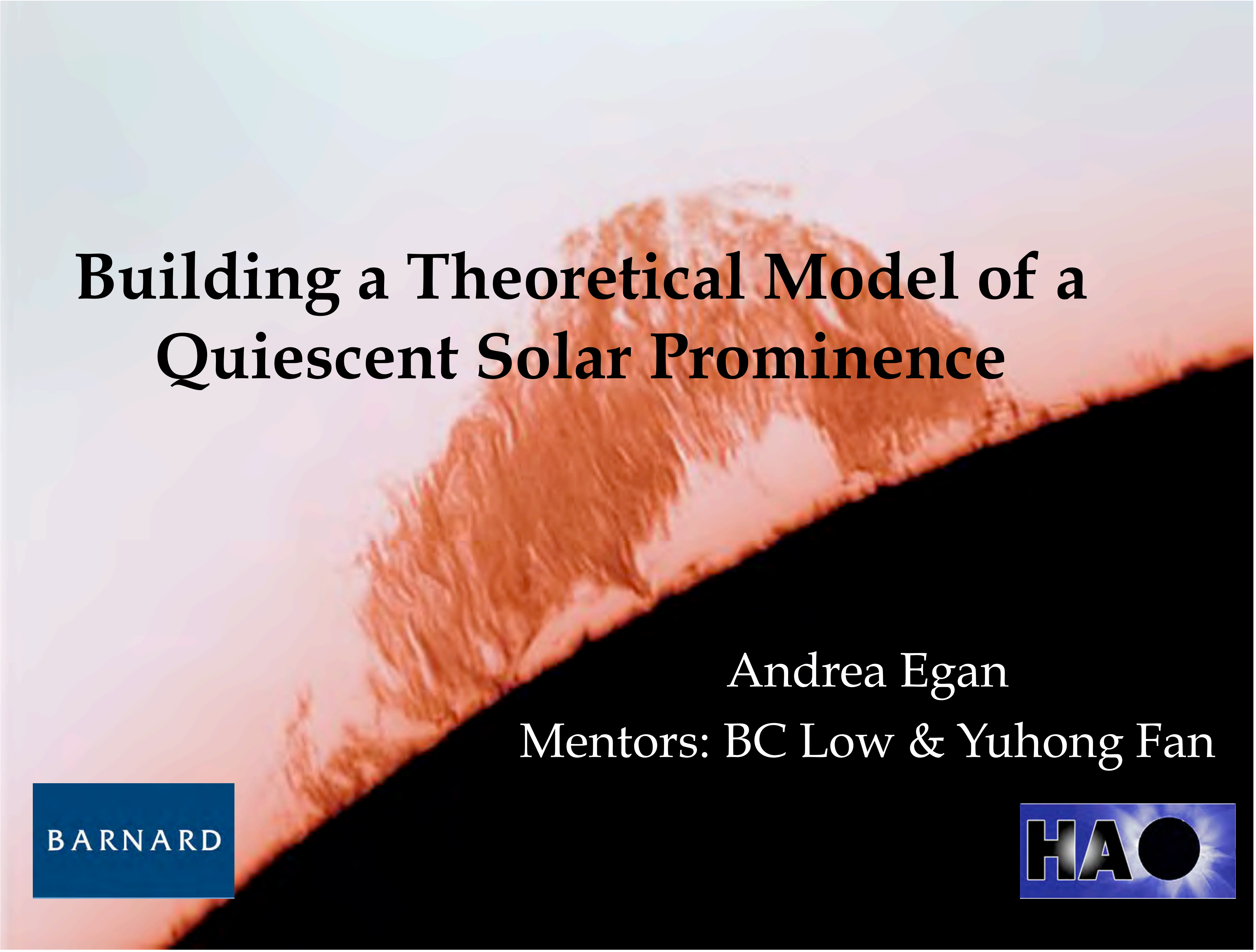

Building a Theoretical Model of a Quiescent Solar Prominence

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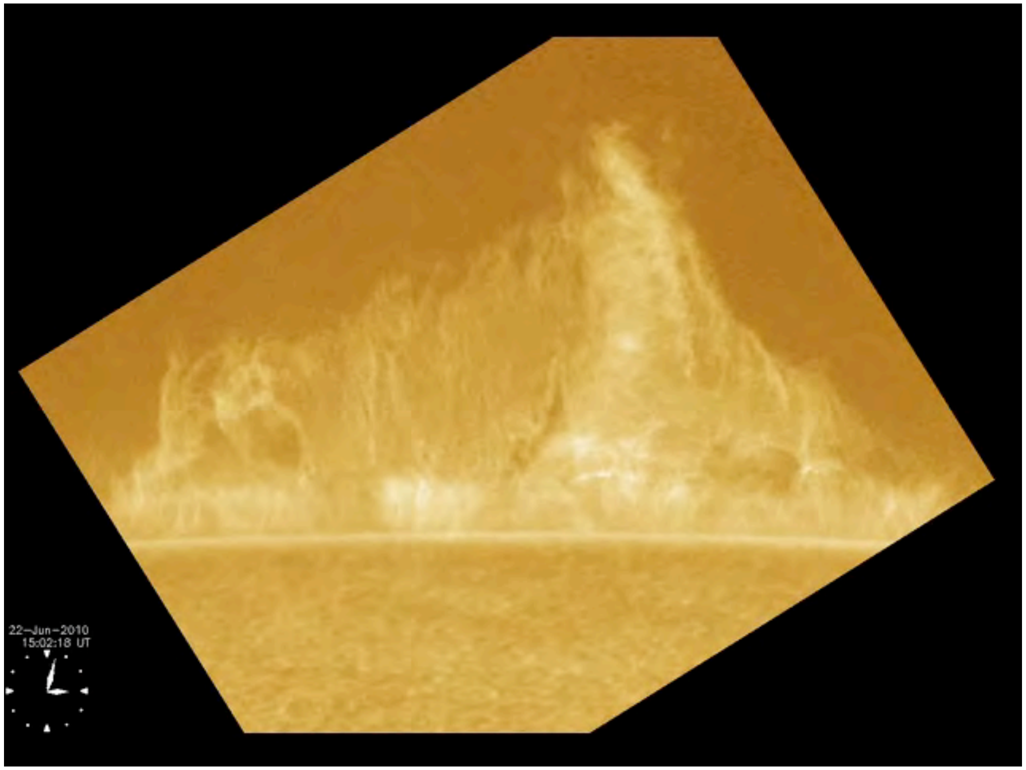
BARNARD

HAO

What is a Solar Prominence?

- Relatively cool dense plasma suspended above the sun's surface in apparent global equilibrium



