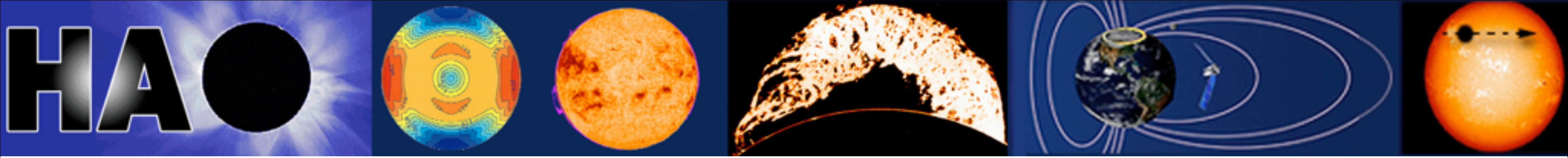
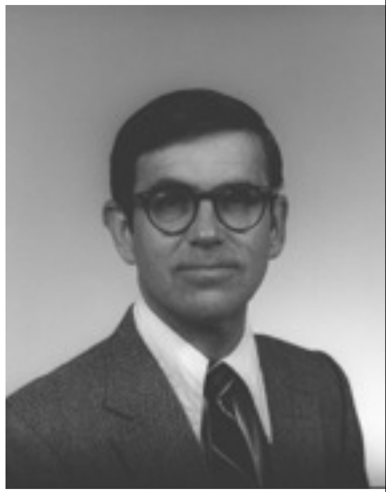
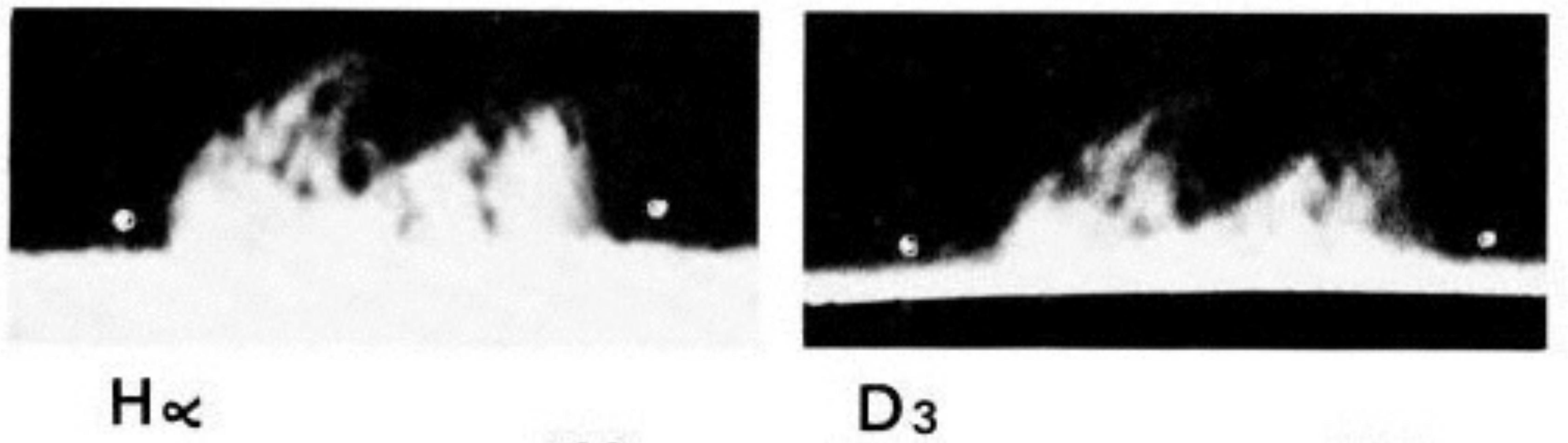


Heasley and Mihalas 1976:

the poetic tragedy of radiative and magnetostatic equilibrium





Observations of Kim, Nikolsky 1973

NCAR

P. Judge, March 2014

THE ASTROPHYSICAL JOURNAL, **205**:273–285, 1976 April 1

STRUCTURE AND SPECTRUM OF QUIESCENT PROMINENCES: ENERGY BALANCE AND HYDROGEN SPECTRUM

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Received 1975 July 24

However, none of this work actually carried out the extremely difficult nonlinear calculation required to *determine* a temperature structure for the prominence consistent with energy balance, and the transfer of radiation (both incident and internal). We present such computations in this paper,

