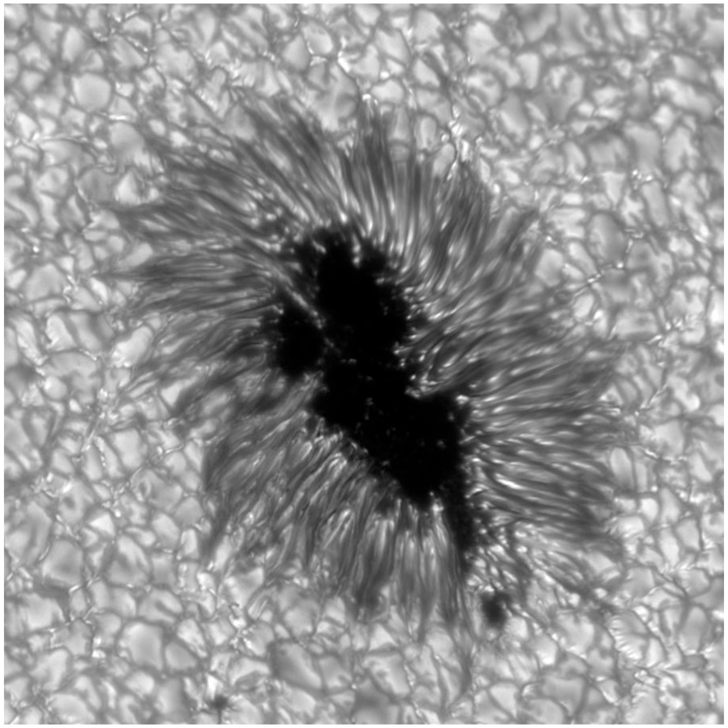
Theoretical models of sunspot structure and dynamics



John H. Thomas

Dept. of Mechanical Engineering and Dept. of Physics & Astronomy, University of Rochester

Topics:

Umbral magnetoconvection

The formation and maintenance of the penumbra, magnetic flux pumping

The inner and outer penumbra

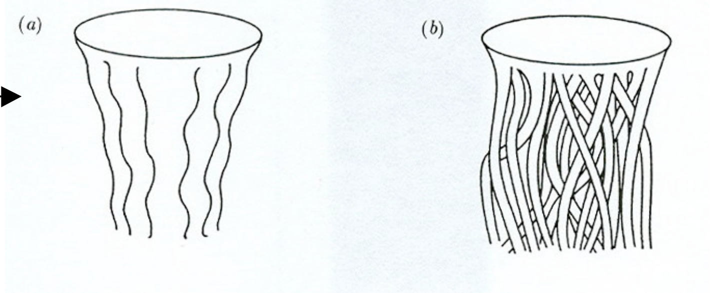
Models of the interlocking comb magnetic field in the penumbra

Realistic numerical simulations of an entire sunspot

The Evershed flow

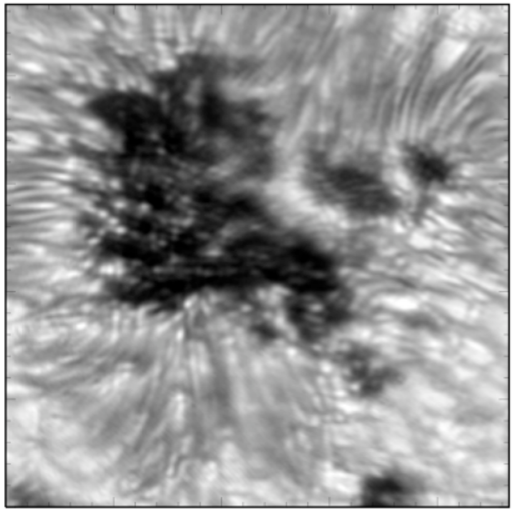
Some important theoretical questions about sunspots:

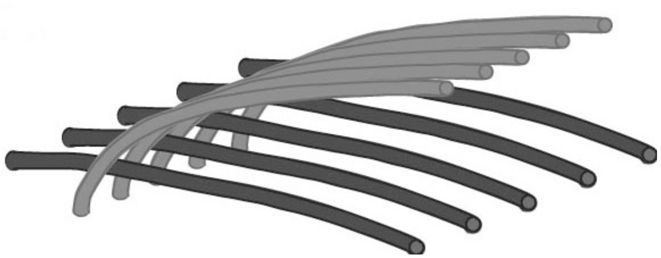
Monolith or cluster? →



What causes the umbral dots?