What is a Solar Prominence?

- Condensed plasma two orders of magnitude cooler than surrounding corona
- Timescale of days to weeks
- 10^{15}g mass can drain in a day

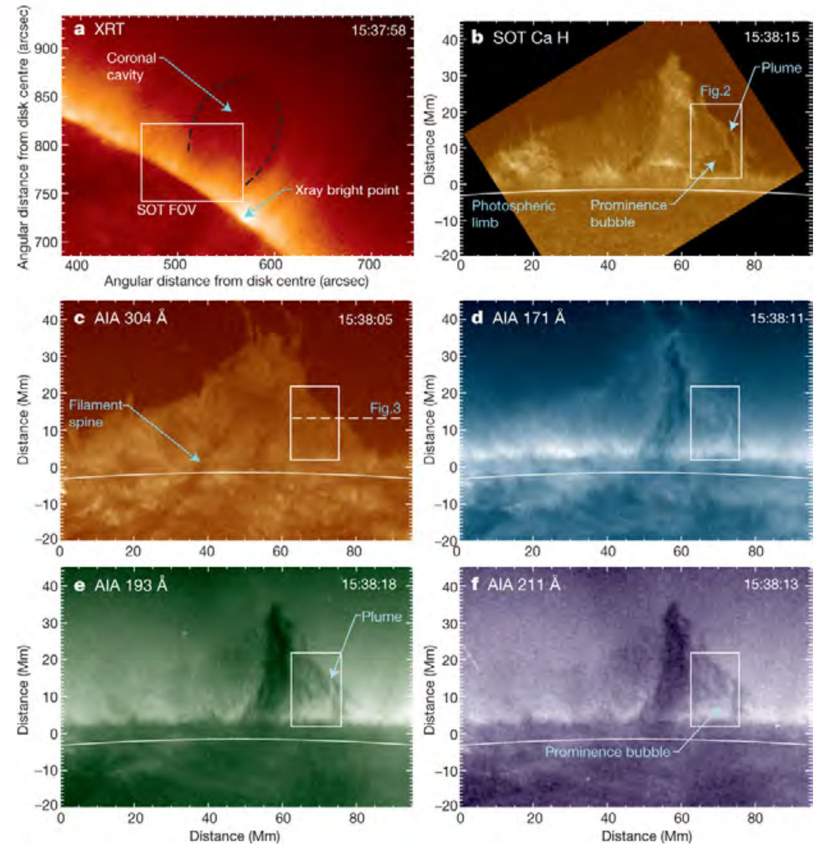
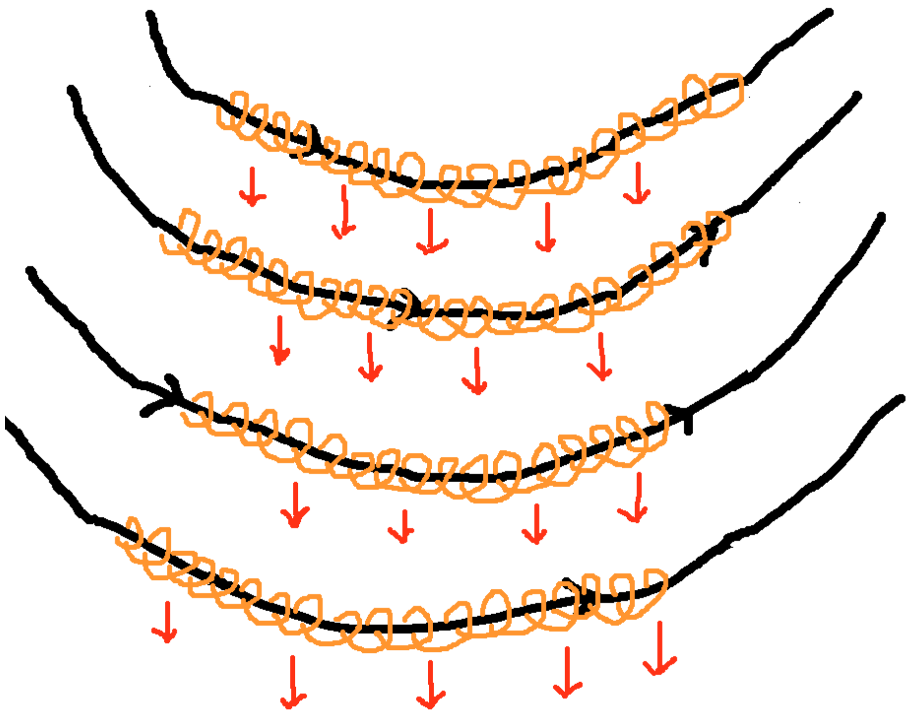


