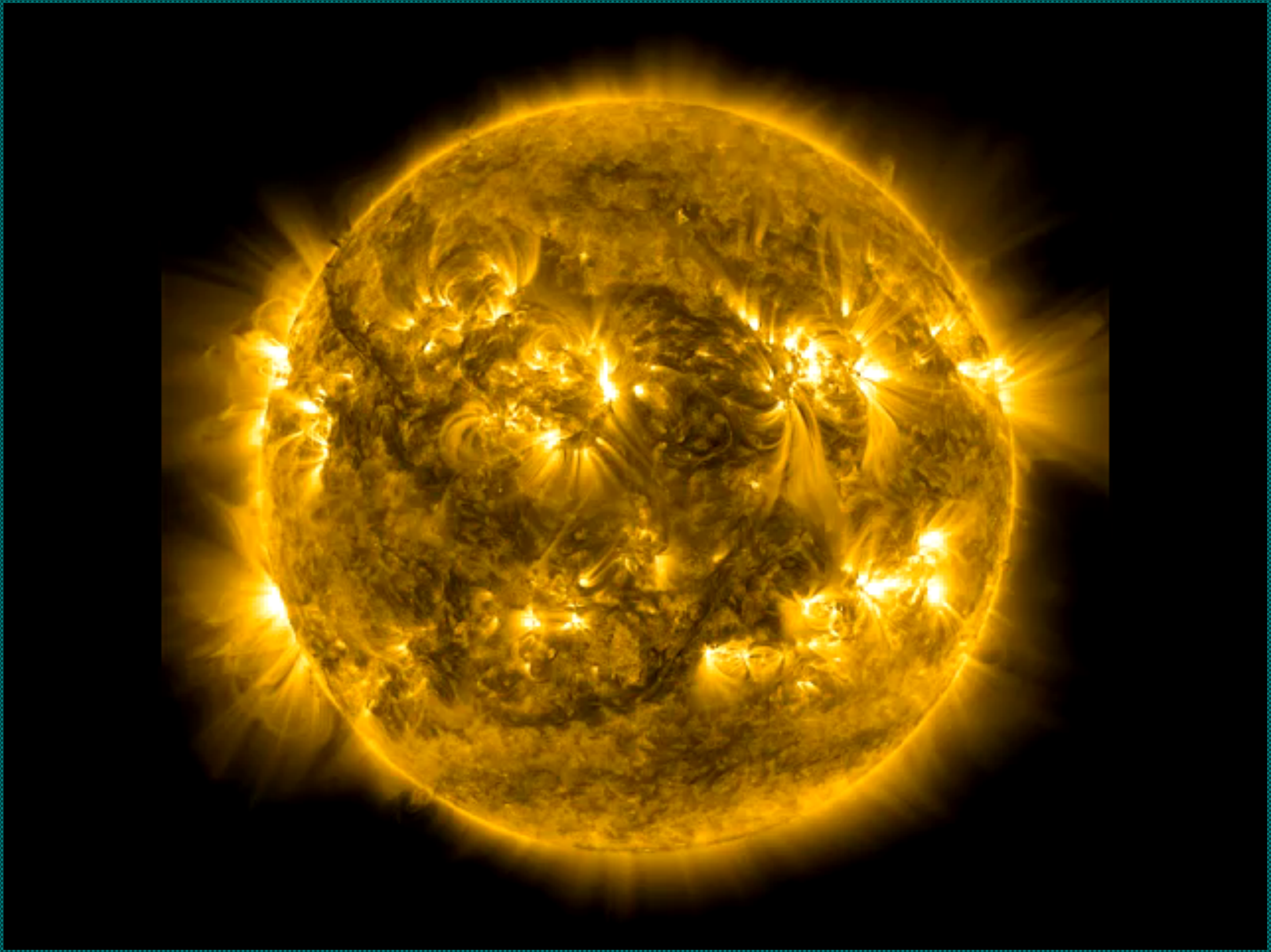
Exploring the Dynamic Corona with Theory and Simulations



Big Unsolved Problems

- How is the corona heated?
- What is the magnetic structure in the regions that produce solar eruptions?
- How does cool plasma remain suspended in the hot corona in those regions?

Canonical View of Coronal Plasma

- Loops are magnetic flux tubes
- Plasma is confined and channeled by magnetic field
- Four types of solutions: static, steady, dynamic, and driven-dynamic
- Static plasma requires symmetry and uniform heating → singular case

1D Hydrodynamic Equations

$$\frac{\partial \rho}{\partial t} + \frac{1}{A}\frac{\partial (A\rho v)}{\partial s} = 0$$ mass

$$\frac{\partial (\rho v)}{\partial t} + \frac{1}{A}\frac{\partial (A\rho v^2)}{\partial s} + \frac{\partial P}{\partial s} = \rho g_{\|}$$ momentum

$$\frac{\partial E}{\partial t} + \frac{1}{A}\frac{\partial [A(E+P)v]}{\partial s} = \rho g_{\|} v + \frac{1}{A}\frac{\partial}{\partial s}\left(A\kappa_o T^{5/2}\frac{\partial T}{\partial s}\right) - n^2\Lambda(T) + Q(s)$$

energy

ideal gas law: P=2nkT

$$E = \frac{1}{2}\rho v^2 + \frac{P}{\gamma - 1}$$

“No meaningful inferences on the heating process can be obtained from static models.” - *Chiuderi et al. 1981*

Static Energy Balance*

Uniform heating: Q

Conduction: $div(F_c) = \nabla \cdot (\kappa \nabla T) \sim T^{7/2} L^{-2}$

Radiation: $N^2 \Lambda(T) \approx C N^2 T^{-b} \rightarrow P^2 T^{-b-2}$

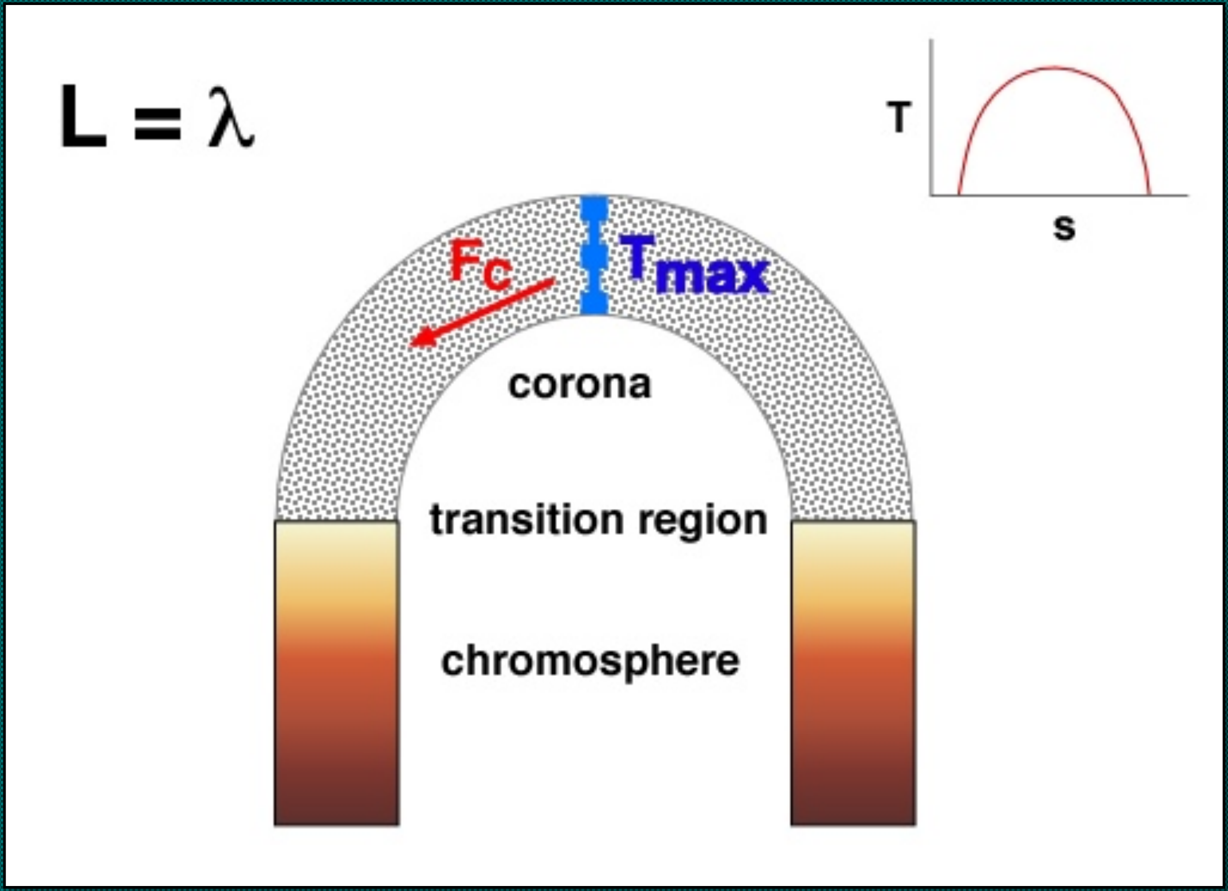
Corona: radiation + conduction *vs* heating

Transition Region: radiation *vs* conduction

Chromosphere: radiation *vs* heating

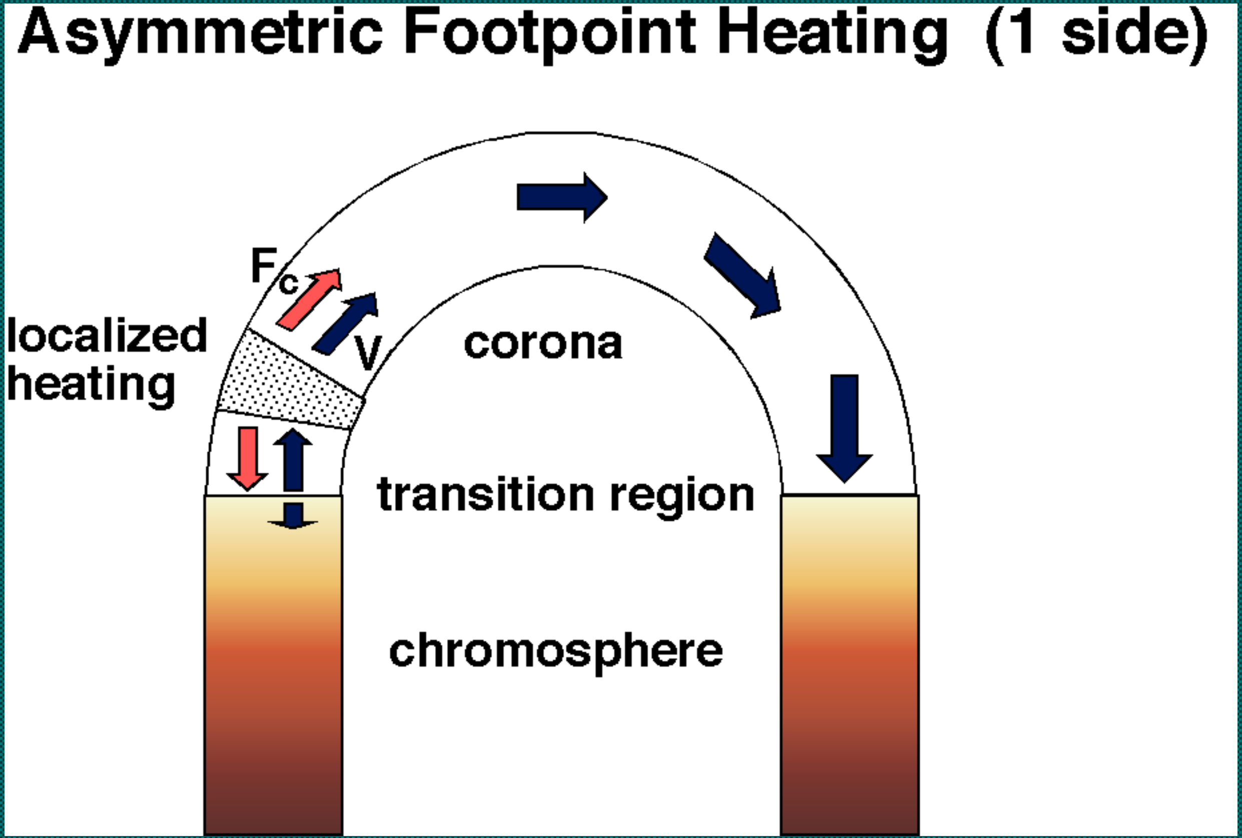
Static scaling laws: $Q \sim T^{7/2} L^{-2} \sim P^2 T^{-b-2}$

Uniform Heating



$N^2\Lambda(T)L \sim Q\,L$

Footpoint heating on 1 side



flows must occur to ensure force balance!

Footpoint heating on 1 side (con't).

