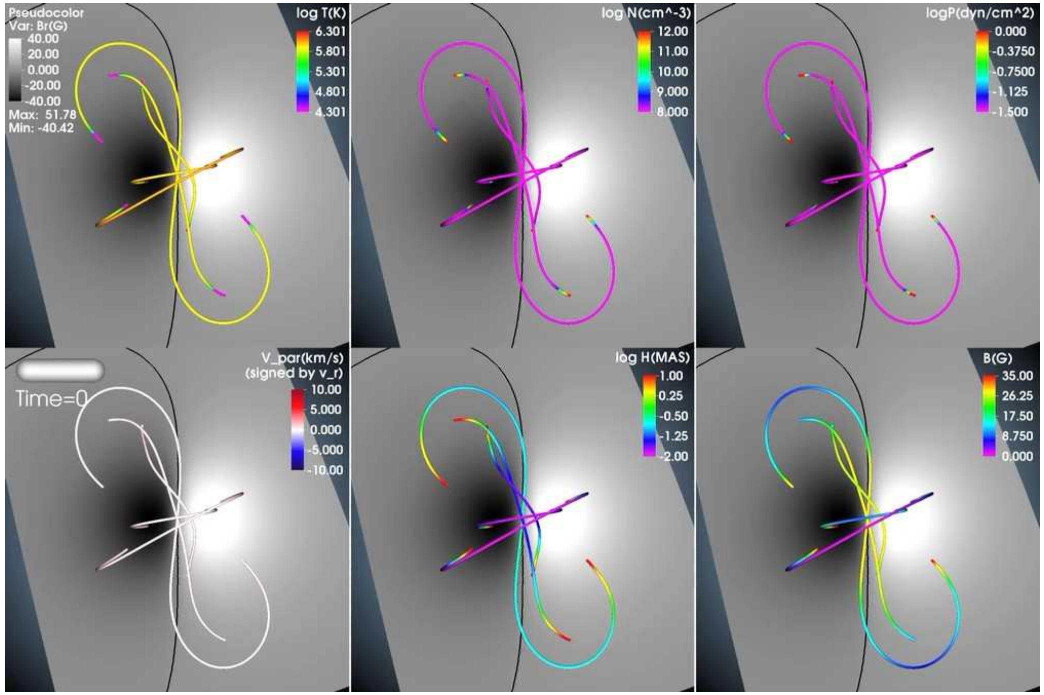
- **Left:** Representative field lines of 3D flux rope configuration, along which 1D loop simulations were performed. Field lines are colored according to $\log T$, $\log n$, $\log P$, $v_{||}$, H, B. The magnetogram, B_r, in G.
- **Right:** Series of 1D simulations along one of the flat field lines shown on the left, using exponential heating. The x axis is the length along the field line, the y axis is time. Plasma temperatures in the range 20,000 K (purple) to 3 MK (red) are depicted in rainbow colors. Six simulations with different total heat flux, q, are shown, with q increasing from left to right.

Plasma Condensations in Fully 3D MHD

- Top panels: field lines of the flux rope colored by plasma density (left) and temperature (right), with iso-volumes of these quantities within the range given in the respective top right corner. at upper boundary is zero).
- Bottom panels: density and temperature in vertical cuts through the flux rope oriented such that the rope axis is perpendicular to the cut. Parcels of cold and dense plasma indicated by black circles in the top panels are visible in these planes.
- Strong heating in the dips destroy the condensations.