Image: Berger et al 2011

How is the plasma suspended?

- Bowed magnetic field lines
- “Frozen in” plasma



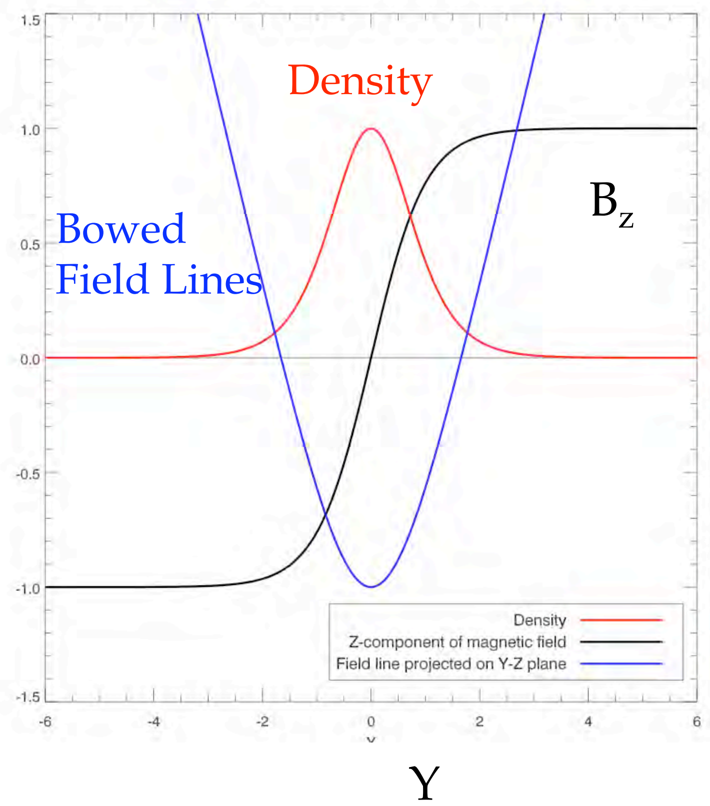
How Can We Model a Prominence?