Kippenhahn-Schluter 1957

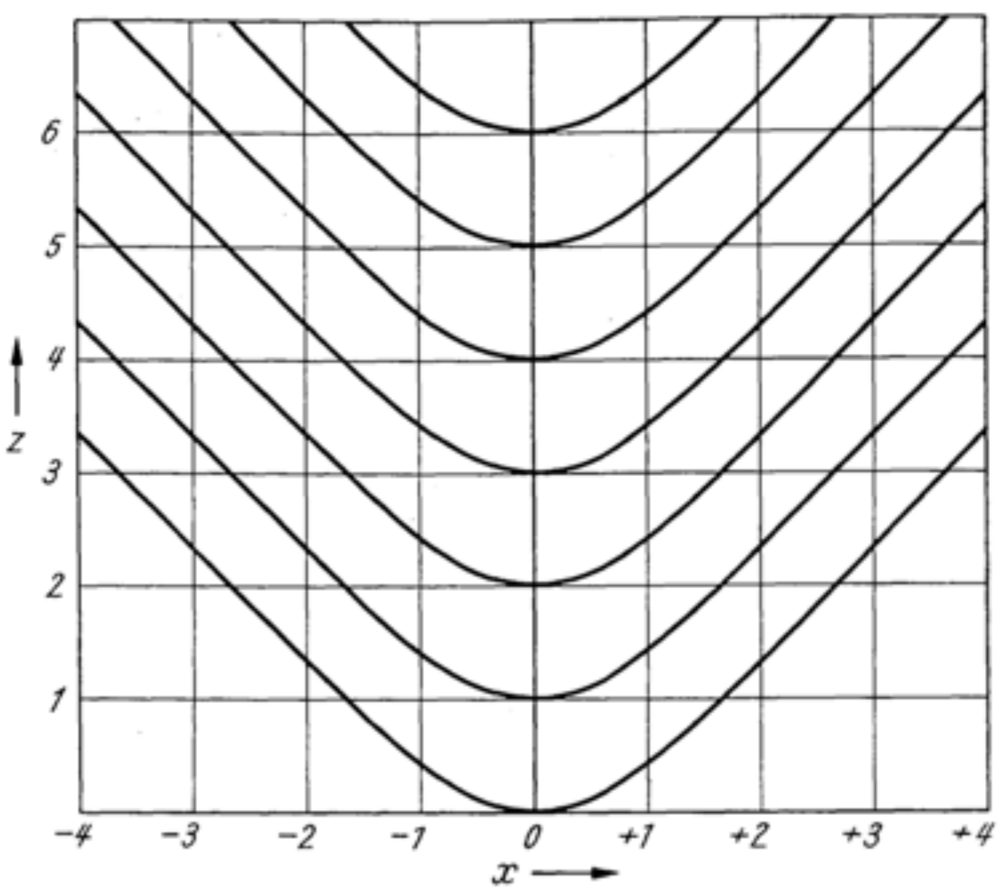


Abb. 4. Verlauf der Feldlinien in einem Filament. Abszisseneinheit $\frac{2hH_x}{H_z^\infty}$, Ordinateneinheit $2h$