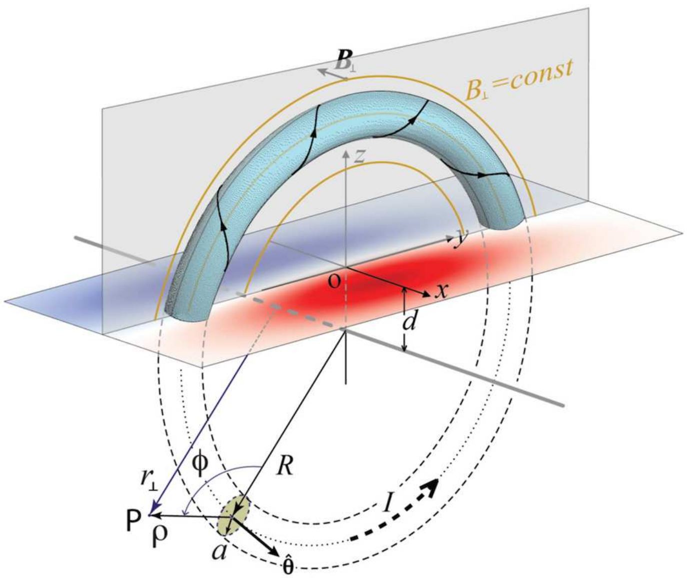


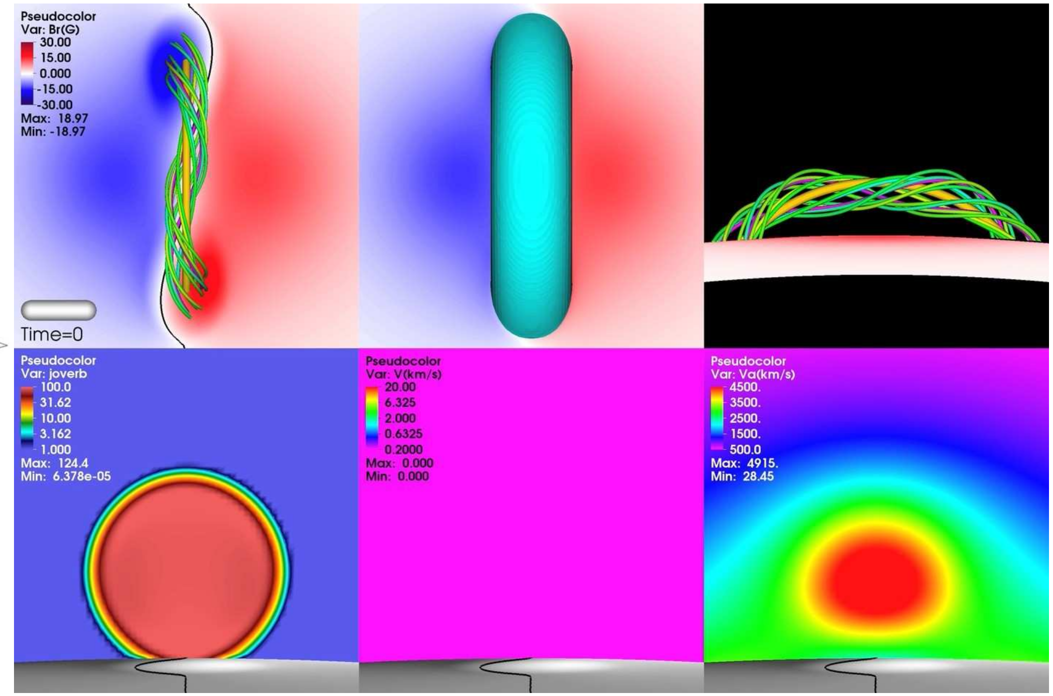
Issues with the Model



- 1D and 3D solutions do not fully fit together.
- The FR continues to reconnect.
- The footpoints of the FR are in very weak field, strong fields only in bipoles whose field lines actually go over the rope.
- B-dependent heating heats only overlying loops but not the FR
- Cumbersome geometrical masks needed to introduce footpoint heating.