- Use MHD equations
- A full 3-D model for all of the variables would be too complex
- Solution: use a model of a solar prominence from 1957 Kippenhahn-Schlüter paper
- Turns 3D model into 1D

Kippenhahn and Schlüter Model

- Static, isothermal slab
- Still allows for variance of all parameters, non-trivial interactions
- $\vec{B} = B_0[0, 1, H(y)]$

The Original Isothermal Static K-S Slab



Using this model…

- Still can't solve the 1D equations with all the parameters
- What can we do?
  - Build up to the full model gradually
  - Learn more about the effects of viscosity, resistivity, etc on the basic plasma behavior along the way
  - Helps to better understand the behaviors of the final solution

Radiation Nonlinear in T

- Generalization of linear radiation calculation in Low et al. 2012
- The Set-Up:
  - Field-aligned thermal conductivity
  - Infinite electrical conductivity
  - Static
  - Nonviscous
  - Radiative loss, $r = \alpha_0 \rho^2 T^n$
  - Simple heating, $h = \gamma_0 \rho$

Radiation Nonlinear in T

Thermal Conduction

Radiative Cooling

- After a lot of math…

$$\frac{1}{10}\beta^2 \frac{d}{dH}\left[\frac{\kappa_0}{1+H^2}\frac{dT^{5/2}}{dH}\right] = (\beta - H^2)T^{n-1} - \beta\gamma$$

Heating

- Balance of heating and radiation
- In Low et al. 2012, n=1 and the differential equation can be analytically solved.
- Radiative loss isn't necessarily linear in T
- What if n=2 or more?

$$r = \alpha_0 \rho^2 T^n$$

Radiation Nonlinear in T

- N=2 leads to a nonlinear differential equation
- Not analytically solvable
- Use Runge-Kutta method to solve

$$r = \alpha_0 \rho^2 T^2$$

This causes a lot of trouble!

$$\frac{1}{10}\beta^2 \frac{d}{dH}\left[\frac{\kappa_0}{1+H^2}\frac{dT^{5/2}}{dH}\right] = (\beta - H^2)T^{2-1} - \beta\gamma$$

Radiation Nonlinear in T

- Does this equation behave the same as the n=1 case?
- Pretty much
- Eigenvalue problem in heating coefficient γ

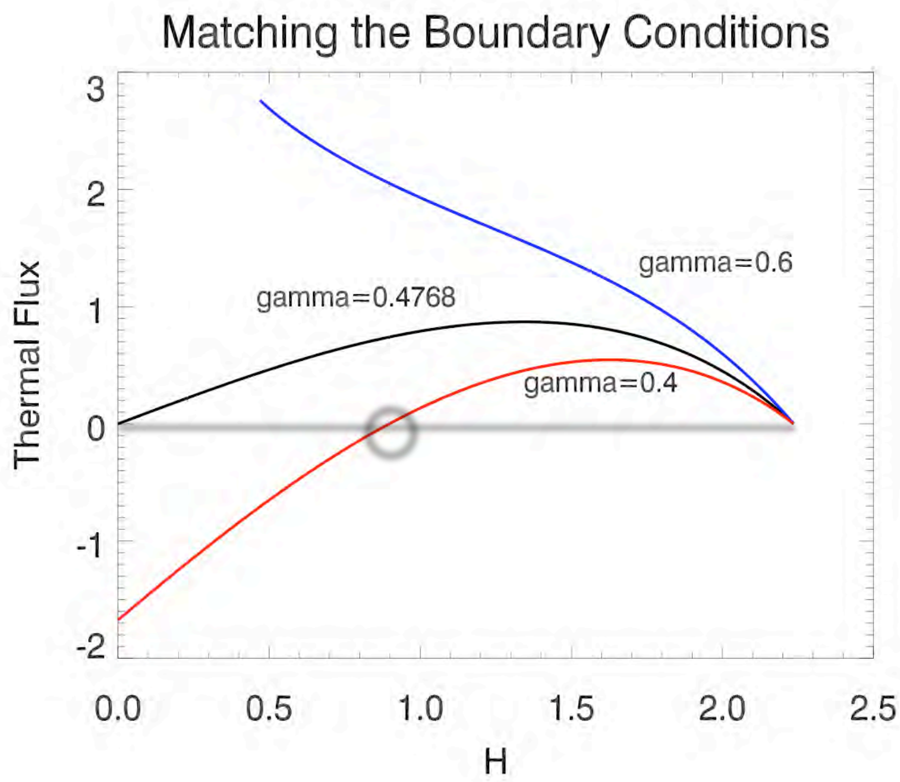
$$r = \alpha_0 \rho^2 T^2$$

This causes a lot of trouble!

$$\frac{1}{10}\beta^2 \frac{d}{dH}\left[\frac{\kappa_0}{1+H^2}\frac{dT^{5/2}}{dH}\right] = (\beta - H^2)T^{2-1} - \beta\gamma$$