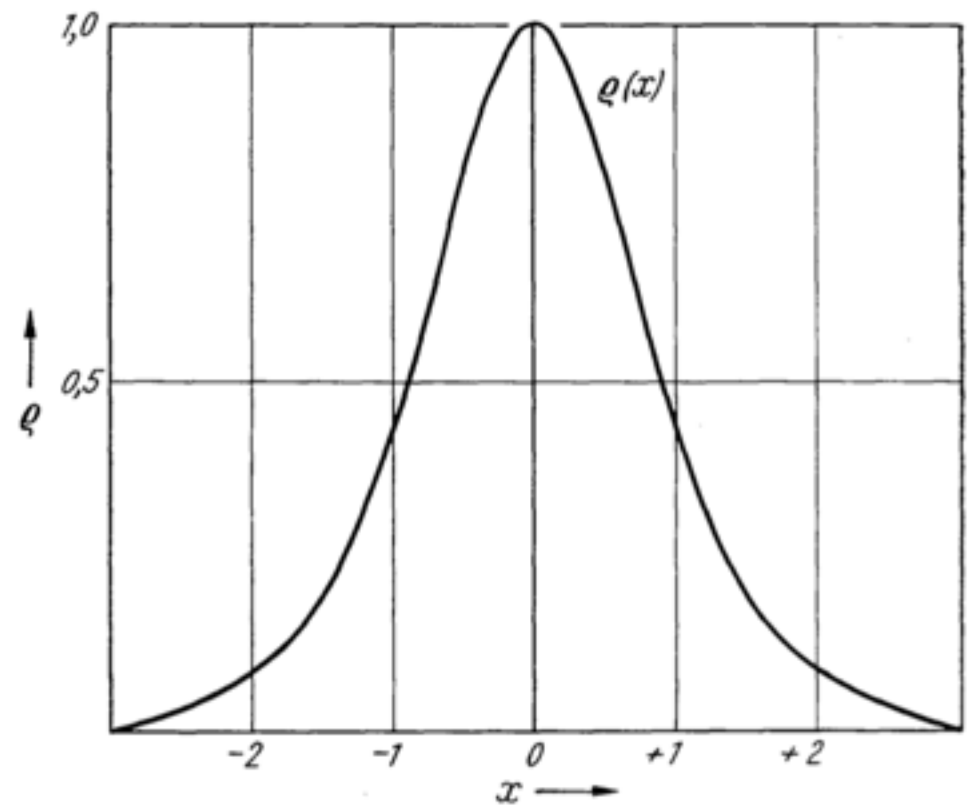


Abb. 5. Dichteverteilung $\varrho(x)$ in einem Filament. Abszisseneinheit $\frac{2hH_x}{H_z^\infty}$. Die Ordinateneinheit ist so gewählt, daß $\varrho(0) = 1$

the problem

- Kippenhahn-Schluter (1957) configuration
- vertical slab subject to Lorentz force, gravity, irradiation
- self-consistent force and energy balance
  - magnetostatic, nLTE radiative (inc. statistical) equilibrium
- reduced to Cartesian 1D (x=coordinate across slab)
  - $\mathbf{B}=(B_x(z), B_{0y}, B_z(x))$
  - BC's: $p=p_0$ in corona, $B_z(\pm\infty)=B_0$, irradiated by surface and corona
  - complete linearization method for RT/nLTE, H, He **only**

$$\nabla p = \frac{1}{4\pi}(\nabla \times \boldsymbol{B}) \times \boldsymbol{B} + \rho \boldsymbol{g}$$

$$\nabla \cdot \boldsymbol{B} = 0\,,$$

$$4\pi \int_0^\infty [\eta_\nu - (\chi_\nu - n_e \sigma_e) J_\nu] d\nu = 0\,.$$

+ nLTE rate equations, H and He

vertical force balance

$$-\frac{\partial B_z}{\partial x} = -\frac{4\pi}{B_x}\rho\left(g + \frac{1}{\rho}\frac{\partial p}{\partial z}\right) - \frac{\partial B_x}{\partial z} .$$