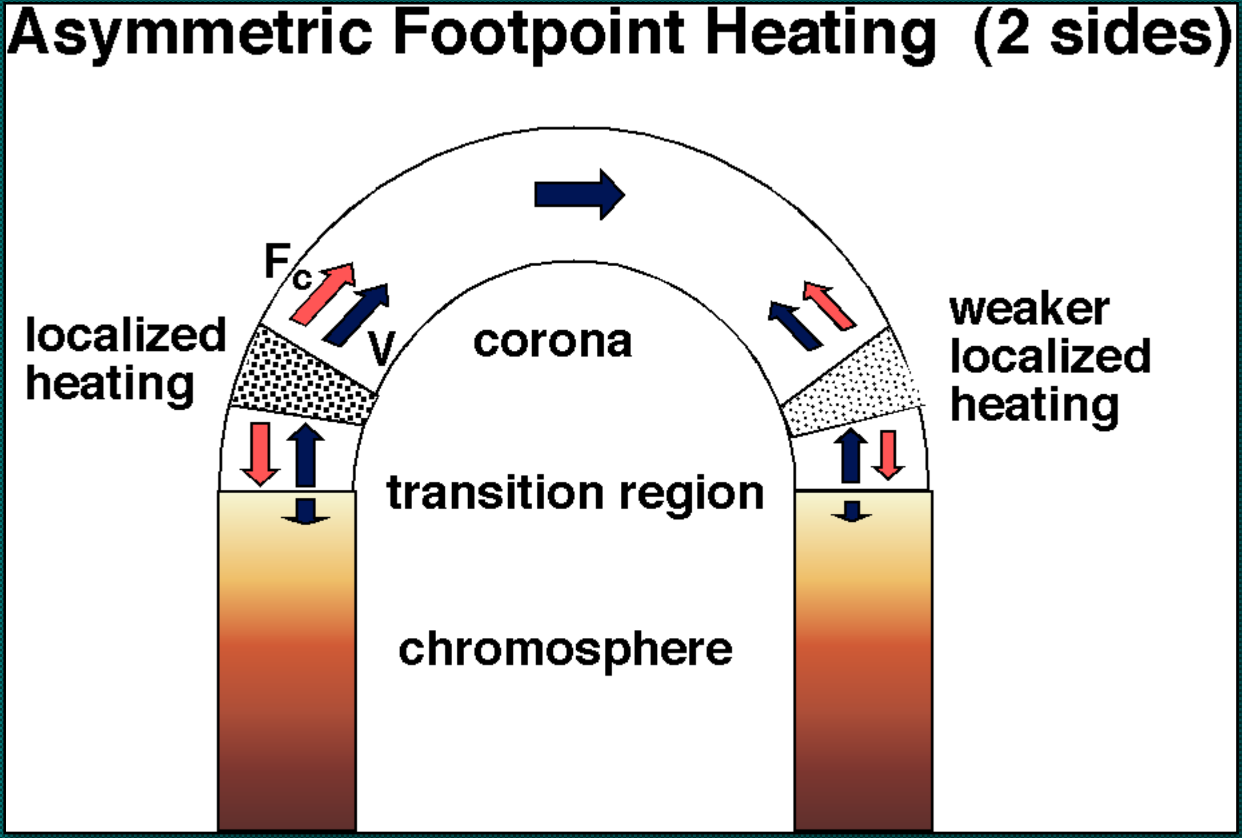
- **Heating drives chromospheric evaporation**
  - **increased radiation *vs* heat flux + enthalpy**
  - **evaporated mass condenses onto far chromosphere**
  - **new state with quasi-steady flow is reached**
  - **<u>not</u> driven by a pressure difference between footpoints**
- **T peaks near heating location**
  - any offset toward apex due to enthalpy flux
- **Steady flow toward unheated leg**
  - V_{max} set by enthalpy flux needed to redistribute energy
- **dT/ds steeper on heated side**
  - less plasma at T.R. temperatures on the heated side
  - downflows brighter than upflows (looking down on loop)

Boris & Mariska 1982, Mariska & Boris 1983, Craig & McClymont 1986, Mariska 1988

Footpoint heating on 2 sides

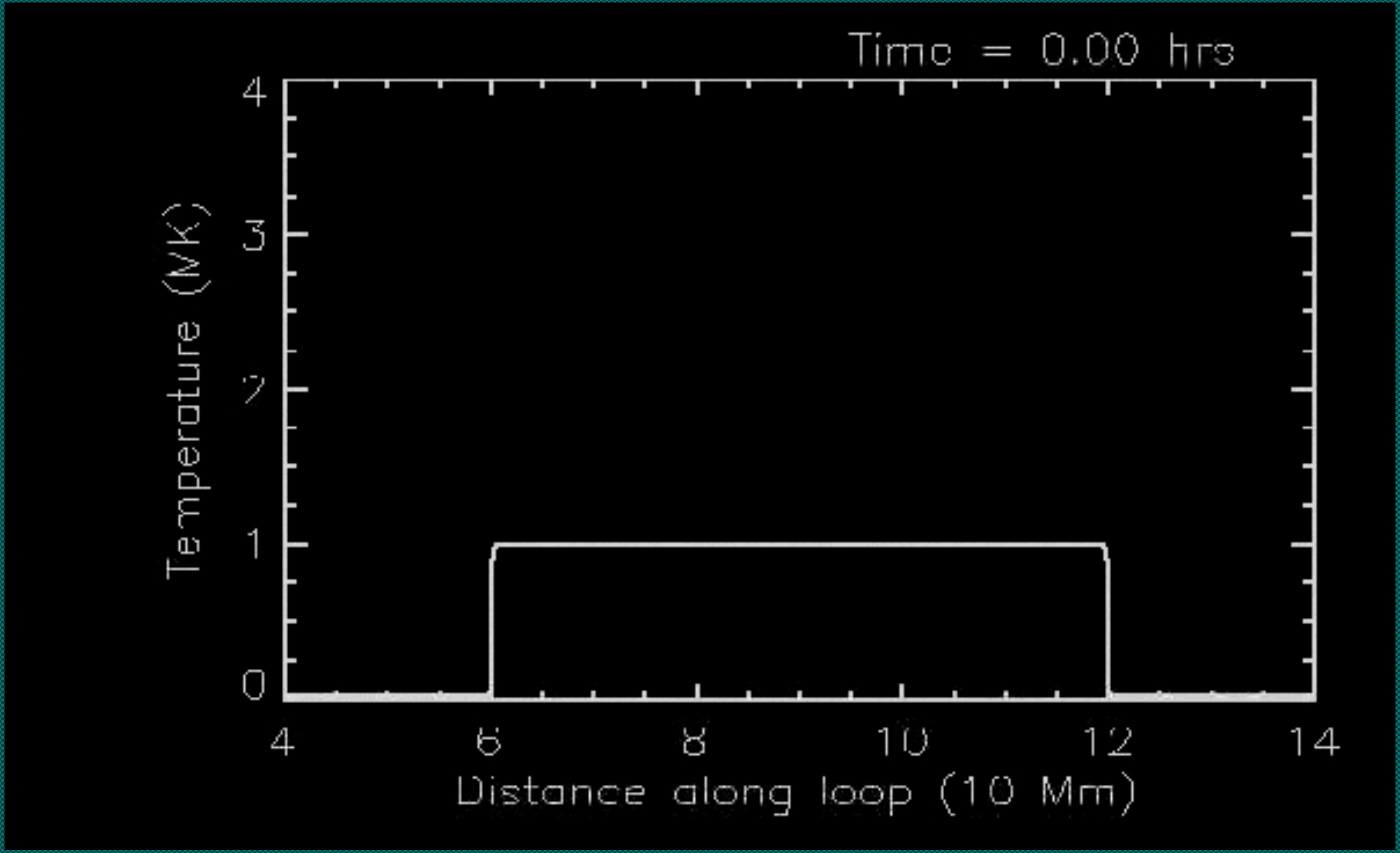
Heat + enthalpy fluxes transport energy through corona

- Heating drives evaporation from both footpoints
- Increased radiation *vs* heat + enthalpy fluxes



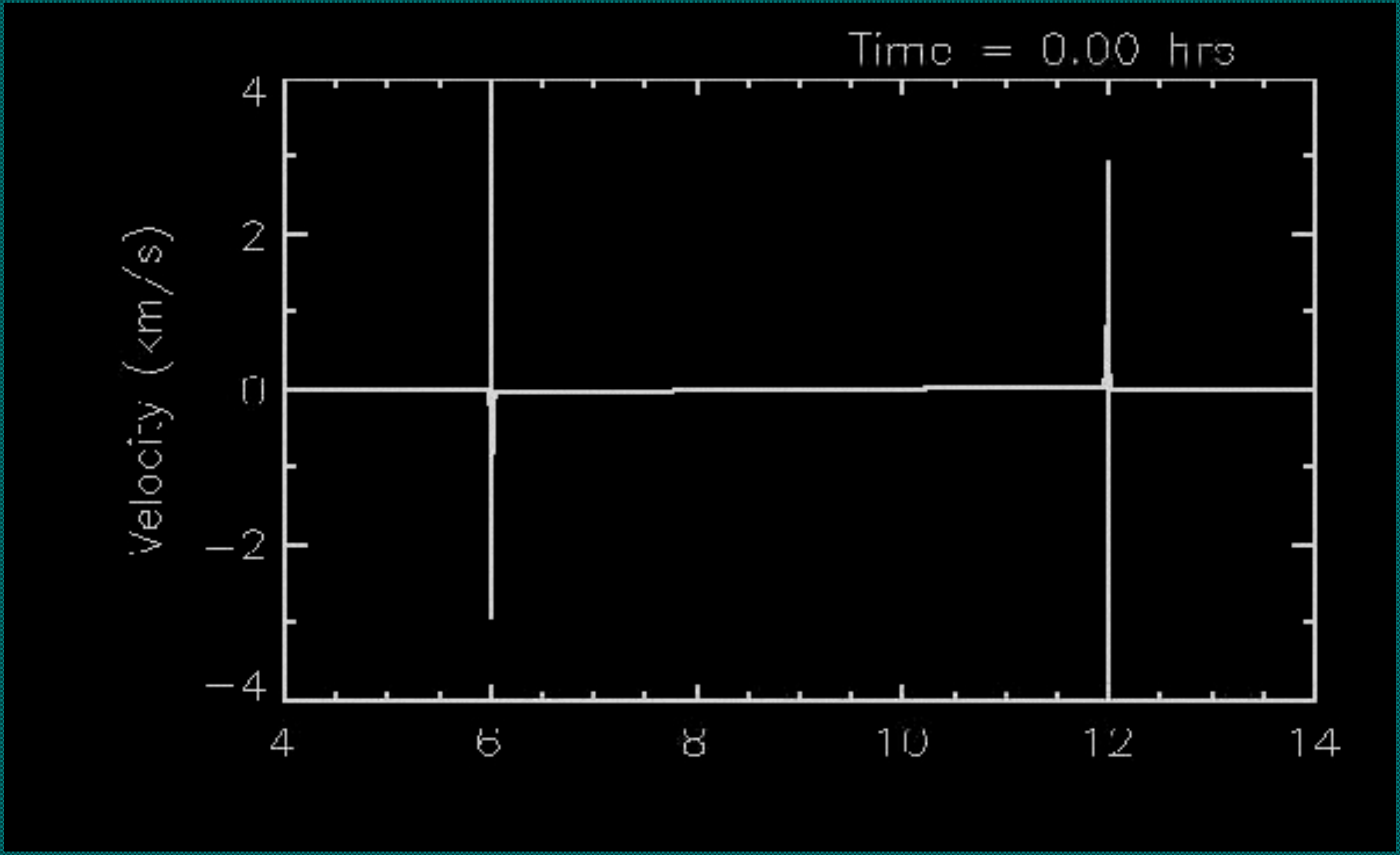
Footpoint heating on 2 sides

Loop length L < 8 λ (λ = heating scale),
Asymmetric heating: higher max. T, ρ and quasi-steady flow toward less heated side

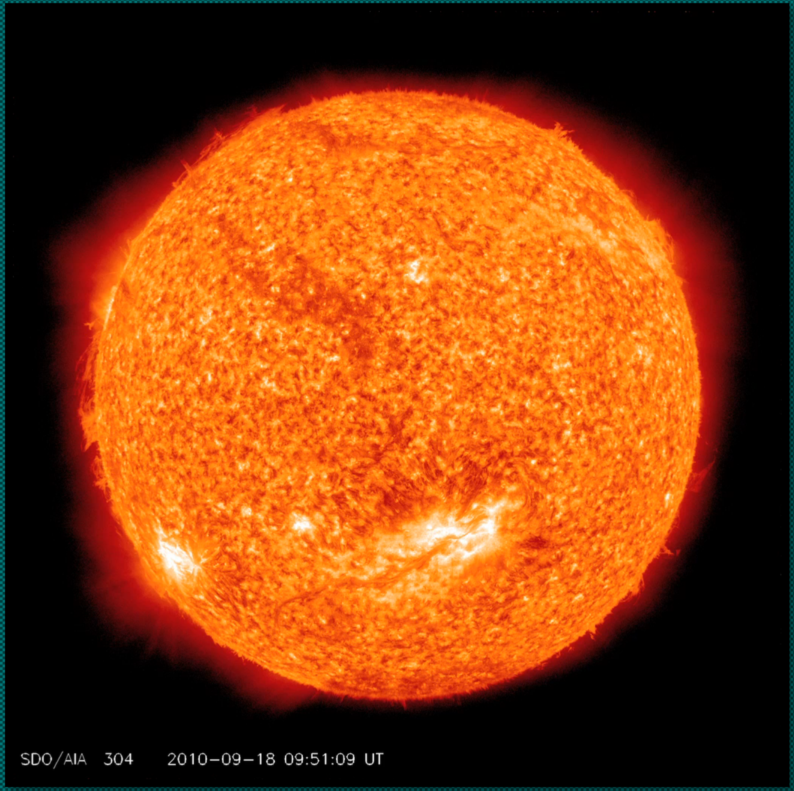


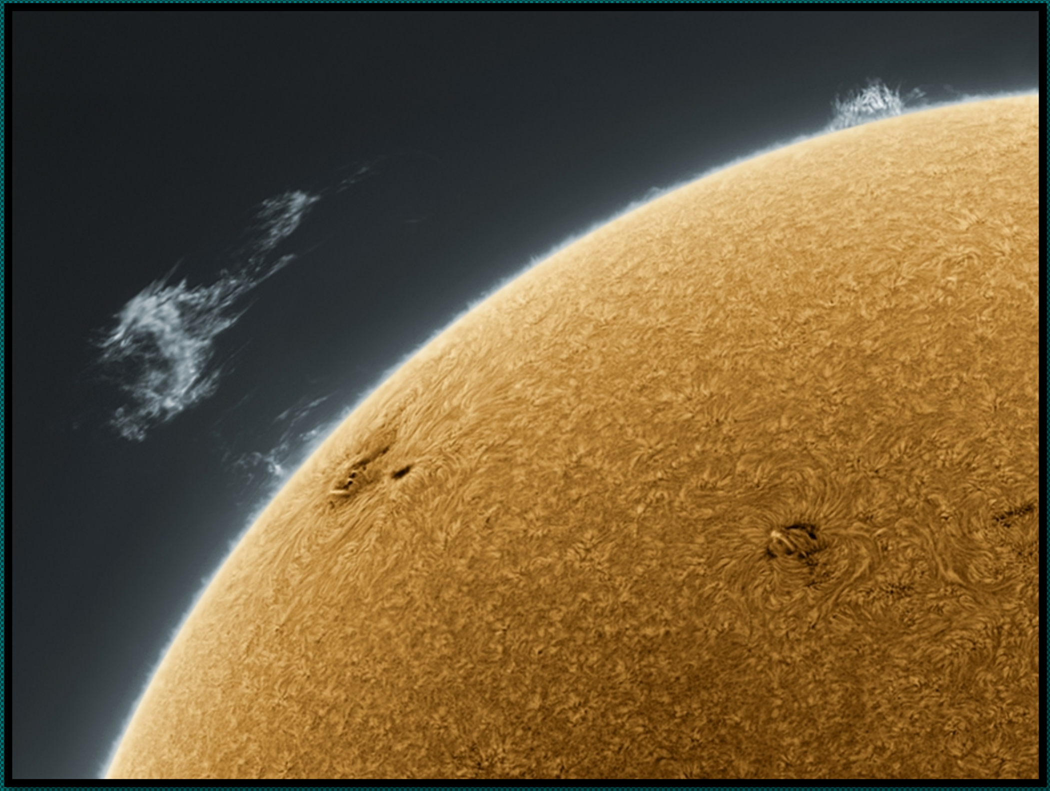
Footpoint heating on 2 sides

L < 8λ, asymmetric heating



What are Prominences?