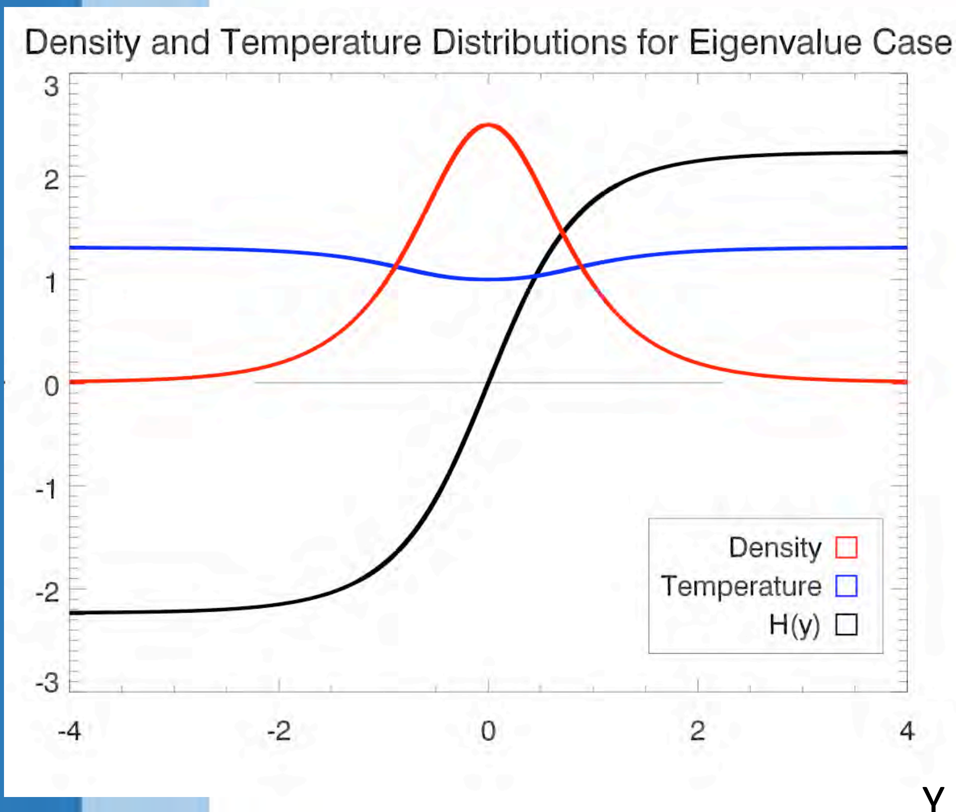
Radiation Nonlinear in T

- Try to match the boundary conditions
- If $\gamma > \gamma_{critical}$, heating everywhere, no equilibrium
- If $\gamma < \gamma_{critical}$, center collapses to cold dense sheet.