$$\frac{dB_z}{dm} = -\frac{4\pi}{B_x}\gamma - \beta , \qquad dm = -\rho dx .$$

$$\gamma \equiv g + \frac{1}{\rho}\frac{\partial p}{\partial z}$$

$$\beta \equiv \frac{1}{\rho}\frac{\partial B_x}{\partial z} .$$

γ, β **treated as** *constants (justified by observations)*

m is the independent variable for the RT/ nLTE calculations

c) *The Collapse of Magnetohydrostatic Equilibrium*

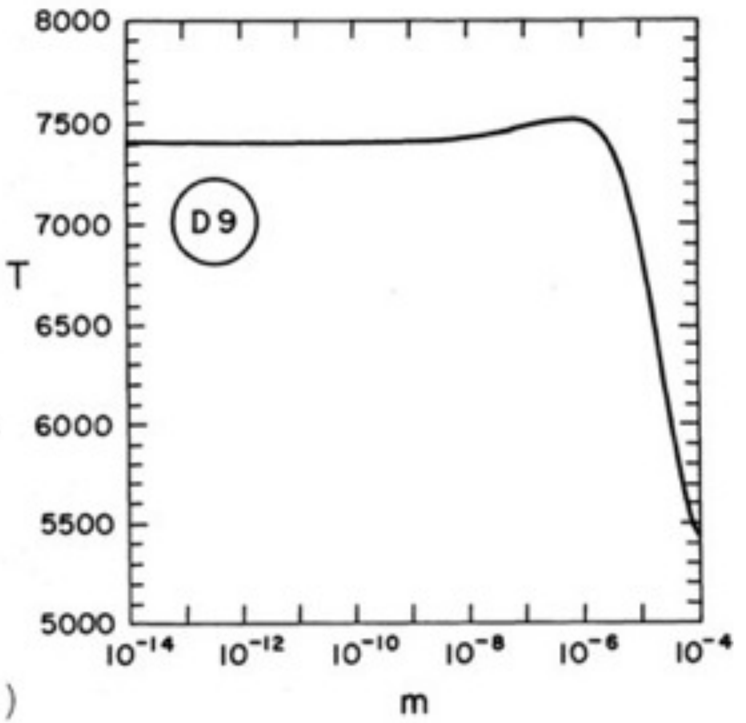
In constructing models in which both the conditions of radiative and magnetohydrostatic equilibrium are to be satisfied simultaneously, we immediately encountered a severe problem with the latter constraint. If the coronal pressure p_0 is chosen too high, then the prominence collapses into a geometrically thin sheet, and additional mass produces essentially no increase in thickness.

.......and the predicted Balmer decrement 7.5:1.0:0.27 is in strong disagreement with observation. Similarly, $\tau(\mathrm{H}\alpha)$ is less than 1, in disagreement with observed values. These models are, in short, completely unacceptable.

results

(1) Model Number	(2) M	(3) P_o	(4) B_x	(5) Energy Balance	(6) D	(7) T_o	(8) T_c
M1	2.0-5	.56	10	RE, γ=1.0	1.7+2	7200	5605
M2	2.0-4	.56	10	RE, γ=1.0	8.4+2	7200	4610
M3	6.0-4	.56	10	RE, γ=1.0	8.6+2	7200	4545
R1	2.0-4	.07	∞	RE, γ=1.0	1.1+4	8055	4595
R2	2.0-4	.13	∞	RE, γ=1.0	5.4+3	7680	4590
R3	2.0-4	.26	∞	RE, γ=1.0	2.6+3	7400	4595
R4	2.0-4	.56	∞	RE, γ=1.0	1.2+3	7195	4600

Model Number	$\tau(L_c)$	$\tau(L_\alpha)$	$\tau(H_\alpha)$	$\tau(H_\beta)$	Integrated Intensity* L_α	H_α	H_β	H_γ
M1	2.1+1	3.8+5	0.40	0.06	2.87+4	2.72+5	3.57+4	9.58+3
M2	2.6+2	4.6+6	0.50	0.07	2.50+4	3.30+5	4.43+4	1.19+4
M3	8.0+2	1.4+7	0.48	0.07	2.38+4	3.18+5	4.25+4	1.14+4
R1	2.2+2	3.9+6	0.93	0.13	3.47+4	5.43+5	8.07+4	2.16+4
R2	2.4+2	4.2+6	0.77	0.11	3.13+4	4.73+5	6.79+4	1.82+4
R3	2.5+2	4.5+6	0.63	0.09	2.81+4	4.03+5	5.60+4	1.50+4
R4	2.6+2	4.6+6	0.52	0.07	2.53+4	3.39+5	3.39+4	1.23+4



(a)

thermal and magnetostatic collapse of equilibrium mass sheets

vertical + horizontal force balance:

$$p(m) = p_0 + \frac{\gamma}{B_x}\left(\frac{4\pi\gamma}{B_x} + \beta\right)\left(\frac{M}{2}m - \frac{m^2}{2}\right)$$