How is the filamentary penumbra formed?



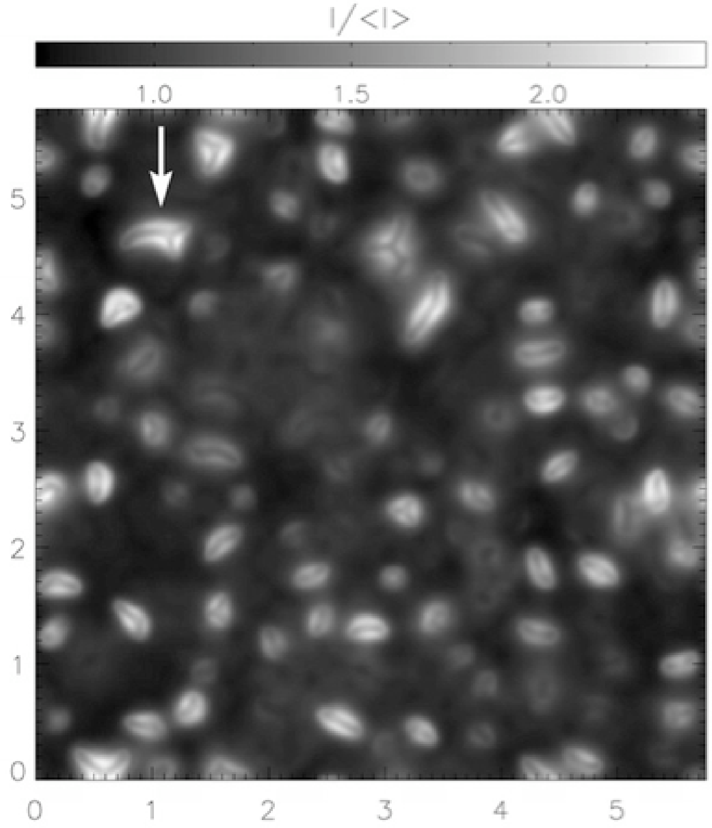


What causes the interlocking-comb structure of the penumbral magnetic field, and the returning flux in the outer penumbra?

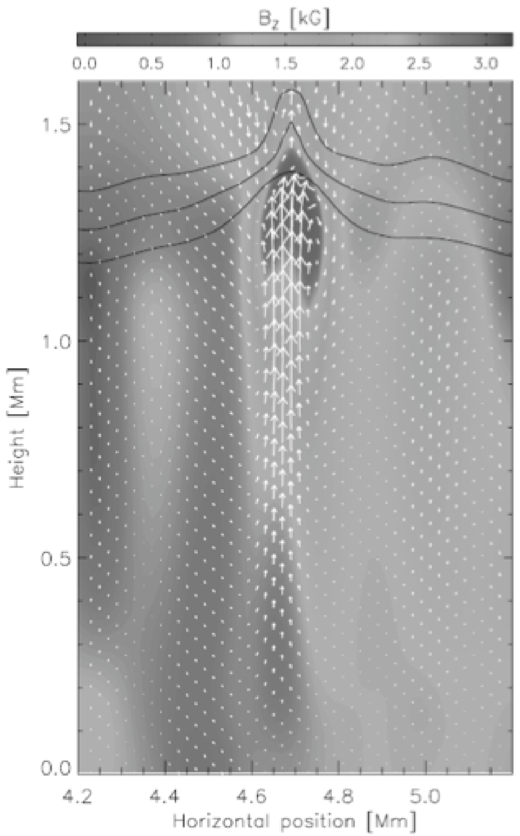
How do we explain the Evershed flow, with supersonic speeds and downflows in the outer penumbra?

Umbral convection

Realistic simulations of umbral convection (Schüssler and Vögler 2006). 3D compressible magnetoconvection in a vertical magnetic field, radiative transfer, partial ionization.



Pattern of surface intensity. Note oval shape of most umbral dots with narrow dark lane along major axis (which is an opacity effect due to increased pressure and density at the head of the plume).



Vertical cut across a rising plume. Shading indicates the strength of the magnetic field, which is reduced at the head of the plume. Arrows represent projected velocity. Dark lines are surfaces of constant optical depth

These simulations reproduce all of the important observed features of umbral dots in the context of a `monolithic' model (see, e.g, Bharti et al. 2007, 2008).

Structure and dynamics of the penumbra.