Radiation Nonlinear in T

$\gamma = \gamma_{critical}$



$\gamma < \gamma_{critical}$

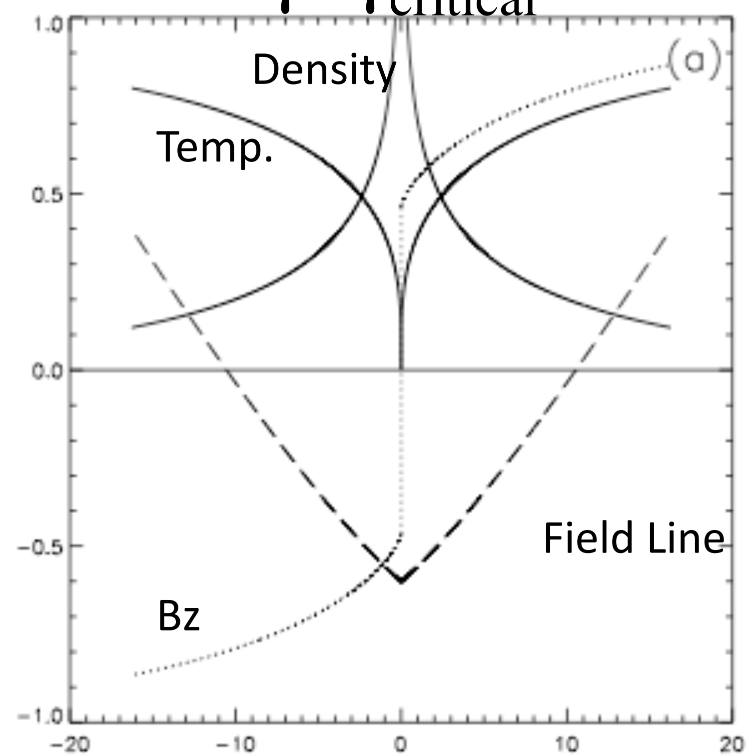
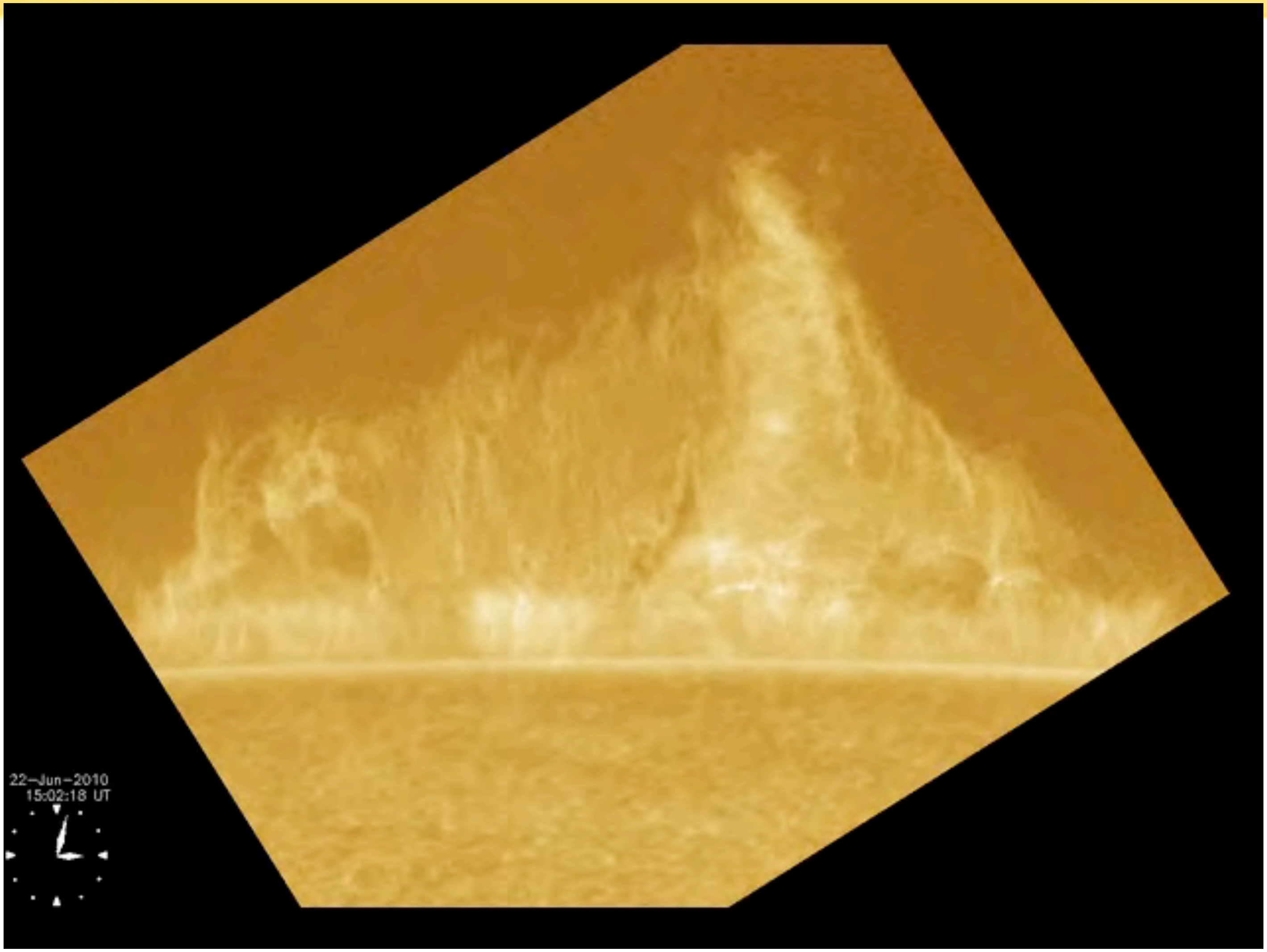


Image: Low et al. 2012

Radiation Nonlinear in T

- Conclusions:
  - Agreement with results from linear case
  - For most parameters, this system produces a cold, collapsed core, consisting of an infinite current sheet
  - This most-likely breaks the frozen-in condition, allowing the material to flow resistively across the magnetic field

Radiation Nonlinear in T



Isothermal Viscous Case

- We need more physics to explain Part I
- Look at resistive flow with viscosity
- Isothermal to remove energy balance
- Resistivity and viscosity taken to be constant