$p(M) \sim M^2$ and $M \sim \rho\,\Delta x$.

but $p \sim \rho T$ and

Heasley-Mihalas energy balance yields $T \sim M^{-\alpha}$, $\alpha \geq 0$

$\Delta x \rightarrow 1 / M^{(1+\alpha)}$

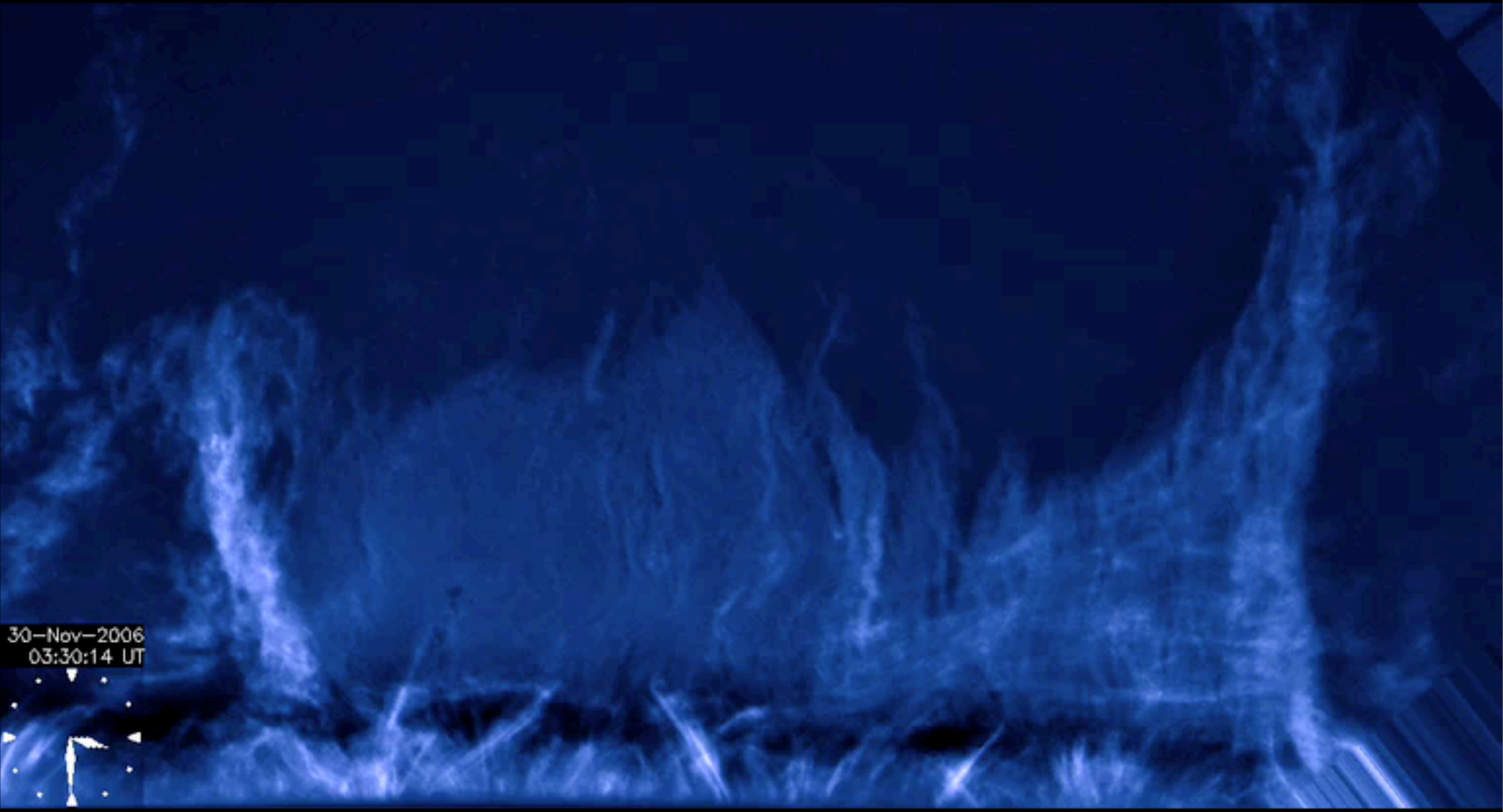
=> geometric thickness $\Delta x \rightarrow 0$ as M increases