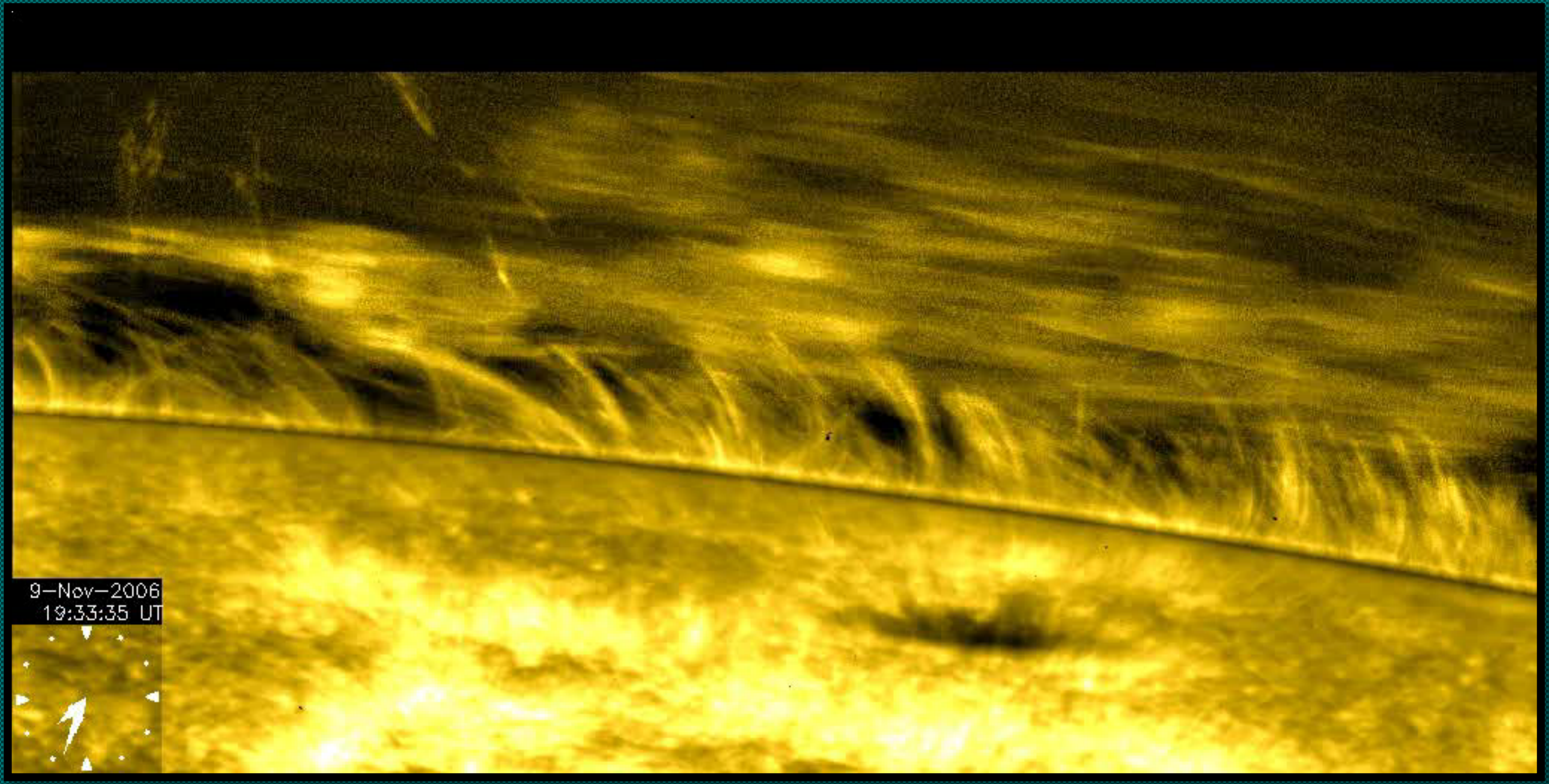




Working definition: cool dense gas suspended in the hot corona, supported by the magnetic field

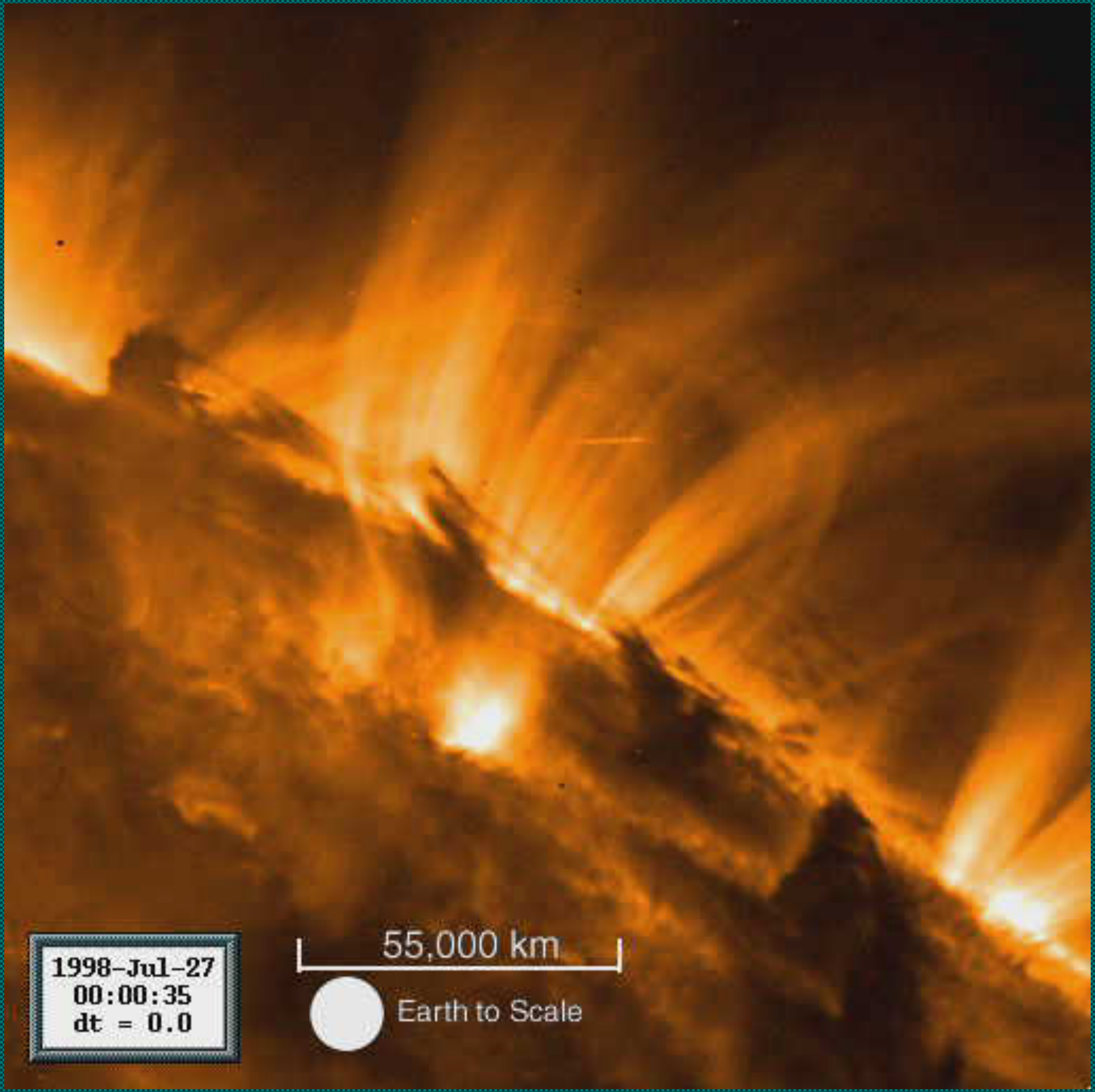
Reviews: Martin 1998, Labrosse et al. 2010, Mackay et al. 2010

Prominence in emission



Hinode/SOT Ca II
from Okamoto et al. 2007

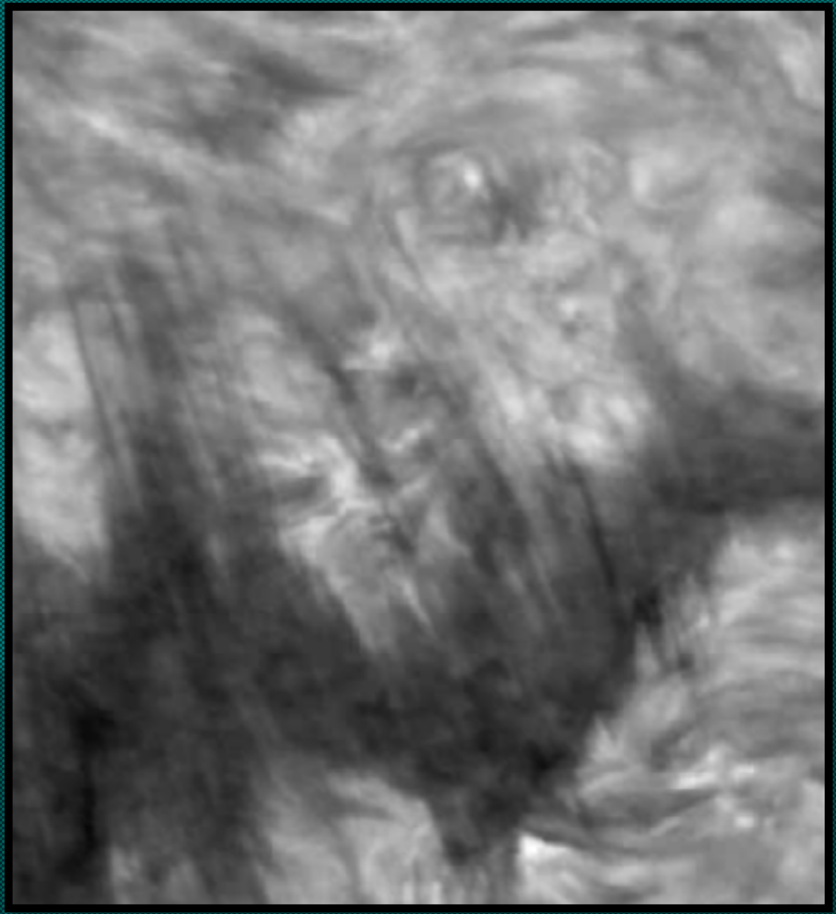
Prominence in absorption



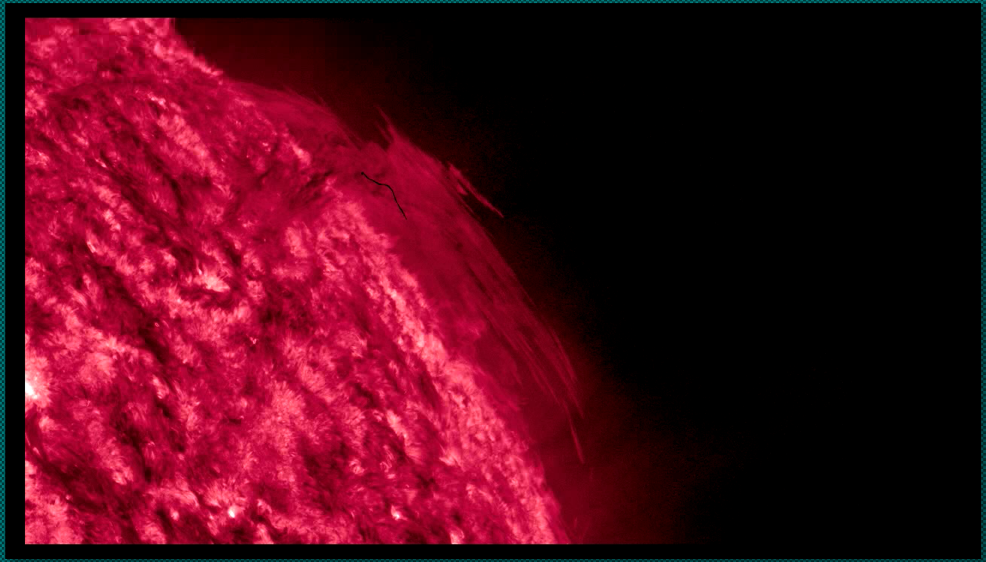
TRACE EUV

Important Plasma Properties

- Covers 10-60% of PIL
- Spine and barbs
- Knots and threads
- Chromospheric T, ρ
- HIGHLY DYNAMIC