Image: indianews99.com

Isothermal Viscous Case

- New force balance equation:

$$\mu_0 \frac{d^2 v}{dY^2} - \rho g + \frac{dH}{dY} = 0$$

Viscous Force

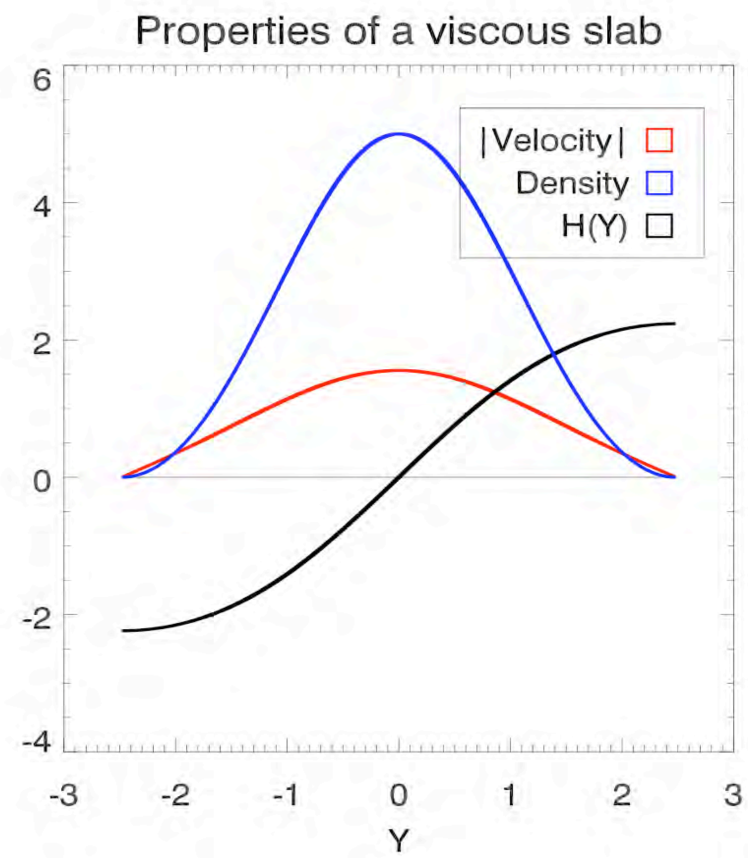
Gravity

Magnetic tension

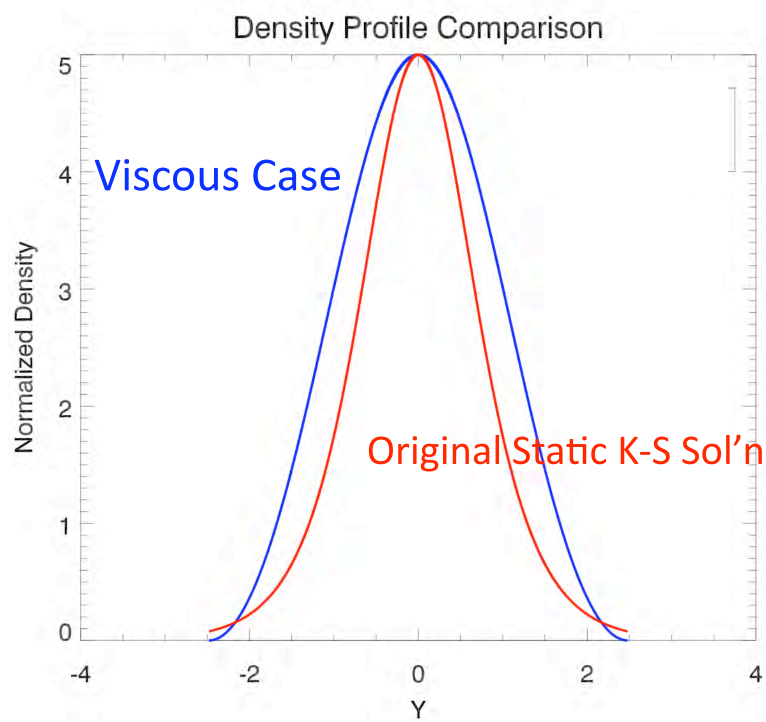
- Direction of force is determined by curvature of velocity distribution

Isothermal Viscous Case

- Solve force-balance for |velocity| and density
- Viscosity lessens effective gravity in center, increases it at ends



Isothermal Viscous Case



- Conclusions:
  - Force at large Y compacts the slab into a finite width
  - Viscous slab is suspended in vacuum by external potential field

Conclusions

- Perfect balance of heating and radiative loss is rare and unstable
- Future Work:
  - Resistive and viscous heating (steady-state), everything together
  - Understand how all of the different forces and processes work together to produce the behavior seen in prominences.