It is useful to distinguish between the inner and outer penumbra:

Inner penumbra:	Outer penumbra:
- dominated by bright filaments with slender dark cores	- bright and dark filaments of roughly equal width
- inward moving penumbral grains	-outward moving penumbral grains
-small differences in inclination of the magnetic field	-two distinct families of magnetic field lines, with a difference of inclination of about 30º. The more inclined fields are in the dark filaments, which contain the Evershed flow.
- ouflows in the narrow dark cores	-strong Evershed flows in the dark filaments, with speeds up to 10 km/s or higher (supersonic).
	-downward-plunging, ‘returning’ magnetic field lines containing Evershed flows

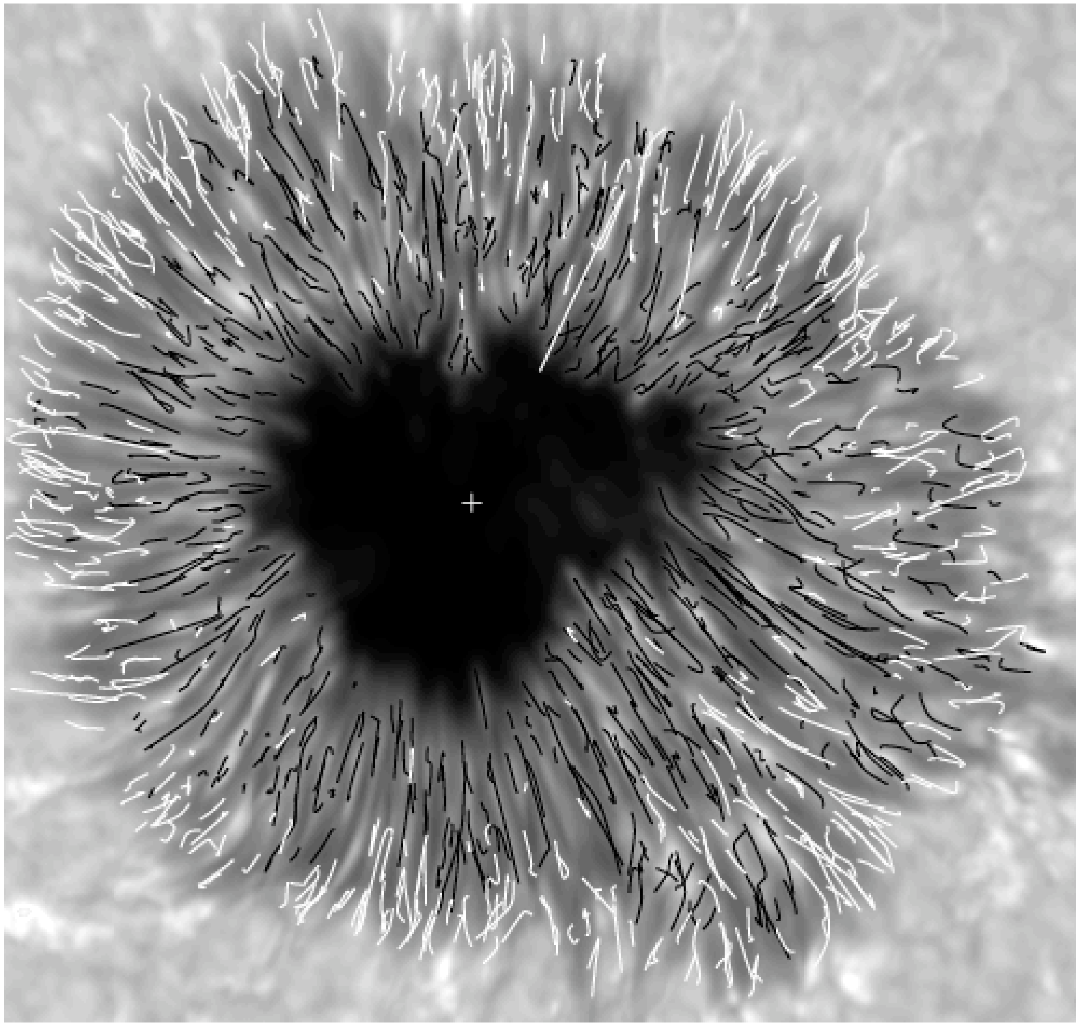
Inner and outer penumbra: penumbral grains move radially inward in the inner penumbra and radially outward in the outer penumbra