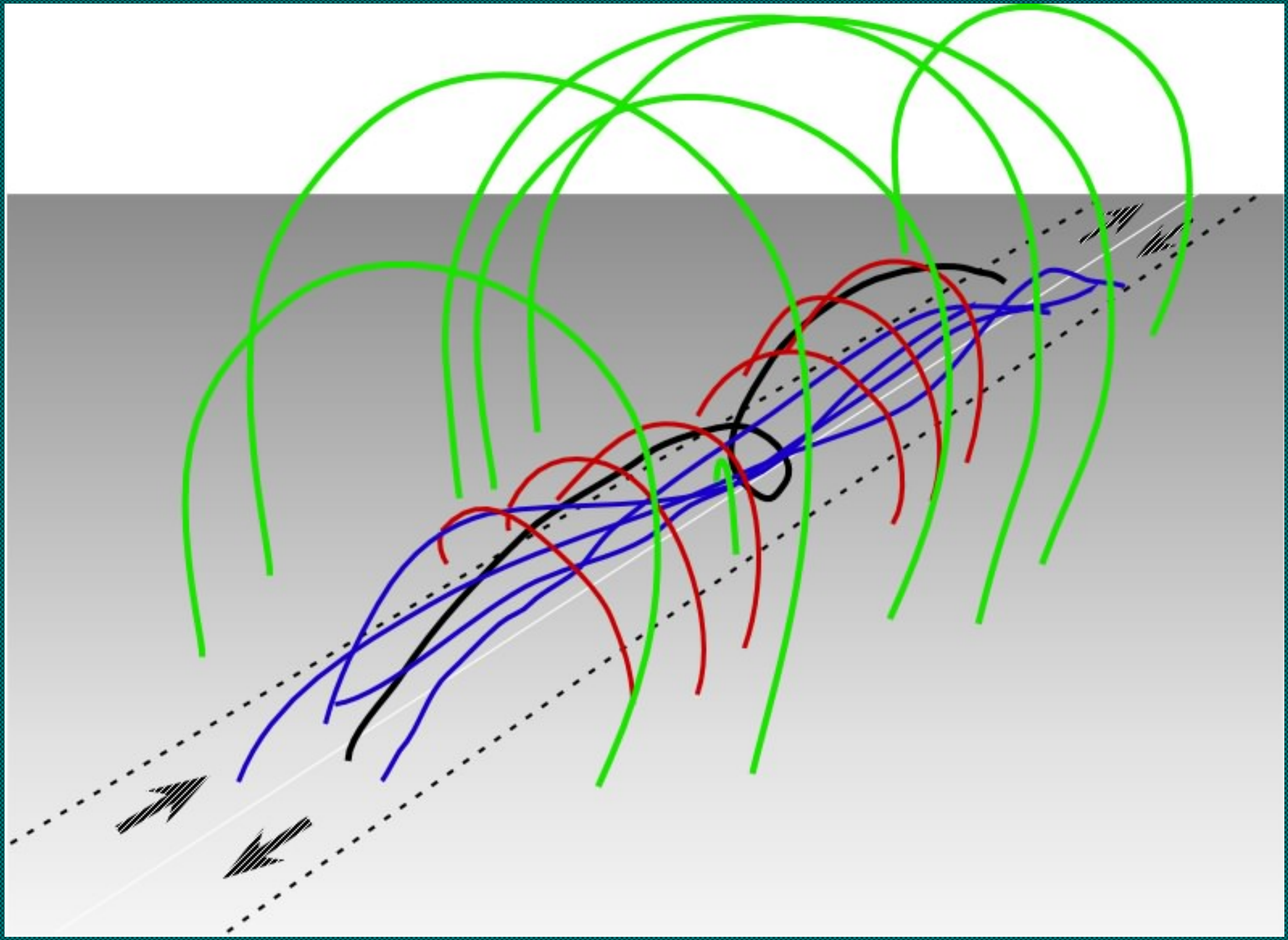


SVST, *courtesy of Y. Lin*



SDO AIA 304Å

Our Magnetic Structure Model: Sheared Arcade



cartoon

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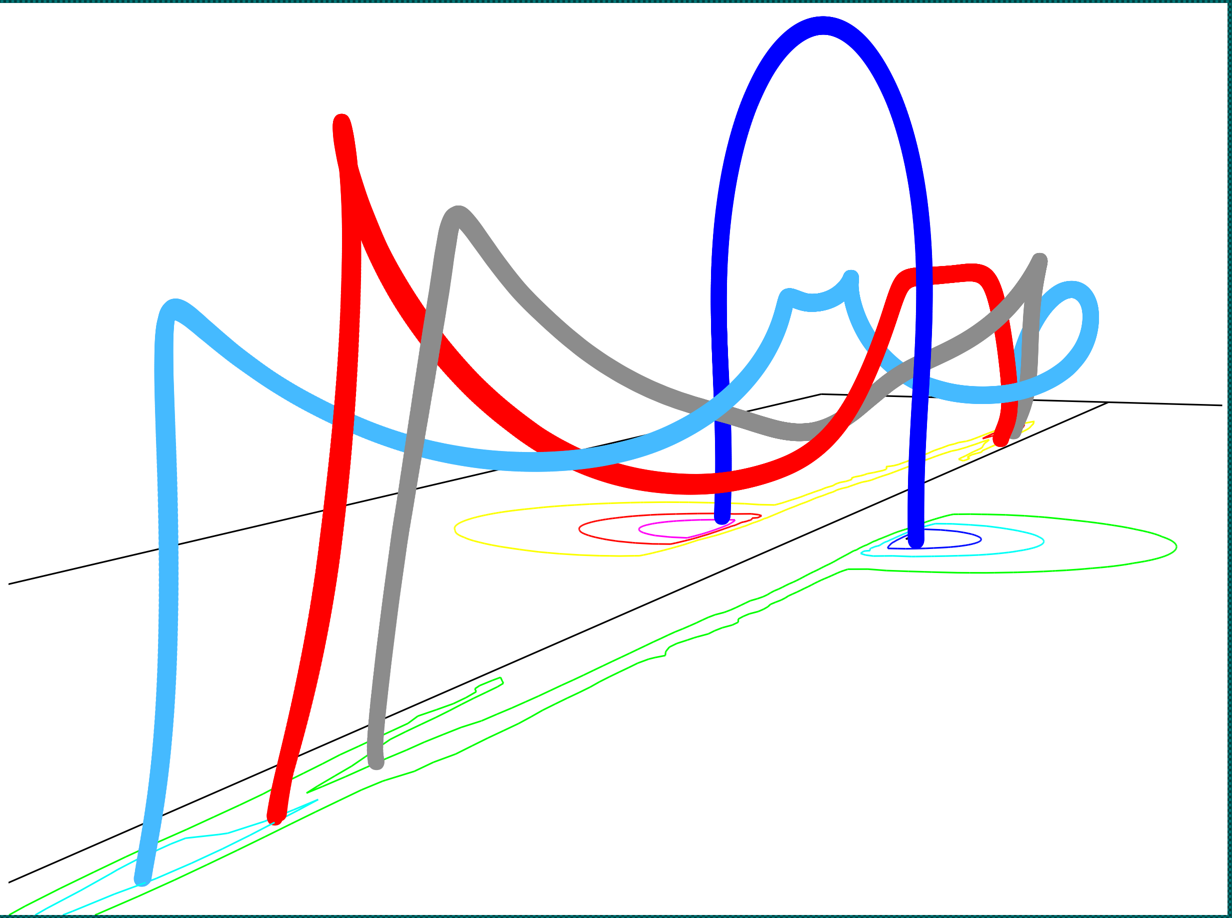


3D MHD simulation

Plasma Model Constraints

- Mass comes from *chromosphere*
- low β
- Mass generally traces magnetic structure (frozen in)
  - ionization fraction 0.2-0.9, neutrals not frozen in but collisionally coupled
- Field-aligned thermal conduction dominates ($\kappa_{||} >> \kappa_{\perp}$)
- Pressure scale height Hg ~ 500 km
- NOT ALL STATIONARY

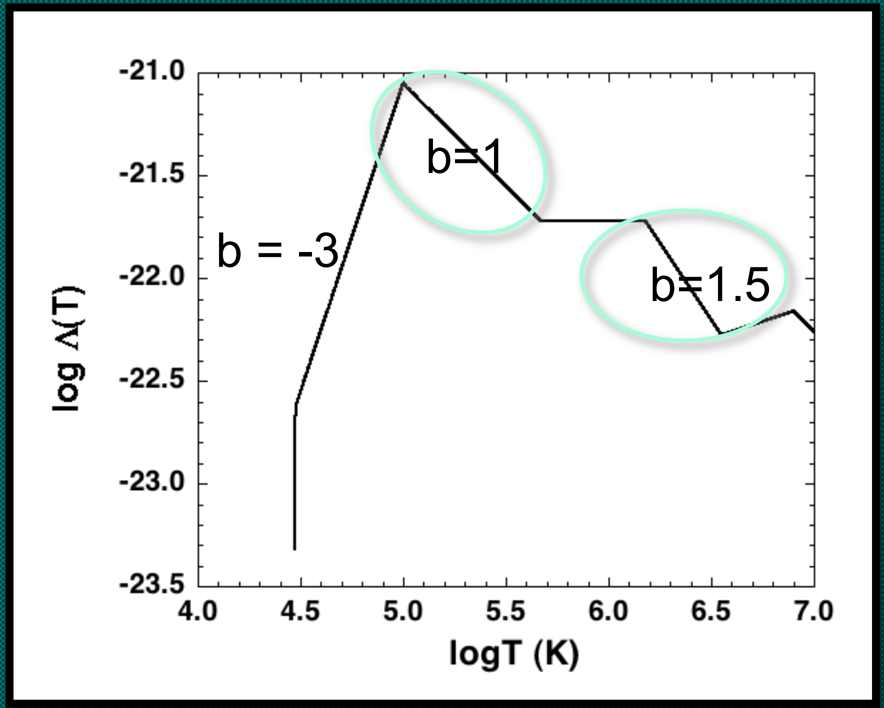
Origins of Thermal Instability

criterion for thermal stability (Parker 1953)

$$\frac{\partial H}{\partial T} \leq \frac{\partial \Lambda}{\partial T}$$

where H=heating

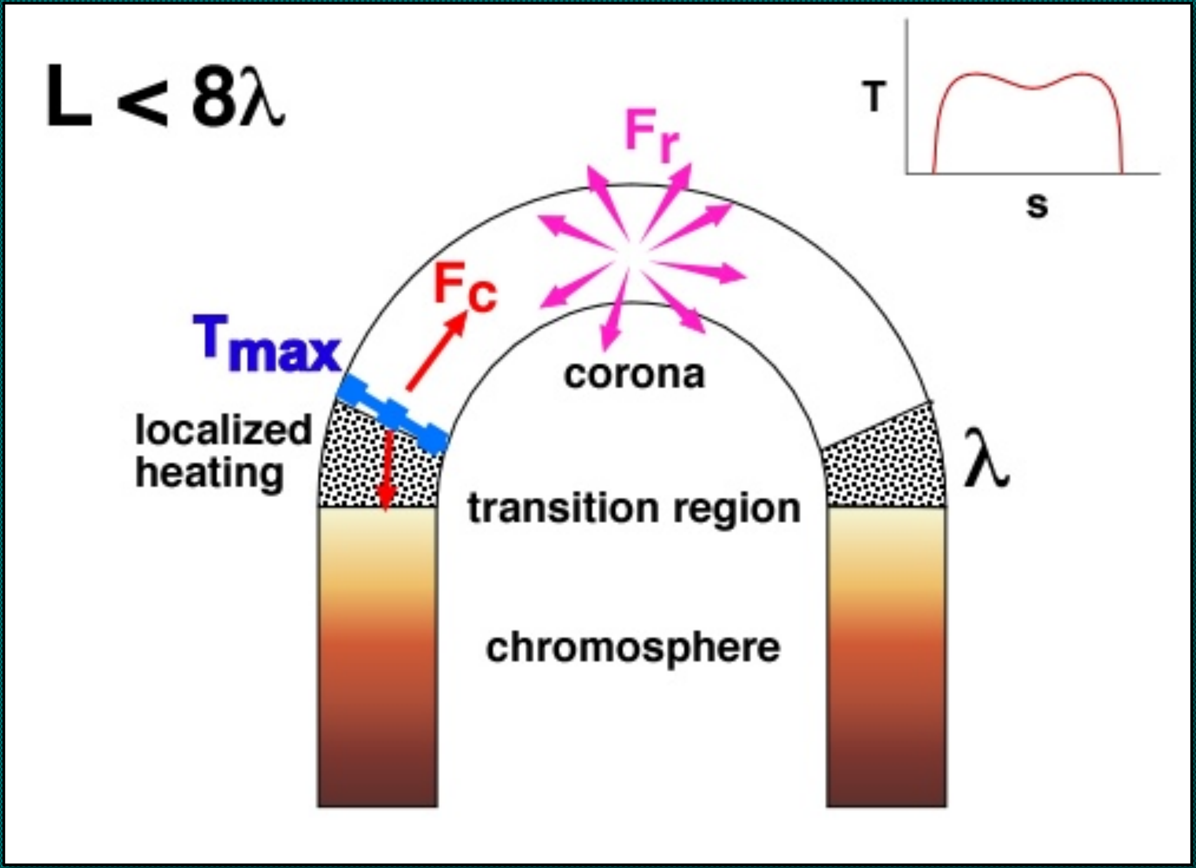
If heating is not temperature dependent, then the plasma will be unstable if b > 0



Optically thin radiative loss function:

$\Lambda(T) \sim N^2 T^{-b}$ (Klimchuk-Raymond)

Symmetric footpoint heating



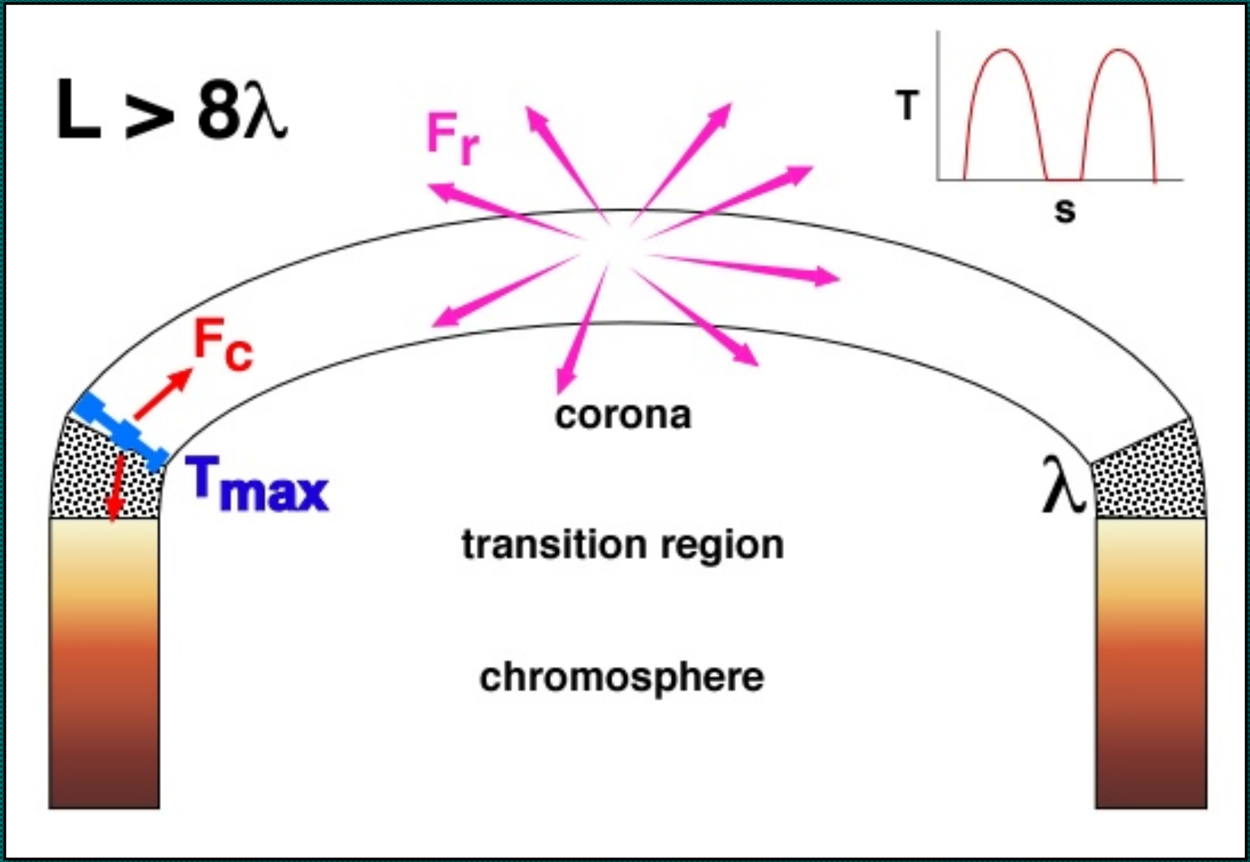
from footpoint to T_{max}:

$N^2\Lambda(T)\ \lambda \sim Q\ \lambda$

from T_{max} to apex:

$N^2\Lambda(T)\ L \geq Q\ \lambda$

Symmetric footpoint heating



from T_{max} to apex: $N^2\Lambda(T)\, L \gg Q\, \lambda$

Why does condensation form?