Hinode data, Berger et al. 2008

Ca II H line

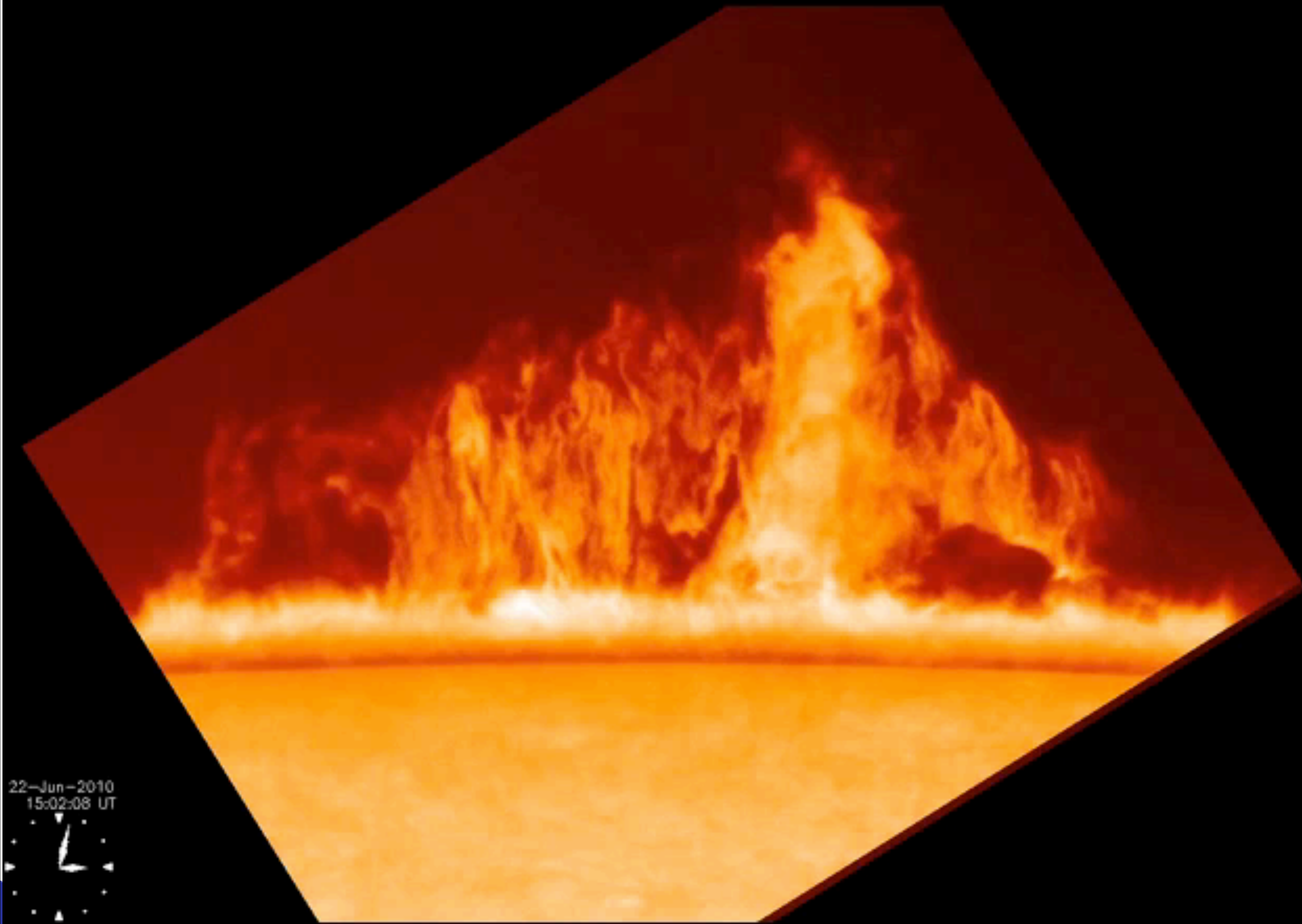
quiescent limb prominence

30 November 2006


30-Nov-2006
03:30:14 UT

Hinode data, Berger et al. 2011

Hinode/SOT H-alpha 656.3 nm filtergram
quiescent prominence
22-June-2010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Problem: thermal and magneto-convection in low beta plasma?