Paths of proper motions of bright penumbral grains: →

<u>black curves:</u> inward-moving grains

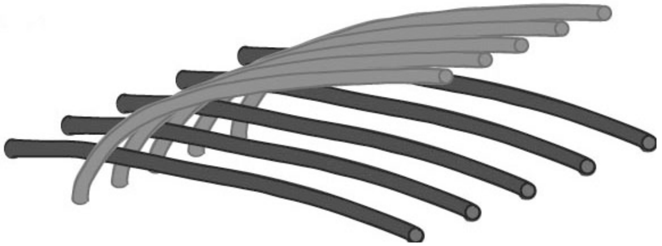
<u>white curves:</u> outward-moving grains

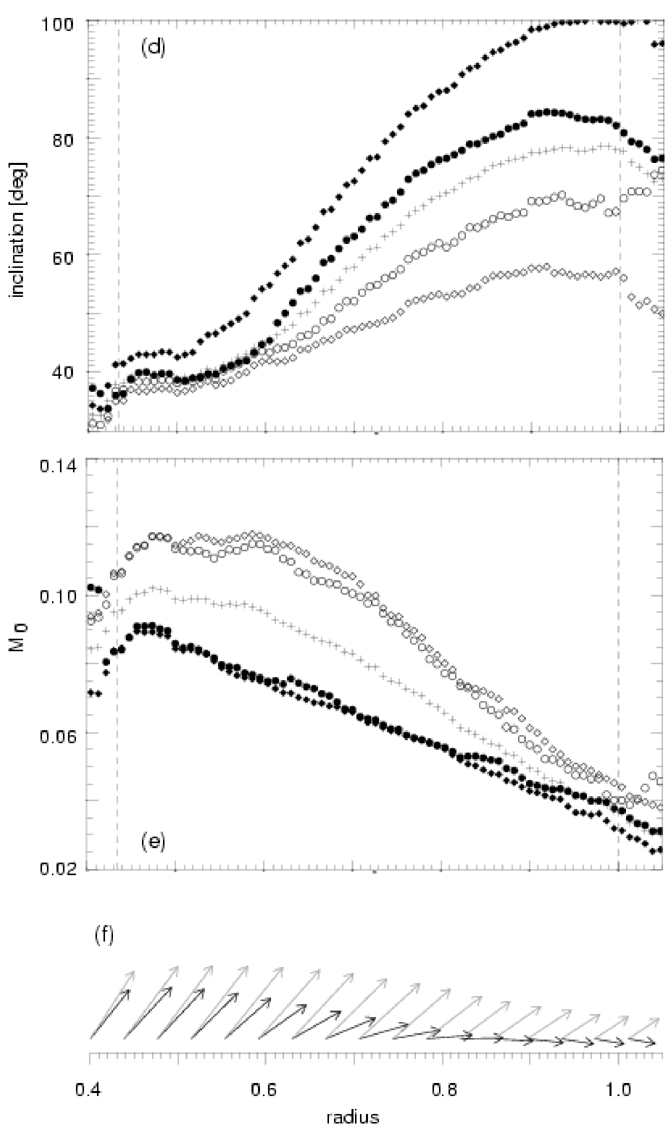
(From Sobotka and Sütterlin 2001)



We might take the boundary between the inner and outer penumbra to be the dividing line between inward and outward moving penumbral grains, lying at about 60% of the radial distance between the inner and outer edges of the penumbra and dividing the penumbra into roughly equal areas.

Interlocking-comb structure of the penumbral magnetic field





← Field inclination
(to the local vertical

Hollow symbols: bright (stronger) component
Filled symbols: dark (weaker) component
Diamonds: components distinguished by field strength
Circles: components distinguished by intensity

← Relative field strength

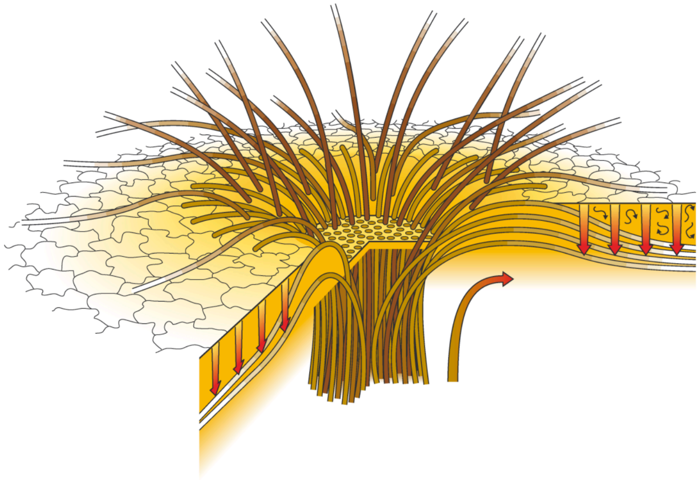
← Average vector field in the strong (gray) and weak (black) components