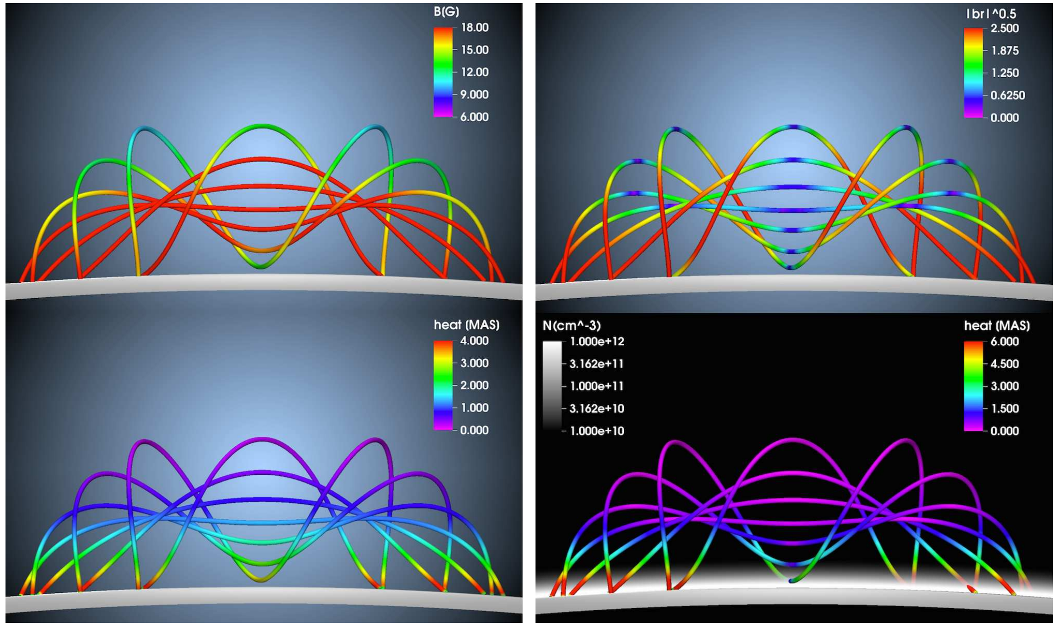
Introducing the TDm Model





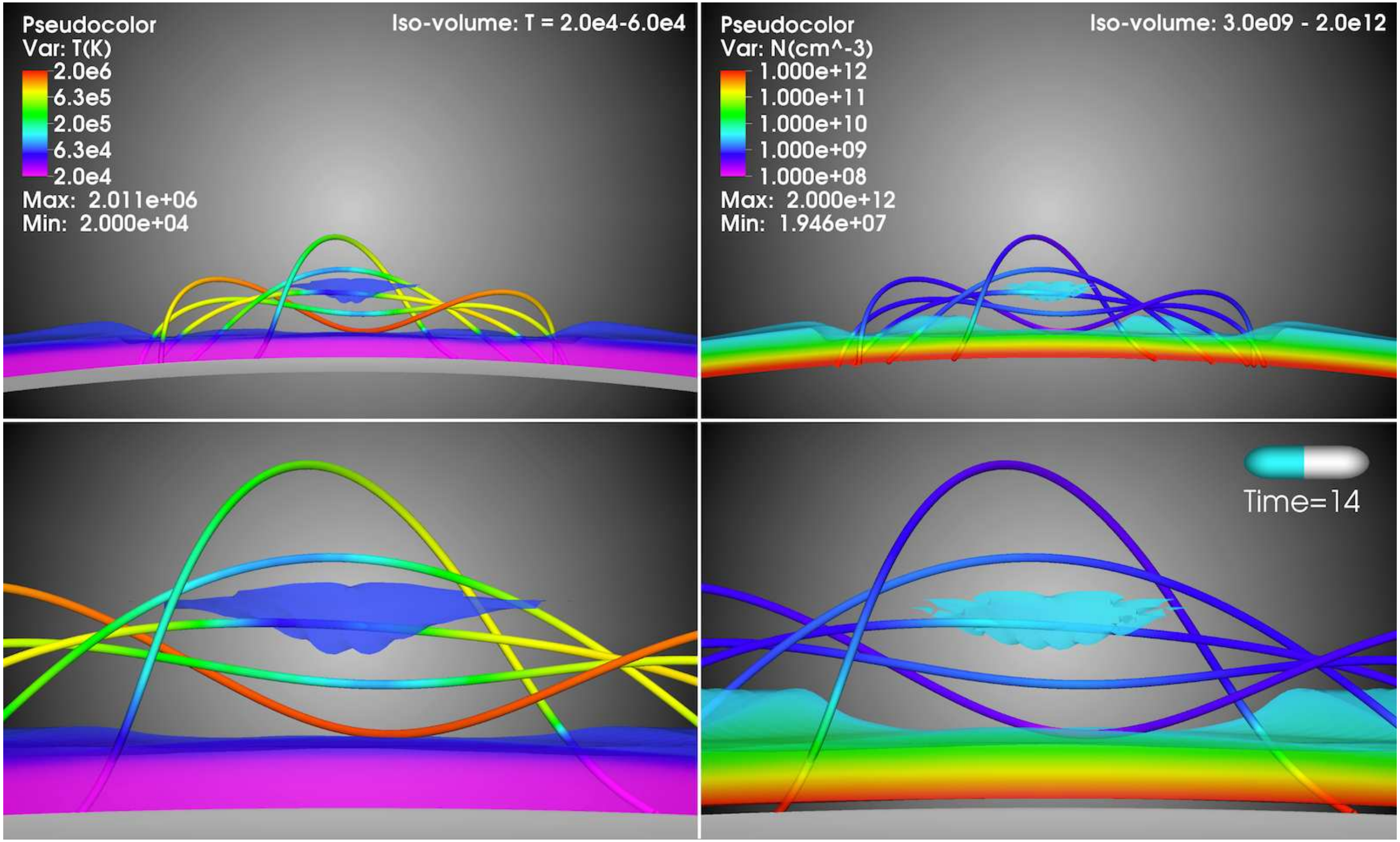
- TDm model is an extension of Titov & Démoulin (1999).
- The FR is modeled by a current ring that is partially submerged below the photospheric plane.
- We can insert a FR in force-free equilibrium into any given ambient magnetic field, as long as that field is locally bipolar.
- This is done by calculating the equilibrium FR current from the strength of the perpendicular component of the ambient $\mathbf{B}$ at the location of the FR axis.
- We find the most stable solution, with no field line movements.

Heating for the TDm Model



- Field lines in TDm model move less especially before thermodynamics is switched on.
- Exponential heating is large in low-lying field-line dips: condensations never develop; Condensations that develop on weakly dipped (or no dip) field lines slide down to the chromosphere.
- **Left:** This does not improve with B-dependent heating, $H = H_0|B|\exp((r - R_\odot)/\lambda)$
- **Right:** We replace $|B|$ by $|B_r|$ in the above heating expression. Now we get only little heating around field line dips since $B_r = 0$ at a dip.

Persistent Condensations in the TDm Model



- Since only little heating is deposited in the line dips, persistent condensations are formed.
- However, FR continuously moves downward during simulation. Reason not yet clear: gravity, diffusion, thermodynamics?

Outlook

Next steps:

- Further testing with B_r-dependent heating (e.g., introduce mask so that heating is localized in footpoints of flux rope (avoids strong condensations in field o verlying the rope).
- Experiment with wave-turbulence heating (first 1D then 3D).
- Model prominence formation in a magnetic configuration of an observed event (e.g., July 14, 2001 event).