- Chromospheric evaporation increases density throughout corona ➔ increased radiative losses
- T is highest within distance ~ λ from site of maximum energy deposition (*i.e.*, near base)
- **when L > 8 λ, conduction + local heating cannot balance radiation at apex**
- Rapid cooling ➔ local pressure deficit, pulling more plasma into the condensation
- a new chromosphere is formed at apex, reducing radiative losses (compared with T.R.)

1D Hydrodynamic Equations

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energy

ideal gas law: P=2nkT

$$E = \frac{1}{2}\rho v^2 + \frac{P}{\gamma - 1}$$

"No meaningful inferences on the heating process can be obtained from static models." - *Chiuderi et al. 1981*

Numerical Approach

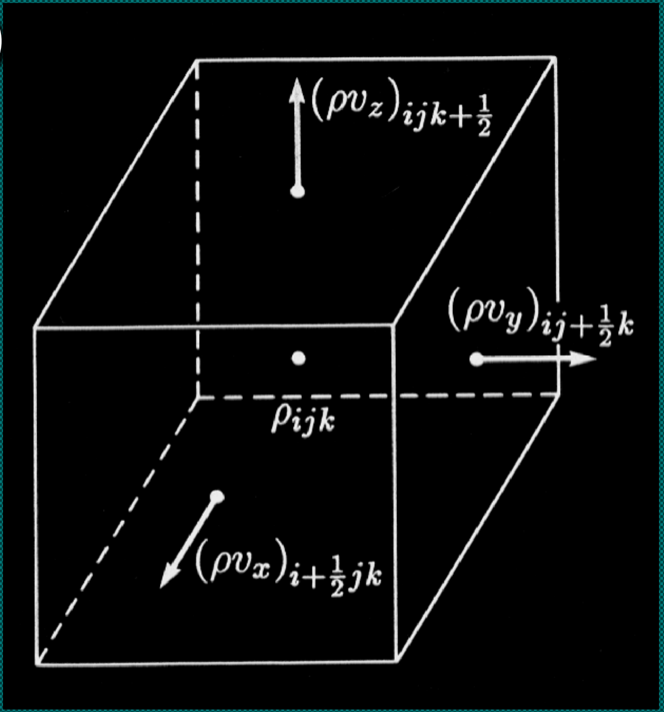
- Coupled nonlinear time-dependent equations
- Derivatives converted to finite differences
- Potential problems:
  - unstable solutions (e.g., Δt too big)
  - inaccurate solutions (e.g., Δx too big)
  - non-monotonic solutions (e.g., oscillations at discontinuities)
  - inappropriate boundary conditions
  - excessive memory and/or time requirements

Our Hydrodynamic Simulations

- **Plasma evolution governed by 1D hydrodynamic equations:**
  - Low β plasma → motion along rigid flux tube
  - Conductivity κ along magnetic field >> perpendicular κ
- **Plasma evolved in time and space with our 1D *Adaptively Refined Godunov Solver* (*ARGOS*):**
  - Solar gravity and flux tube cross-sectional area (~1/B)
  - Ideal ionized hydrogen gas
  - Energetics: coronal heating localized at footpoints, collisional thermal conductivity, and optically thin radiative losses
  - Adaptive mesh refinement: puts smallest cells where selected gradient is steepest. **Cannot solve this problem without it!**

Time and Space, Discretized

- Timestep limiting: smallest of
  - convective timestep = CFL condition (~ $f\Delta s/v_{signal}$)
  - radiative timestep (~ $T/n\Lambda[T]$)
  - conductive timestep (~$\Delta s^2/T^{5/2}$)
- Spatial discretization
  - Cells have center and face
  - Fluxes calculated at faces
  - Divergences at centers
  - Adaptive mesh puts smallest cells at steepest density gradients



Asymmetric footpoint heating

Loop length $L > 8\ \lambda$:

NO STATIONARY EQUILIBRIUM!

- thermal nonequilibrium occurs but condensation forms toward less heated side
- cycle of condensation formation, motion, and destruction by falling onto nearer ftpt
- process applies to a wide range of loop geometries (shallowly dipped to arched)
- for loop heights > Hg, cycle is chaotic

Why is asymmetric case unstable?

Constraints: $P_1 = P_2$, $L_1 + L_2 = L >> \lambda$

Dynamic scaling laws yield: $P \sim E^{(11+2b)/14} L^{(2b-3)/14}$

✣ *e.g.*, for b = 1, $P \sim E^{13/14} L^{-1/14}$

Equilibrium position: $L_1 / L_2 = (E_1 / E_2)^{(11+2b)/(3-2b)}$

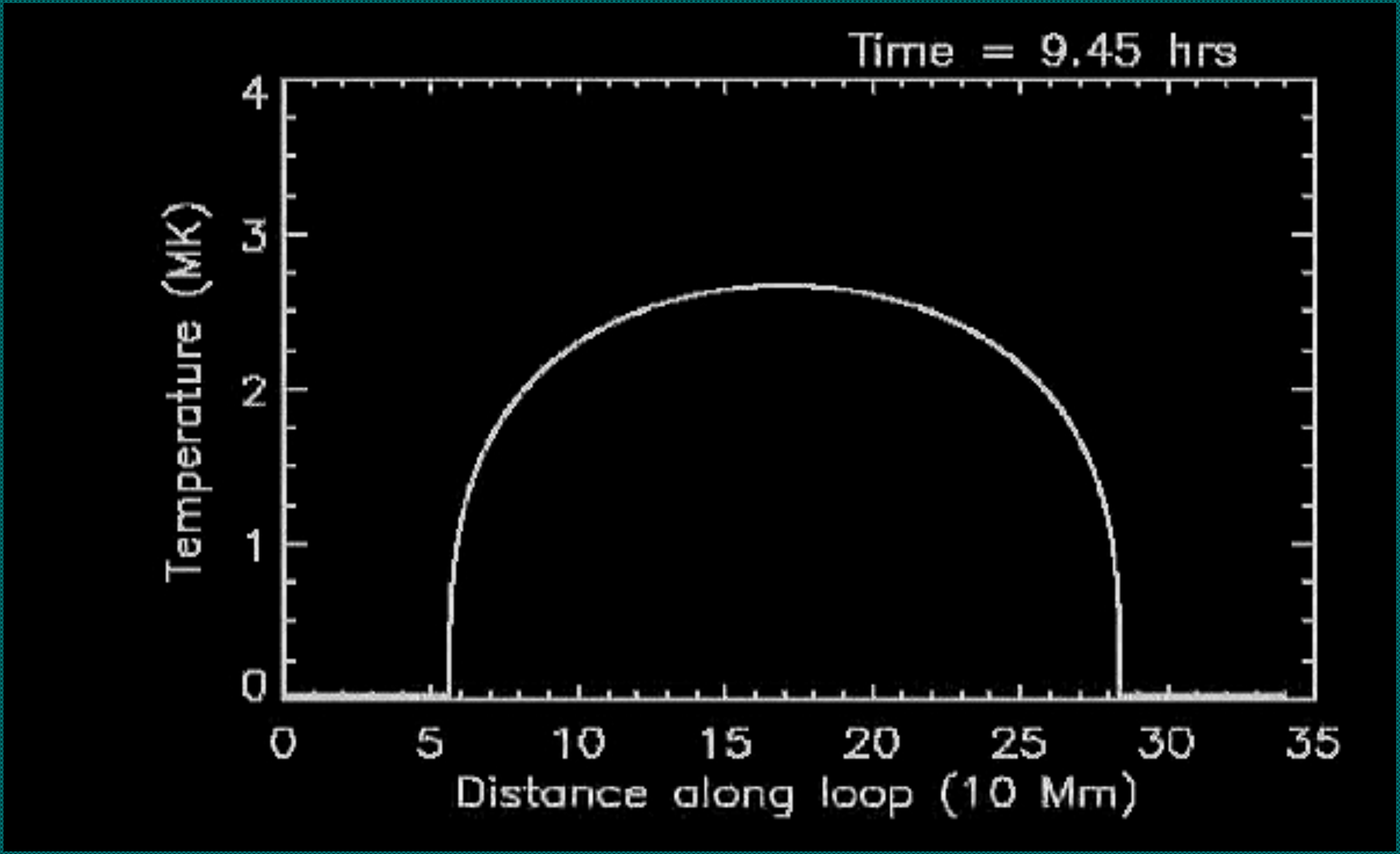
✣ for b = 1, $L_1 / L_2 = (E_1 / E_2)^{13}$!!

✣ for $b \geq 3/2$, no equilibrium possible

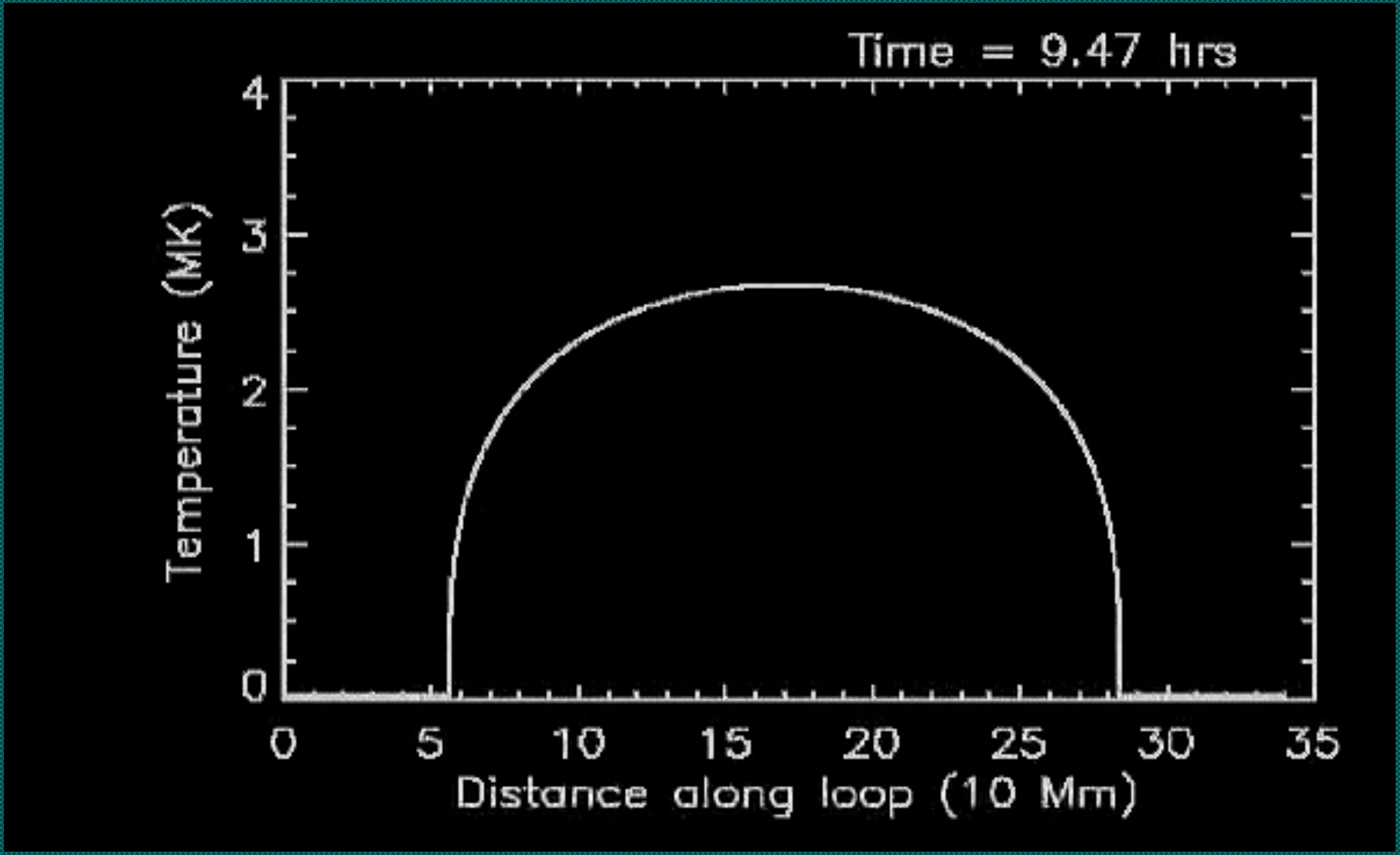
Initial and Boundary Conditions

- **Loop properties:** L_{cor}=220 Mm, T_{cor}~ 3-4 MK
- Field geometry represented by gravity variation as a function of distance along loop.
- T_{min} = 30,000 K (no radiative transfer)
- No flow through boundaries
- Deep chromospheres (remote boundaries)
- **Steady Heating at both footpoints**:
  $Q = Q_o + f\, Q \exp[(s-s_o)/\lambda]$, where $Q_o = 10^{-5}$ erg cm^{-3} s^{-1}, $Q = 10^{-2}$ erg cm^{-3} s^{-1}, λ=10 Mm, s_o is base of corona, and f = 0 -1 at each footpoint