(From Langhans et al. 2005)

Scenario for the formation and maintenance of the filamentary penumbra

(Thomas, Weiss, Tobias, & Brummell 2002; Weiss, Thomas, Tobias, and Brummell 2004)

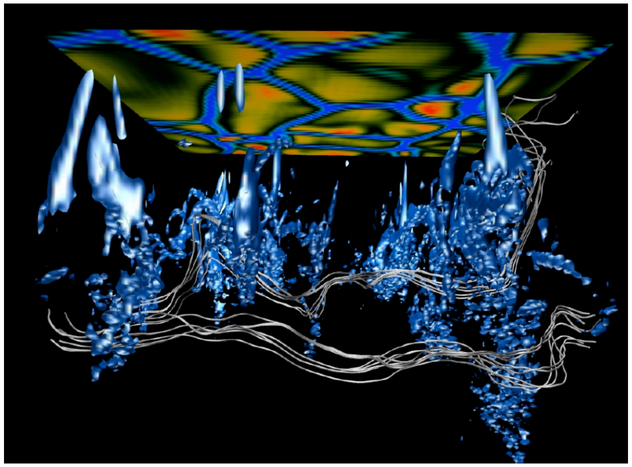
- A sunspot forms by coalescence of pores into a growing pore with increasing total magnetic flux.
- As the total magnetic flux increases, the inclination of the field (to the vertical) at the outer boundary of the flux tube increases.
- At some critical angle the configuration becomes unstable to convectively driven filamentary (i.e., azimuthally periodic) perturbation (Tildesley 2003; Hurlburt and Alexander 2003).
- The nonlinear development of this instability leads to fluting at the boundary of the flux tube (Tildesley and Weiss 2004)
- The more horizontal spokes of the fluted magnetic field are depressed into the granulation layer in the surroundings, where the are subject to *downward pumping by the turbulent granular convection*. Some of this flux is pumped downward, forming the returning magnetic flux tubes, while the remainder stays above the surface, forming the low-lying magnetic canopy.



- The largest pores are bigger than the smallest sunspots. This hysteresis indicates that the instability is associated with a subcritical bifurcation (Rucklidge, Schmidt, and Weiss 1995). Magnetic flux pumping provides a physical mechanism for this hysteresis: as a sunspot decays, pumping keeps fields in the dark filaments submerged even when the total magnetic flux is less than that at which the transition from a pore to a sunspot occurs.

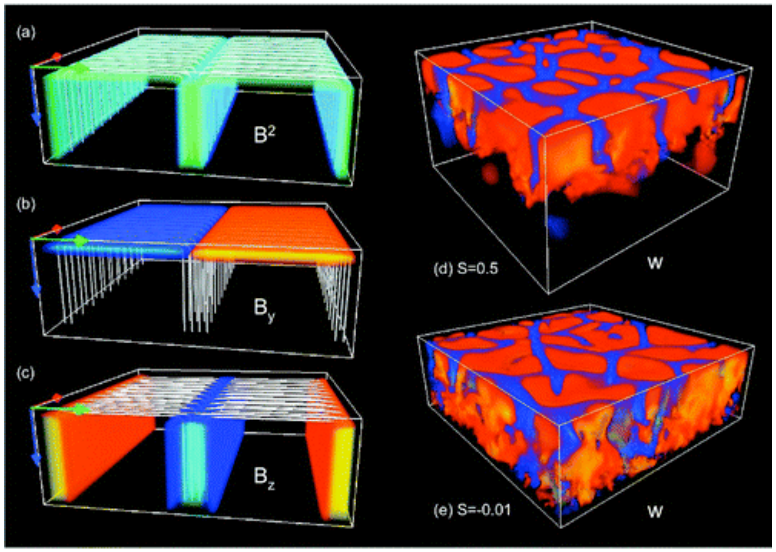
Model calculations of flux pumping by the solar granulation. (Thomas et al. 2002; Weiss et al. 2004)

Fully compressible, nonlinear, 3D magnetoconvection in a two-layer box: highly superadiabatic granulation layer above, weakly superadiabatic layer below.



Latest simulations (Brummell, Tobias, Thomas, and Weiss 2008, ApJ, 686, 1454) have a double-arched magnetic field configuration to better represent a sunspot and magnetic curvature forces.