Thermal conduction

Simple heating

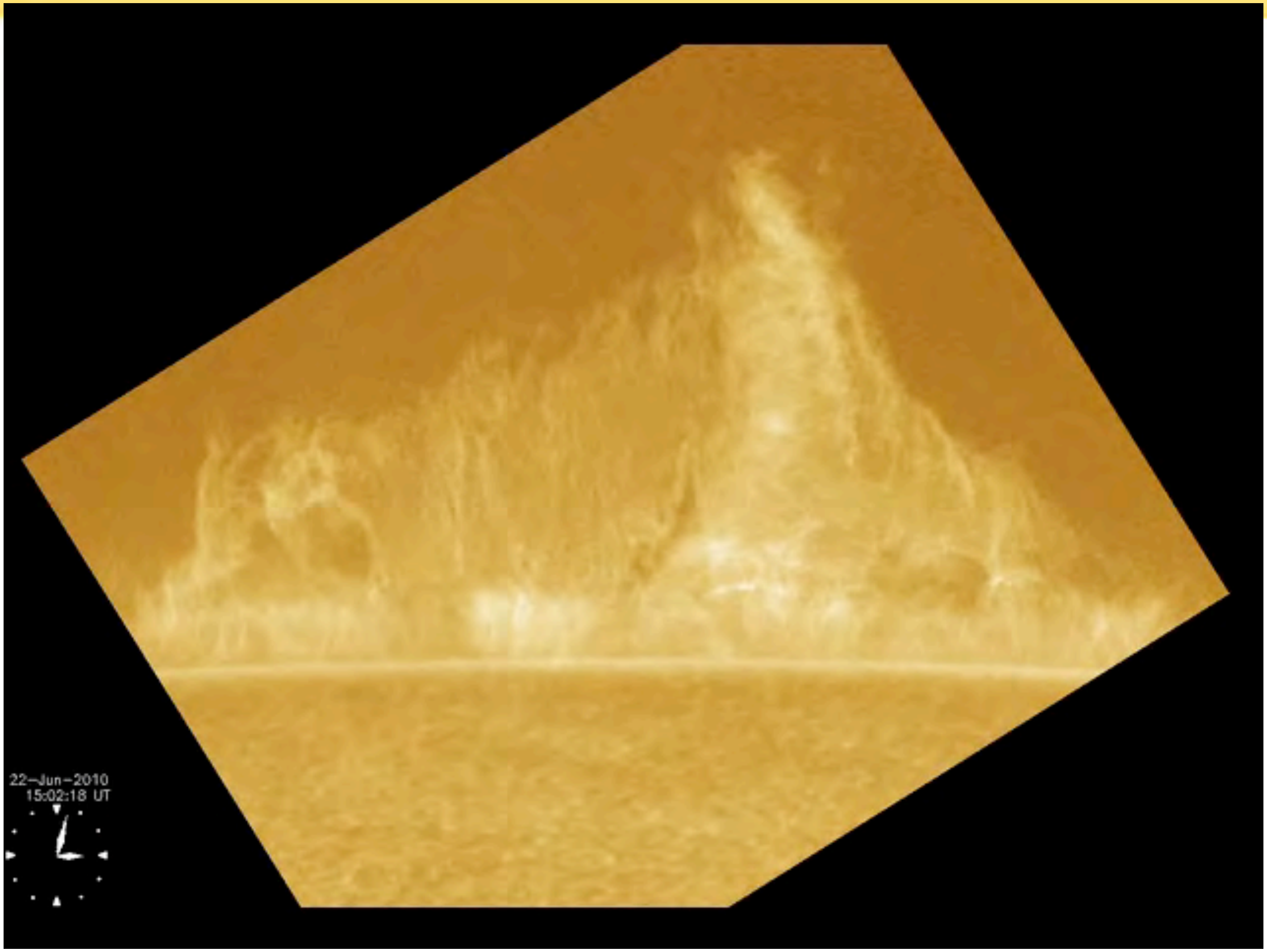
Resistive heating

$$\frac{d}{dY}\left[\frac{\kappa_1 K(\theta)}{1+H^2}\frac{d\theta}{dY}\right] = D^2\theta^n - \gamma_1 D - \eta_1\left[\frac{\epsilon}{4\pi}M(\theta)\left(\frac{dV}{dY}\right)^2 + E(\theta)\left(\frac{dH}{dY}\right)^2\right]$$

Radiative loss

Viscous heating

Conclusions



References

- Berger, T. E., et al. 2011, Nature 472, 197
- Kippenhahn, R. & A. Schlüter 1947, Z. Astrophs. 43, 36
- Labrosse, N. et al. 2010, Space Sci Rev 151, 243
- Liu, W., T. E. Berger, & B. C. Low 2012, ApJ 745, L21
- Low, B.C. et al. 2012, ApJ 755, 34
- Low, B.C. et al., 2012, In Press
- Mackay, D. H. et al. 2010, Space Sci Rev 151, 333

Thank You!

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