TNE in Moderately Arched Loop

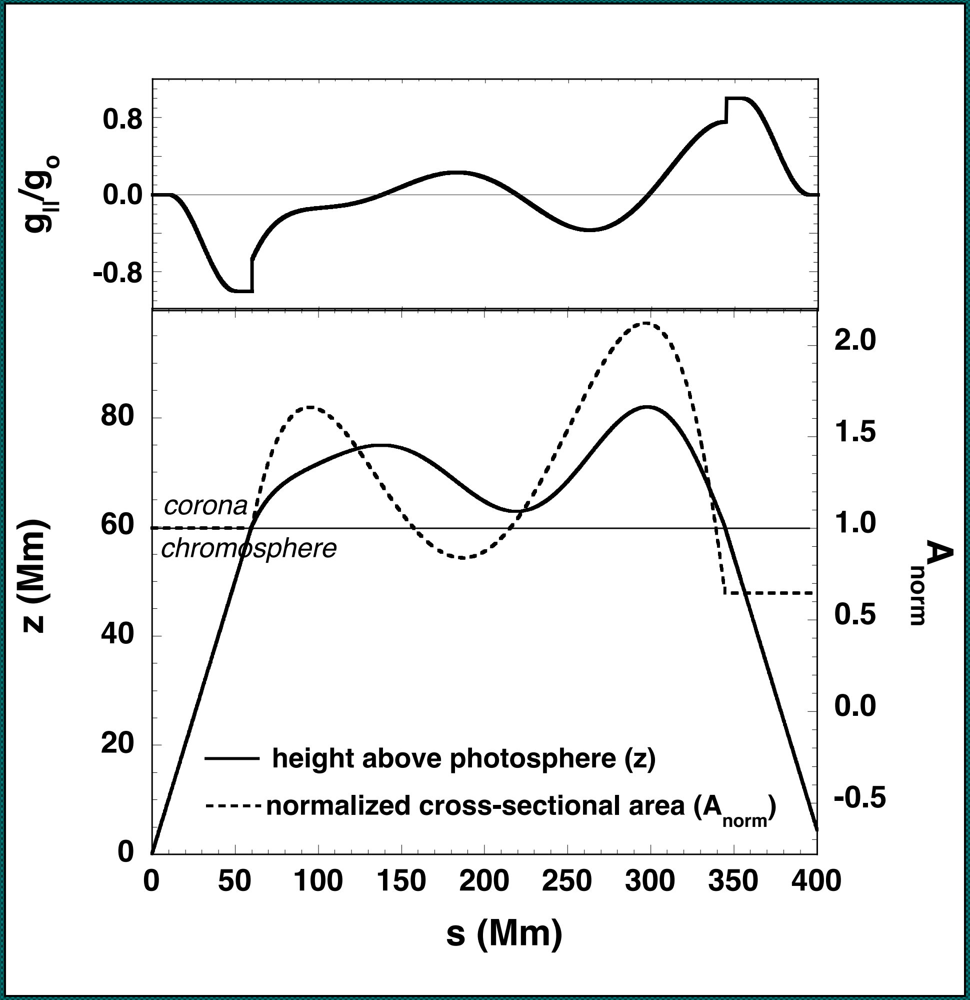


TNE in Highly Arched Loop

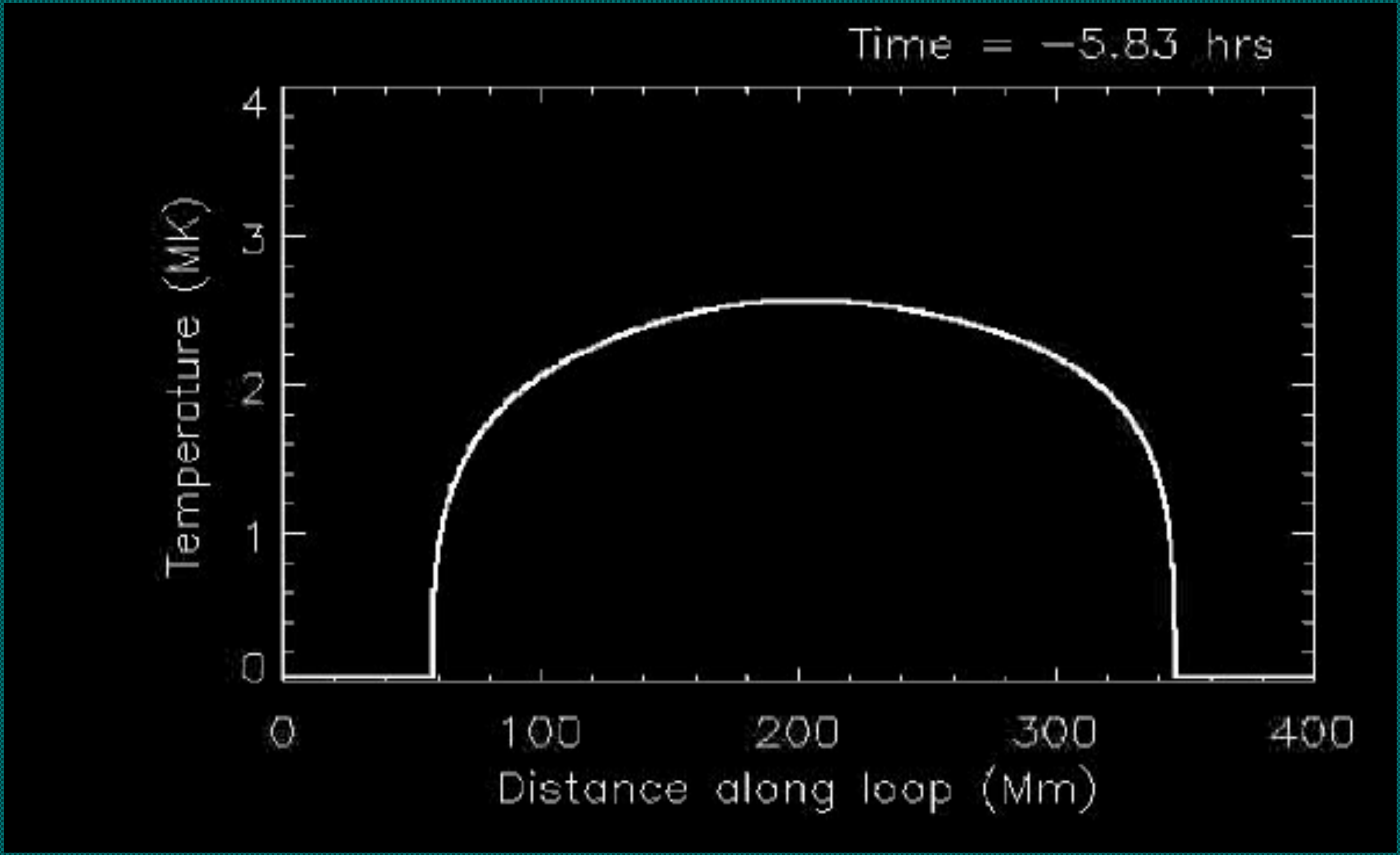


- looks like observed coronal rain
- steady heating can produce very dynamic evolution