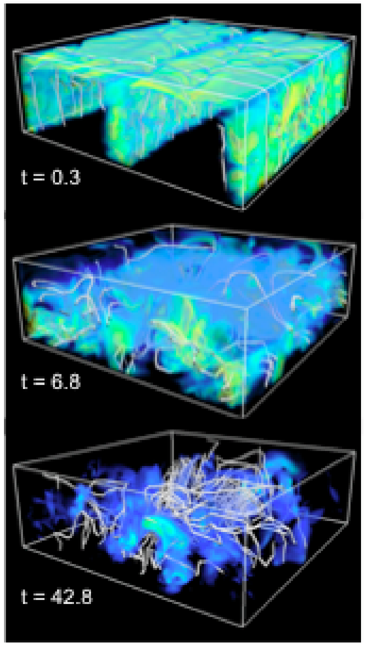
Initial state



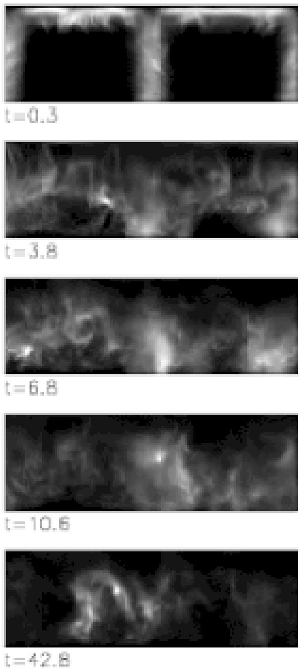
magnetic field　　vertical velocity

Evolved states

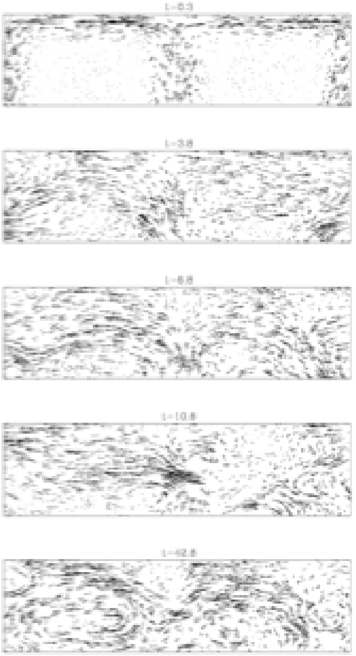
B^2



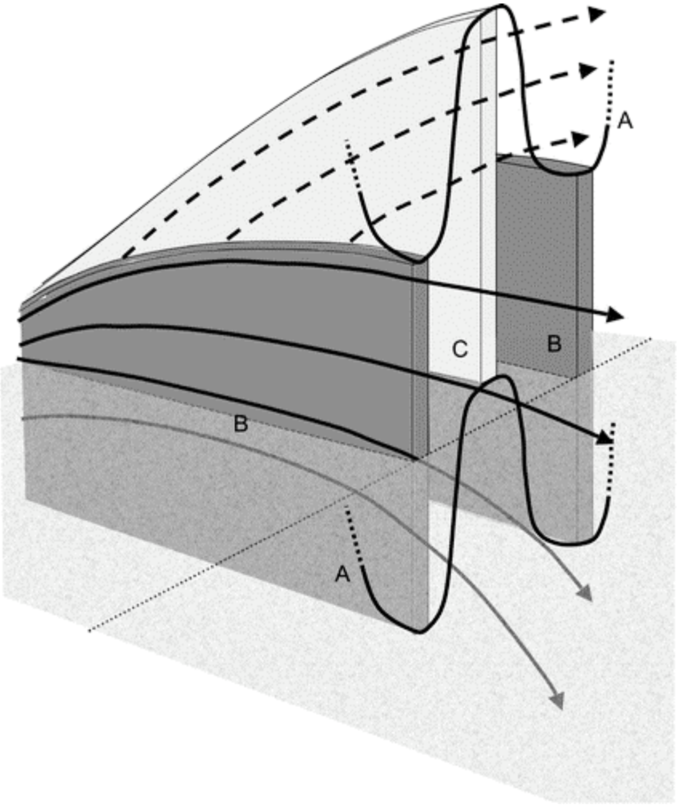
x - averaged B^2



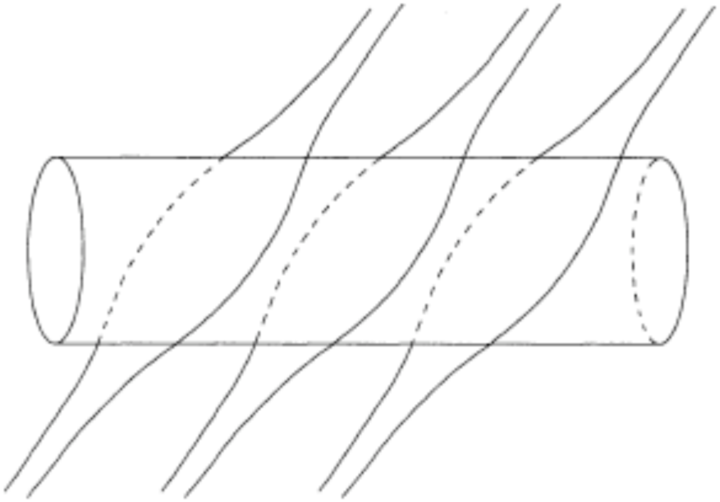
x - averaged (B_y, B_z)



Schematic models of the interlocking-comb magnetic field geometry in the penumbra

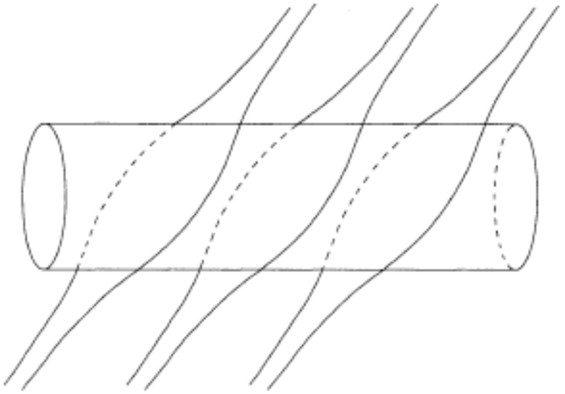


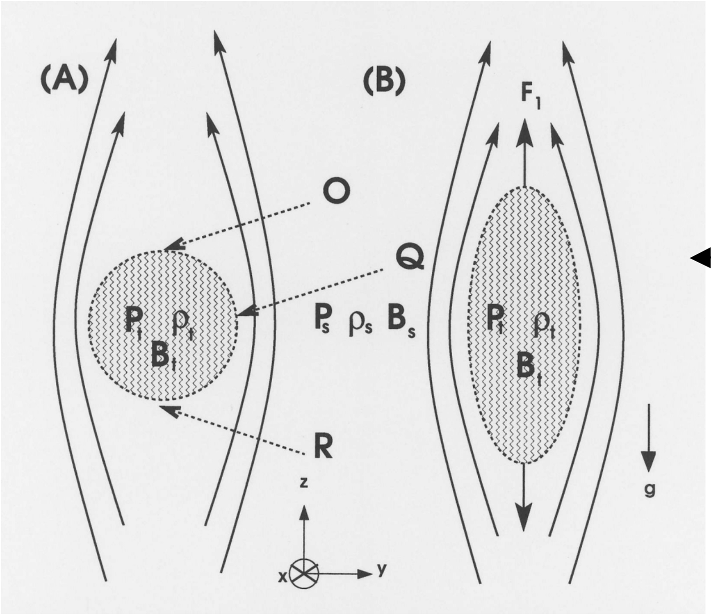
“Interleaved sheet” model (Brummell et al. 2008): a fluted magnetopause (A) and alternating slabs