- frozen fields on macroscopic scales
- plasma motions show prominences internally dynamic
- yet magnetic stresses dominate

- solution: **flux sheet collapse**, breakdown of ideal MHD
  - neutral-ion slip
  - large local grad **B**, **significant** $\eta\nabla^2$**B,** topology change
  - **tangential discontinuities**

HAO

New theoretical work based on Heasley-Mihalas 1976

THE HYDROMAGNETIC INTERIOR OF A SOLAR QUIESCENT PROMINENCE. I. COUPLING BETWEEN FORCE BALANCE AND STEADY ENERGY TRANSPORT

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ABSTRACT

This series of papers investigates the dynamic interiors of quiescent prominences revealed by recent *Hinode* and *SDO*/AIA high-resolution observations. This first paper is a study of the static equilibrium of the Kippenhahn–Schlüter diffuse plasma slab, suspended vertically in a bowed magnetic field, under the frozen-in condition and subject to a theoretical thermal balance among an optically thin radiation, heating, and field-aligned thermal conduction. The everywhere-analytical solutions to this nonlinear problem are an extremely restricted subset of the physically admissible states of the system. For most values of the total mass frozen into a given bowed field, force balance and steady energy transport cannot both be met without a finite fraction of the total mass having collapsed into a cold sheet of zero thickness, within which the frozen-in condition must break down. An exact, resistive hydromagnetic extension of the Kippenhahn–Schlüter slab is also presented, resolving the mass-sheet singularity into a finite-thickness layer of steadily falling dense fluid. Our hydromagnetic result suggests that the narrow, vertical prominence H_α threads may be falling across magnetic fields, with optically thick cores much denser and ionized to much lower degrees than conventionally considered. This implication is discussed in relation to (1) the recent *SDO*/AIA observations of quiescent prominences that are massive and yet draining mass everywhere in their interiors, (2) the canonical range of 5–60 G determined from spectral polarimetric observations of prominence magnetic fields over the years, and (3) the need for a more realistic multi-fluid treatment.

Key words: conduction – diffusion – magnetic fields – magnetohydrodynamics (MHD) – Sun: corona – Sun: filaments, prominences

The Astrophysical Journal, 757:21 (15pp), 2012 September 20 doi:10.1088/0004-637X/757/1/

THE HYDROMAGNETIC INTERIOR OF A SOLAR QUIESCENT PROMINENCE. II. MAGNETIC DISCONTINUITIES AND CROSS-FIELD MASS TRANSPORT

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Received 2012 June 8; accepted 2012 July 26; published 2012 August 31

ABSTRACT

This second paper of the series investigates the transverse response of a magnetic field to the independent relaxation of its flux tubes of fluid seeking hydrostatic and energy balance, under the frozen-in condition and suppression of cross-field thermal conduction. The temperature, density, and pressure naturally develop discontinuities across the magnetic flux surfaces separating the tubes, requiring the finite pressure jumps to be compensated by magnetic-pressure jumps in cross-field force balance. The tangentially discontinuous fields are due to discrete currents in these surfaces, δ-function singularities in the current density that are fully admissible under the rigorous frozen-in condition but must dissipate resistively if the electrical conductivity is high but finite. The magnetic field and fluid must thus endlessly evolve by this spontaneous formation and resistive dissipation of discrete currents taking place intermittently in spacetime, even in a low-β environment.

The physical picture emerging completes the hypothesis formulated in Paper I that this intermittent process is the origin of the dynamic interiors of a class of quiescent prominences revealed by recent *Hinode*/SOT and *SDO*/AIA high-resolution observations.

Key words: conduction – diffusion – magnetic fields – Sun: corona – Sun: filaments, prominences

Dimitri's genius continues to educate us in our search for new understanding, decades later, in unanticipated ways.

His work on prominences is just one example of the poetic and unexpected irony of how science progresses, when it is done well.

Thank you, Dimitri.