Flux Tube with Nonuniform Area and Asymmetric Heating

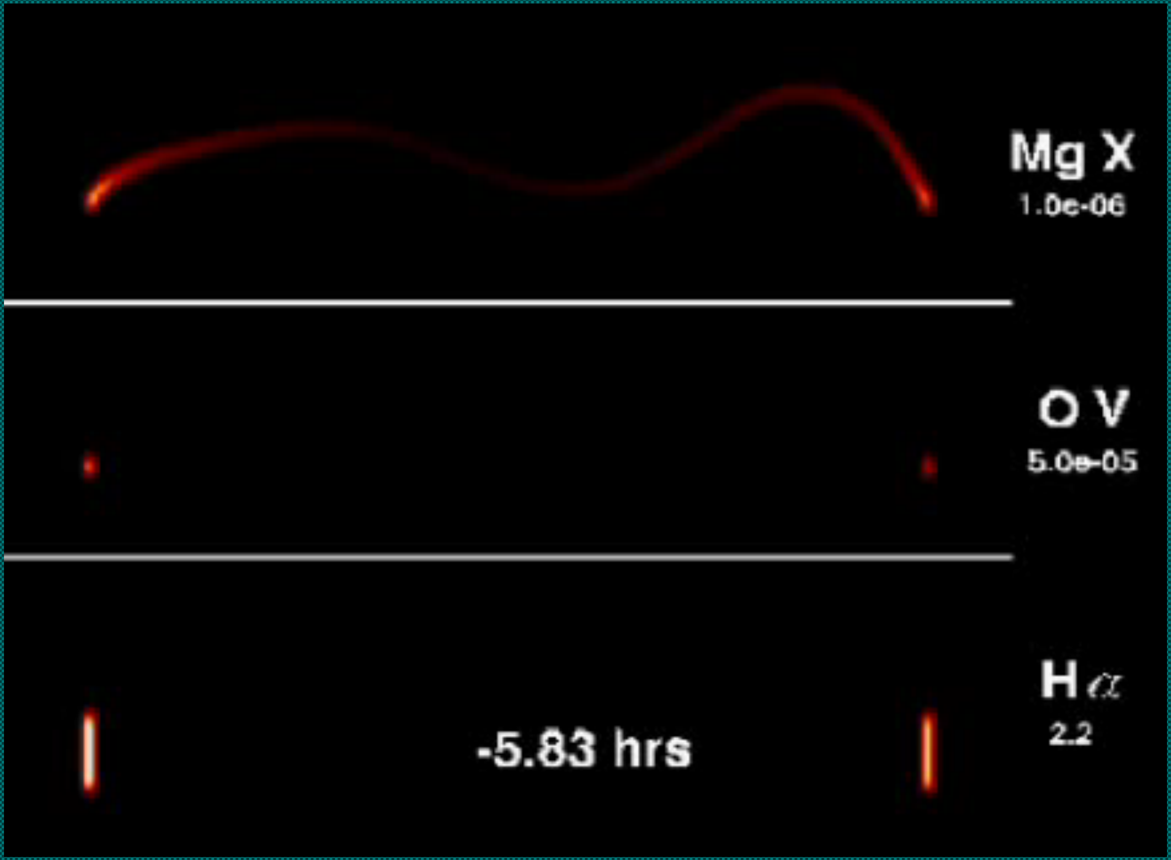


Effects of Heating Asymmetry



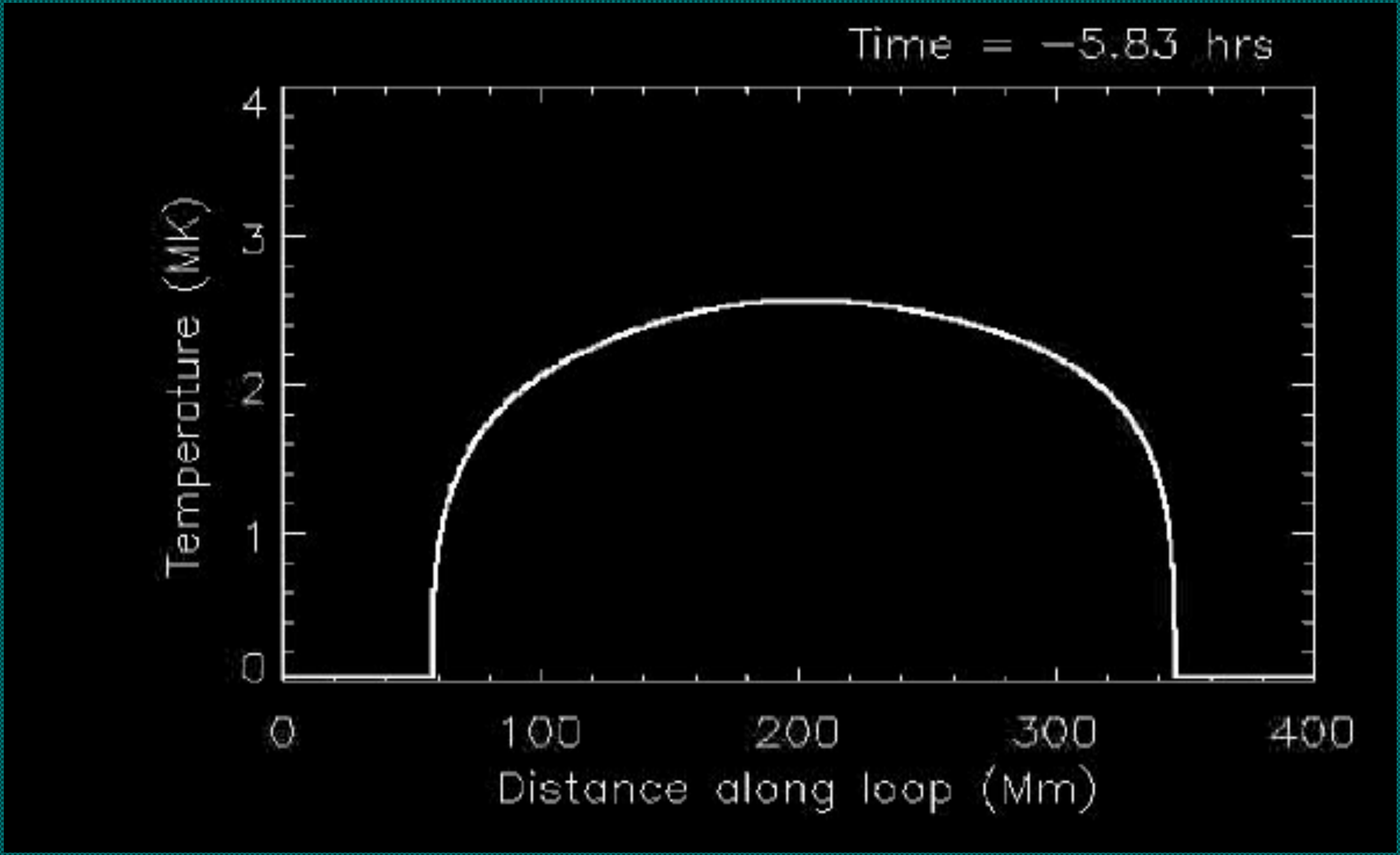
$Q_{right} > Q_{left}$

Effects of Heating Asymmetry



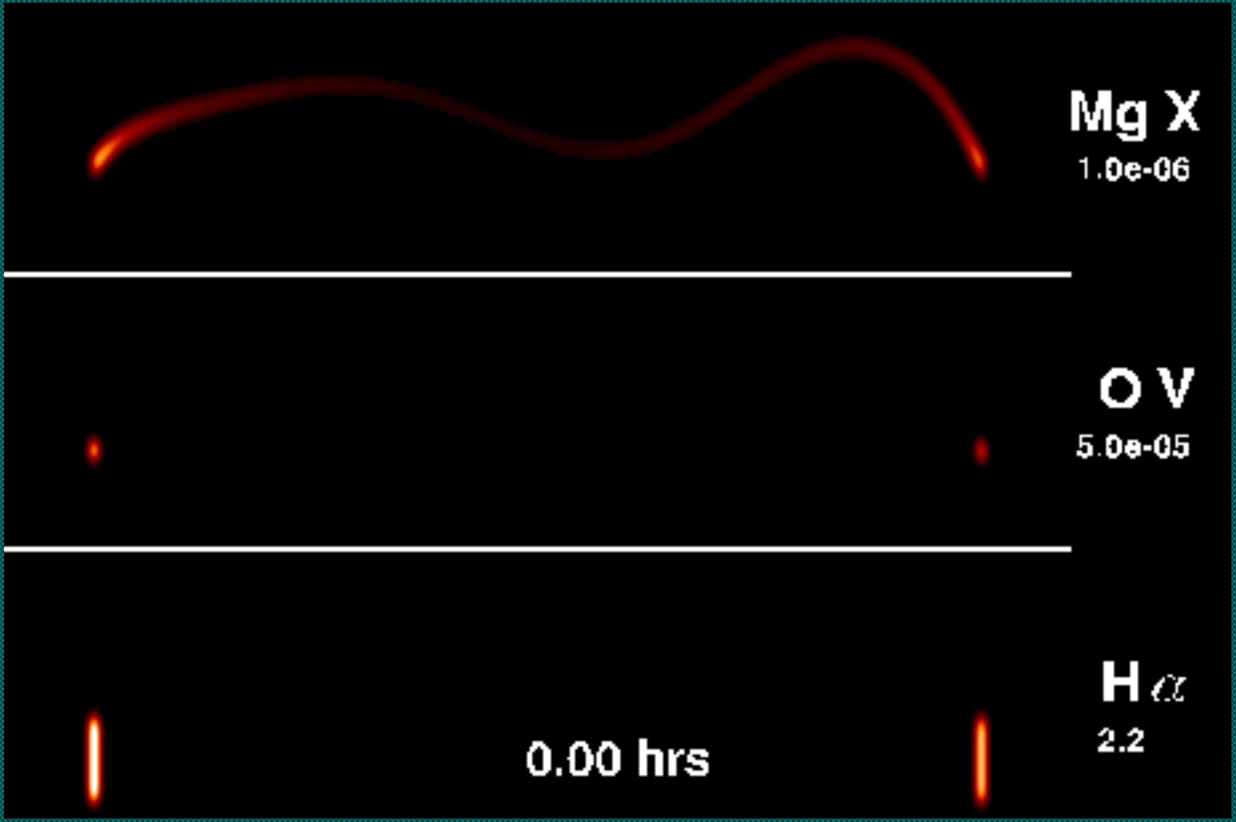
$Q_{right} > Q_{left}$

Effects of Heating Asymmetry



$Q_{left} > Q_{right}$

Effects of Heating Asymmetry



$Q_{left} > Q_{right}$

Summary of Single Flux Tube Results

- Dynamic condensations are produced by normal coronal heating at base of long flux tubes
- Shallowly dipped flux tubes have longest condensations
- Don’t need time-varying heating to get a wide range of dynamic and stationary features; just need different geometry and heating asymmetry
- Episodic heating produces condensations if sufficiently frequent (pulse interval & duration < radiative cooling time)
- With same heating, some flux tubes (too short, too high, or too deeply dipped) do not produce features consistent with prominence observations
- Changing heating after formation moves condensation

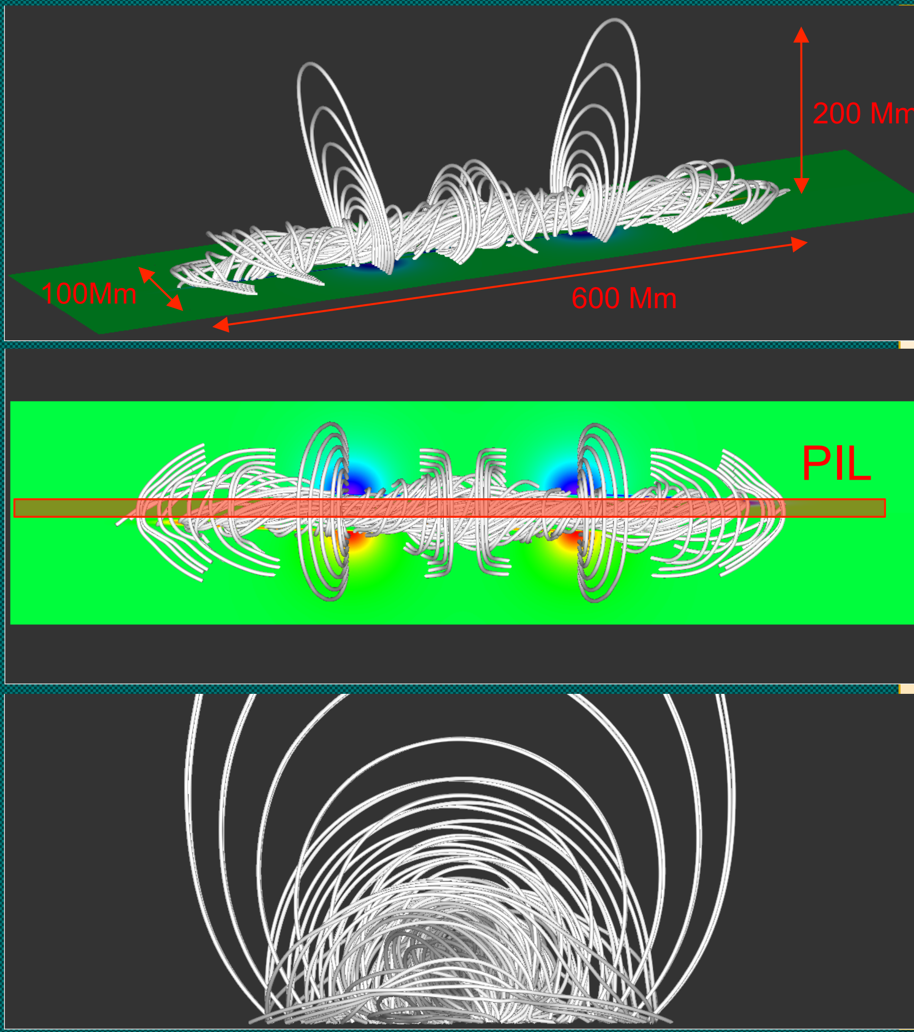
Next Step: 3D Prominence Model

Magnetic structure assumed to be a *sheared arcade* formed by merger of 2 adjacent arcades

For selected flux tubes from 3D MHD simulation:

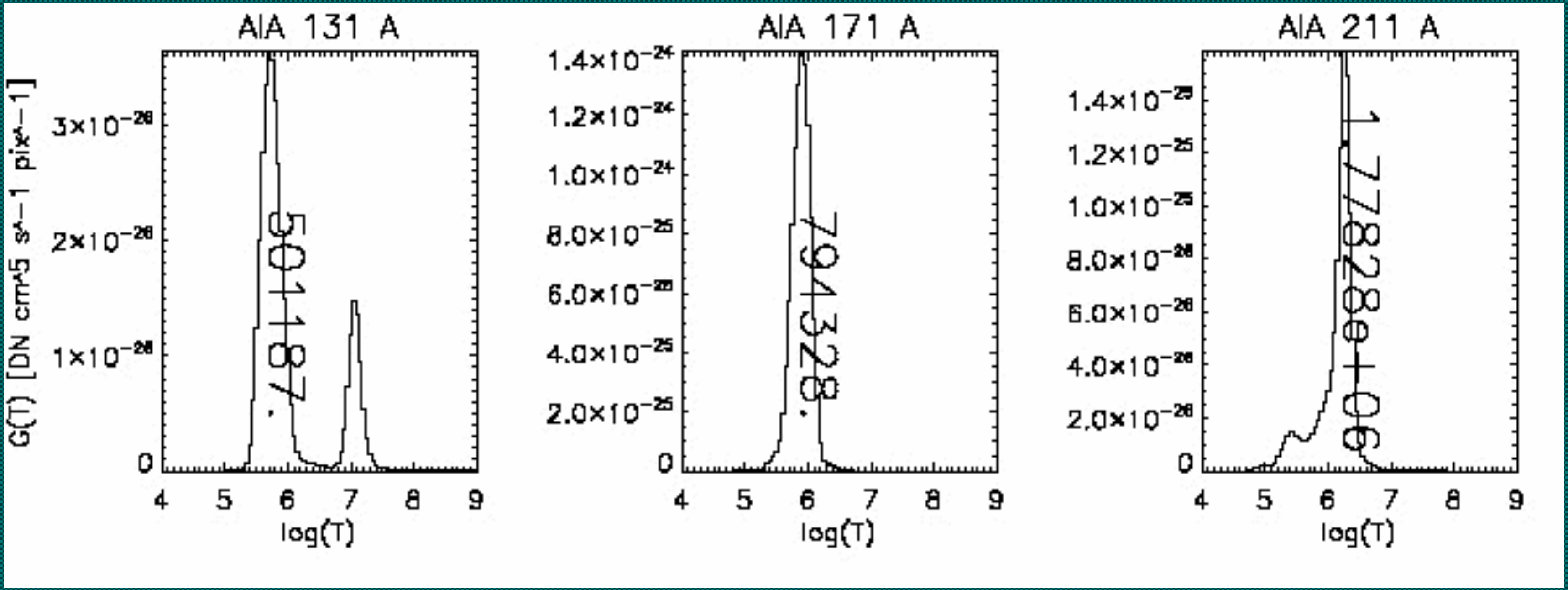
- Derive geometry (height and area as functions of distance *s* along flux tube). Note area comes from flux conservation (~ 1/B)
- Simulate plasma response to footpoint heating to obtain T(*s,t*) and ρ(*s,t*) in flux tubes
- Use IDL postprocessing routines to predict emission in selected spectral lines from the ensemble of flux tubes, for different points of view

Magnetic Structure: Sheared 3D Arcade



- **Basic framework:** Inner bundle of long, low-lying field lines + overlying arcade (Priest 1989, Martin 1998).
- Selected 125 flux tubes, with lengths between 80 and 450 Mm.
- Study is focused on the prominence so the cavity is undersampled
- Same heating function and scale as in single-tube studies, *but heating asymmetry is randomly distributed*

Predicting Emissions



SDO/AIA temperature responses

- We visualize the plasma evolution in these three EUV channels with peak temperatures ~0.5 MK, 0.8 MK, and 1.8 MK.
- Temperature-based proxy shows where Hα emission should appear: assume all plasma below 35,000 K emits Hα

Simulated Hα Observations

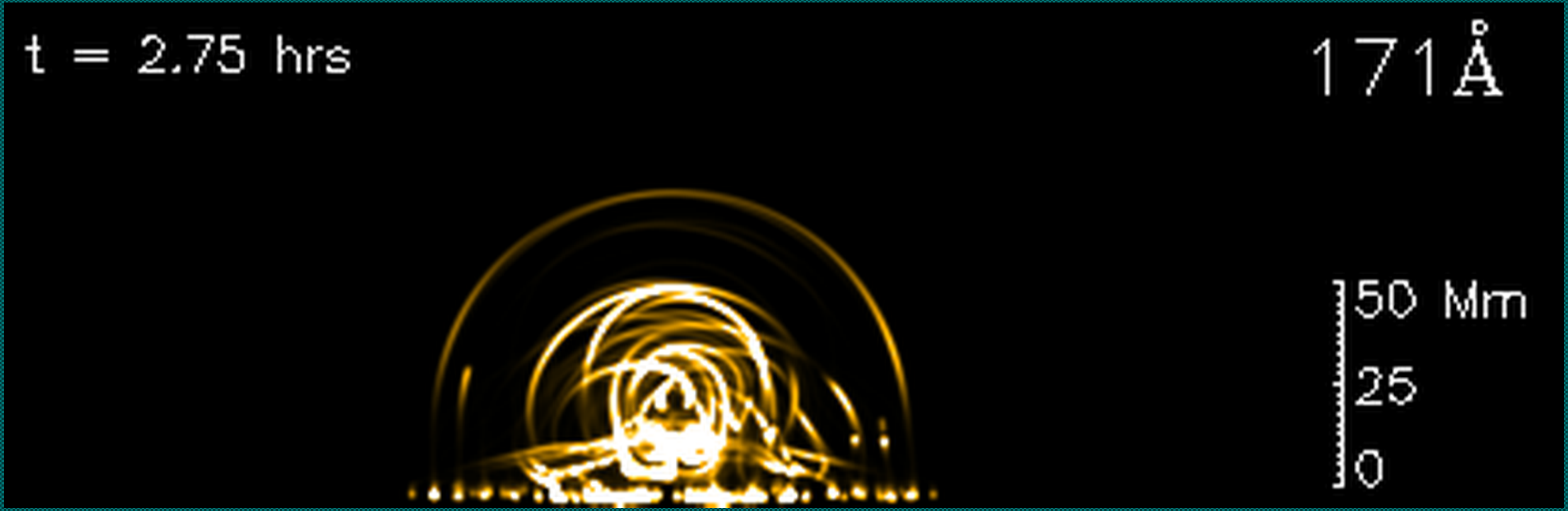
End view:

- Threads form core, surrounded by blobs and coronal rain (except at base)

Side view:

- Threads move horizontally before settling down
- Blobs form and fall frequently = counterstreaming?