of nearly horizontal magnetic field (dark filaments, B) and less steeply inclined magnetic field (bright filaments, C). The nearly horizontal fields extend downward to some depth below the solar surface.



“Uncombed” model (Solanki and Montavon 1993) horizontal flux tube of nearly circular cross-section, embedded in a more vertical background field that wraps around it.

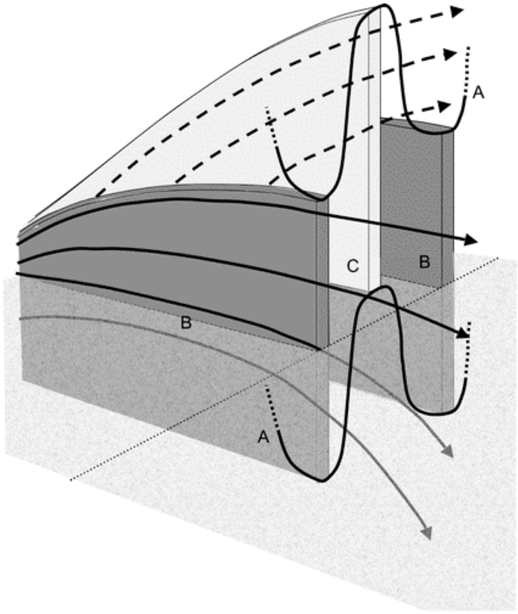
The horizontal flux tube in the uncombed model is subject to elongation in the vertical direction due to the pinching effect of the ambient field. (Scharmer and Spruit 2006)