Simulated SDO/AIA Observations



End view:

- Bright core

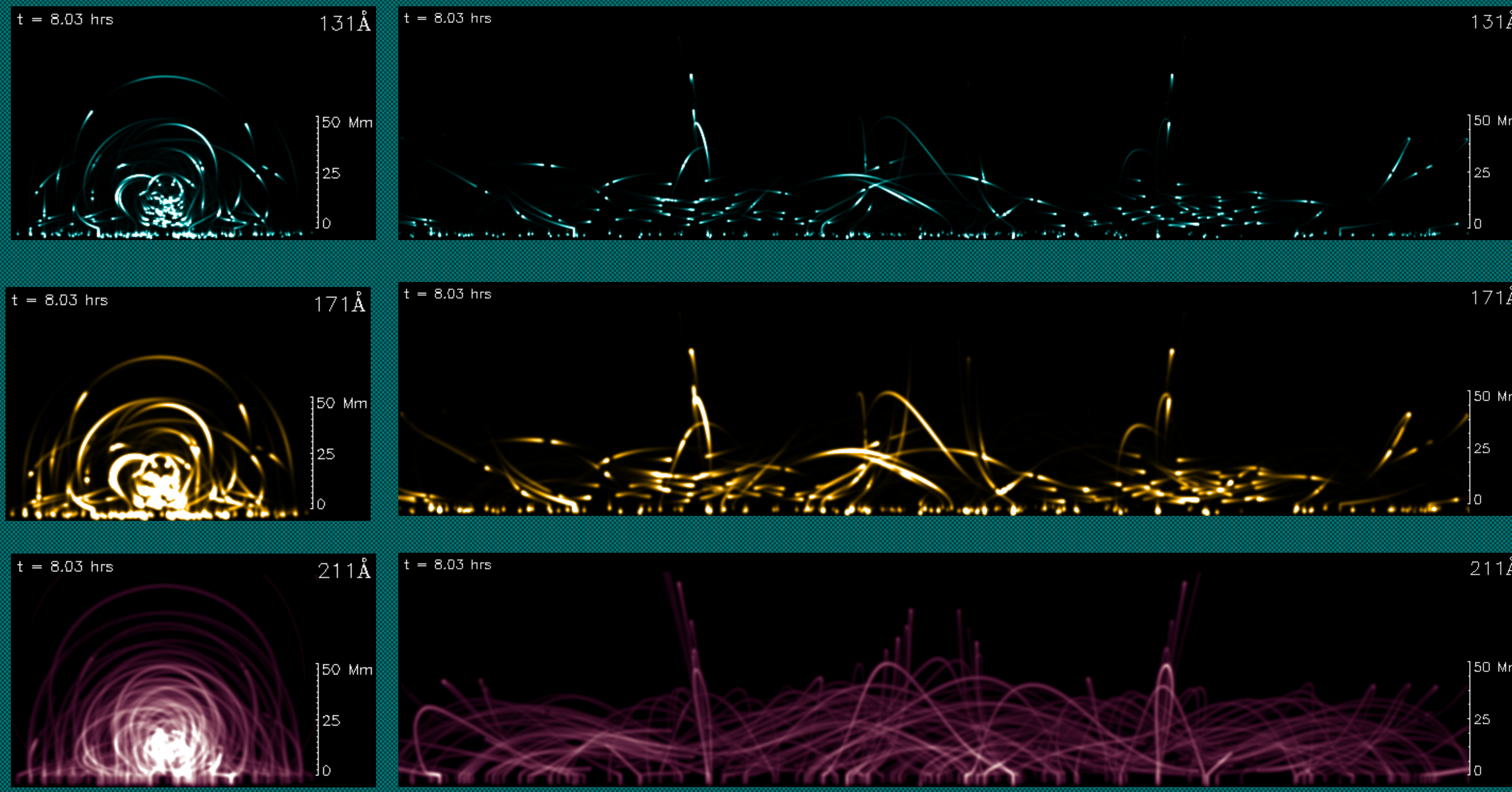
Side view:

- Condensations appear as gaps with bright edges
- Extremely dynamic

Emission from EUV Channels

End view

Side view

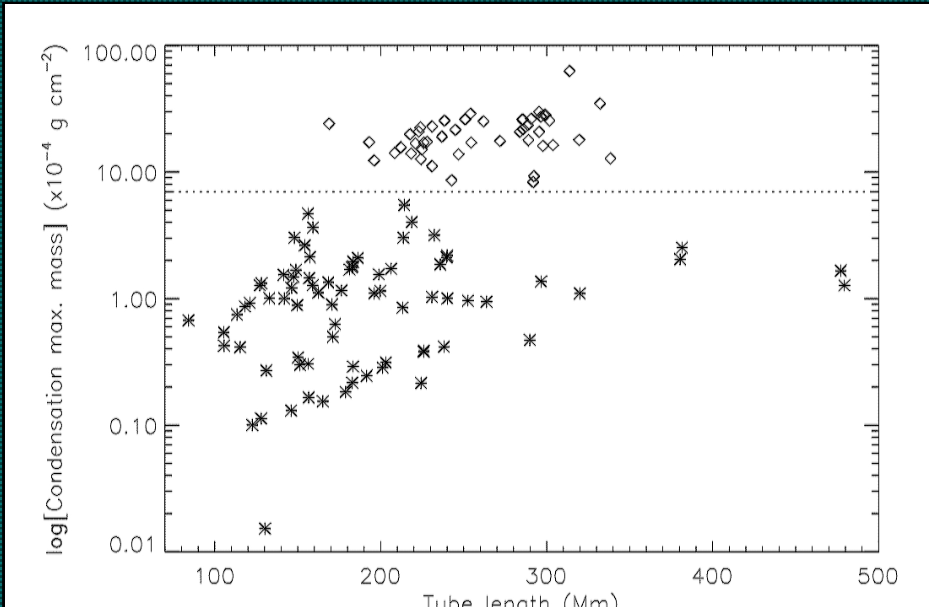


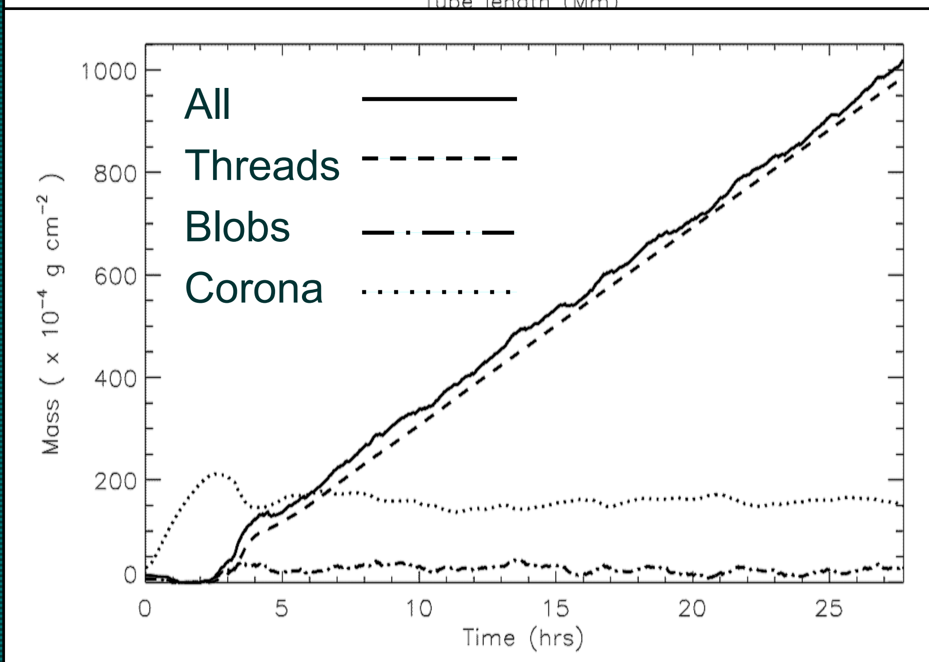
PIL

Saturation values: 1.5 DN/pix/s, 24 DN/pix/s, and 10 DN/pix/s

Maximum values: 9-13 DN/pix/s, 5-19 DN/pix/s, and 143-233 DN/pix/s

Two Populations of Condensations





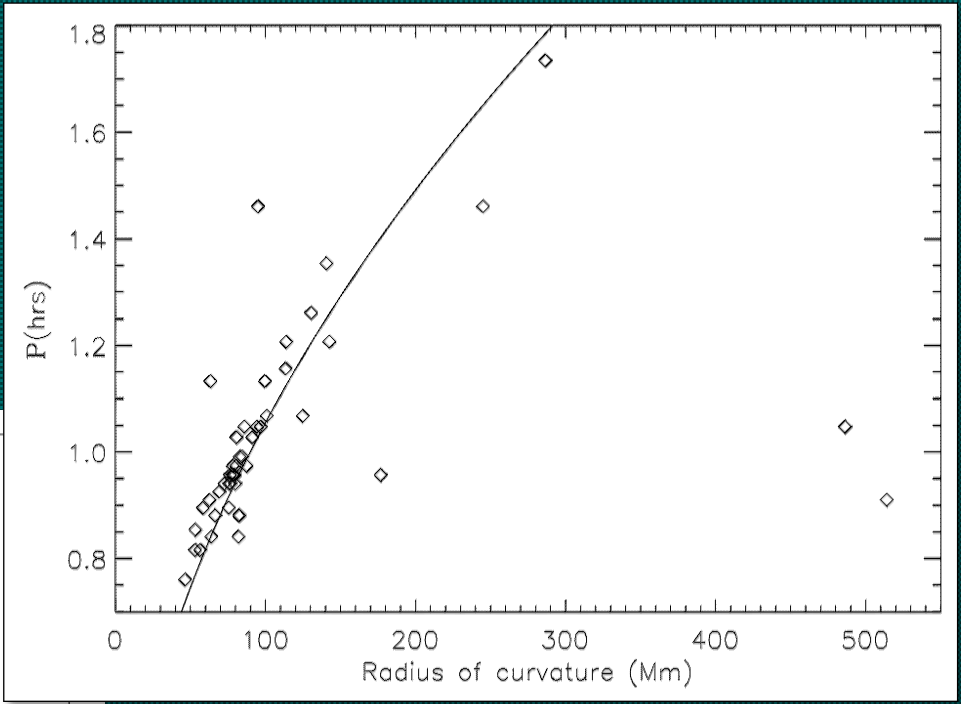
Threads: ◇
- Oscillating then stationary
- Steady growth

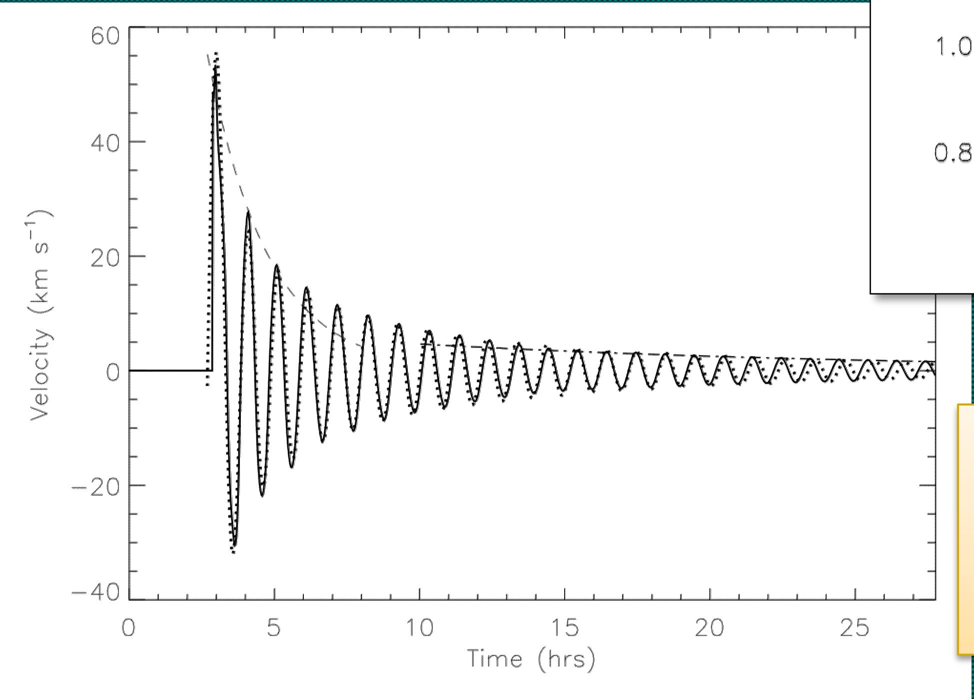
Blobs: ✸
- Dynamic
- Cycles of creation/destruction
- Small mass, length

If tube radius ~ 100 km at one footpoint, total mass M ~ 0.1-2 x 10^{15} g at end of run

Threads Oscillate during Formation

- each condensation = pendulum
- damped initially by increasing mass, later by some non-adiabatic process (e.g., radiation)
- average radius of curvature measured for each dip





- Excellent fit to very simple model!
- New diagnostic for prominence thread properties (mass, dip curvature, B_{min})

Summary of our 3D Prominence Model

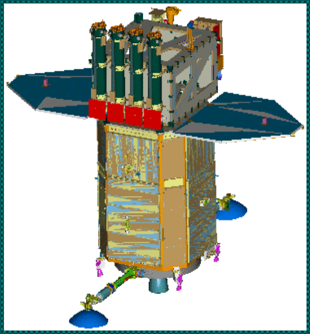
Condensations are ubiquitous

- Threads: stationary and growing (for steady heating)
- Blobs: transient and highly dynamic
- Coronal rain in overlying arcade (same as blobs)

Model generally consistent with observations

- Bright core in coronal spectral lines = chewy nougat?
- Counterstreaming and flows
- "Horns" in cavity above prominence
- Sudden appearance in corona
- Cool thread between bright edges in coronal lines
- Oscillations

SDO/AIA instrument



Best spatial resolution ~ 0.6"

Temporal cadence ~ 10 s

Channel name	Primary ion(s)	Region of atmosphere*	Char. log(T)
304Å	He II	chromosphere, transition region	4.7
1600Å	C IV+cont.	transition region + upper photosphere	5.0
171Å	Fe IX	quiet corona, upper transition region	5.8
193Å	Fe XII, XXIV	corona and hot flare plasma	6.1, 7.3
211Å	Fe XIV	active-region corona	6.3
335Å	Fe XVI	active-region corona	6.4
94Å	Fe XVIII	flaring regions	6.8
131Å	Fe VIII, XX, XXIII	flaring regions	5.6, 7.0, 7.2

EUV Temperature range: 0.5 MK to 2 MK

Symmetric footpoint heating

Loop length L > 8 λ (λ = heating scale)

Apex height < gravitational scale height

Results:

- Small heating increase ➔ new static solution with higher T,ρ at apex
- Larger heating increase ➔ steady solution with T_{min} at apex (growing condensation)

Thermal Nonequilibrium (con't.)

For $L > 8\lambda$, enthalpy flux must sustain conduction + radiation far from heat source

<u>Dynamic</u> Scaling Laws:

$E\lambda \sim PV$

$PV \sim T^{7/2} L^{-1} \sim P^2 L T^{-b-2}$

where b = 1 for T > 0.1 MK

-3 for T < 0.1 MK