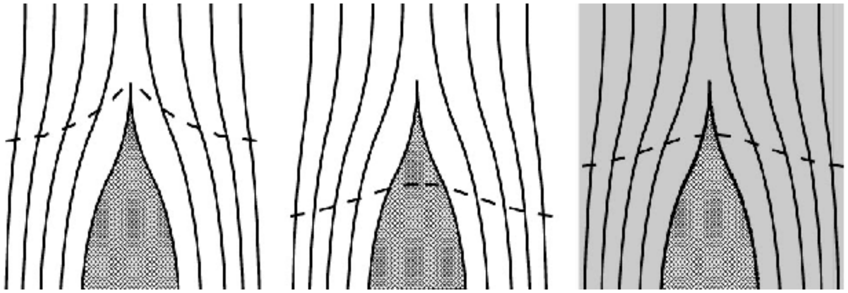
The vertical elongation might be limited by buoyancy forces, producing a horizontal flux tube with vertically elongated cross-section (Borrero, Rempel, and Solanki 2006)

If the elongation is significant, then the model begins to look much like the interleaved-sheet model (Brummell et al. 2008)



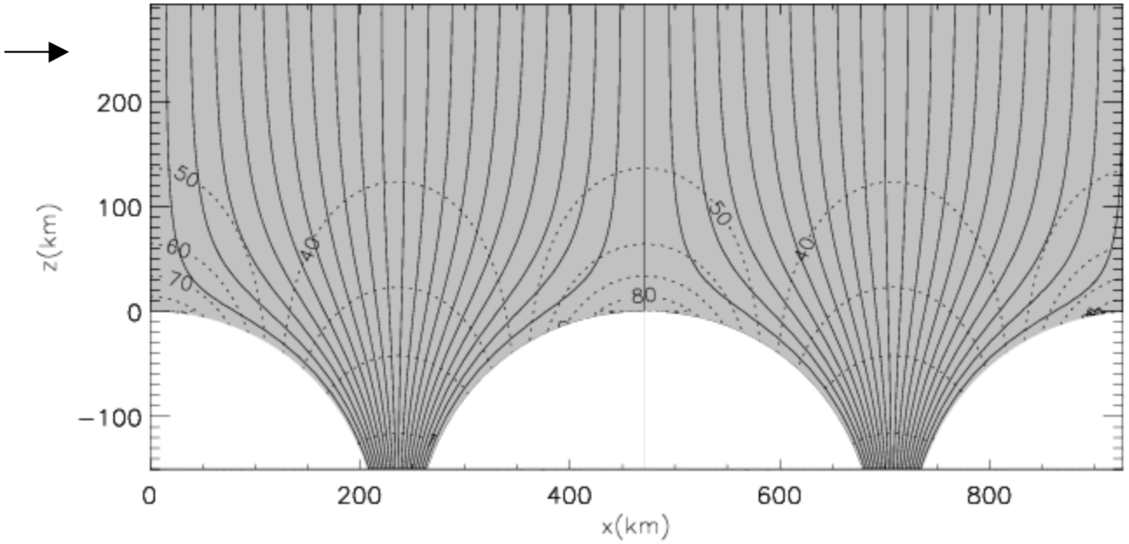
An alternative model: the ‘gappy penumbra’

(Spruit and Scharmer 2006; Scharmer and Spruit 2006). Based on the cluster model.



Postulates field-free, radially aligned gaps (the bright filaments) in the magnetic field below the surface, protruding into a potential magnetic field configuration. Convection in the field-free gaps supplies the penumbral heat flux and creates the dark central cores as an opacity effect.

Proposed magnetic field configuration, projected onto a vertical plane perpendicular to the long axis of the filaments. The contours of constant inclination show that the magnetic field is nearly horizontal above the bright filaments (the gaps) and more nearly vertical above the dark filaments, in contradiction to observations (e.g., Rimmele 1995, Stanchfield et al. 1997, Westendorp Plaza et al. 2001, Langhans et al. 2005, Jurcak and Bellot Rubio 2008, Borrero and Solanki 2008).



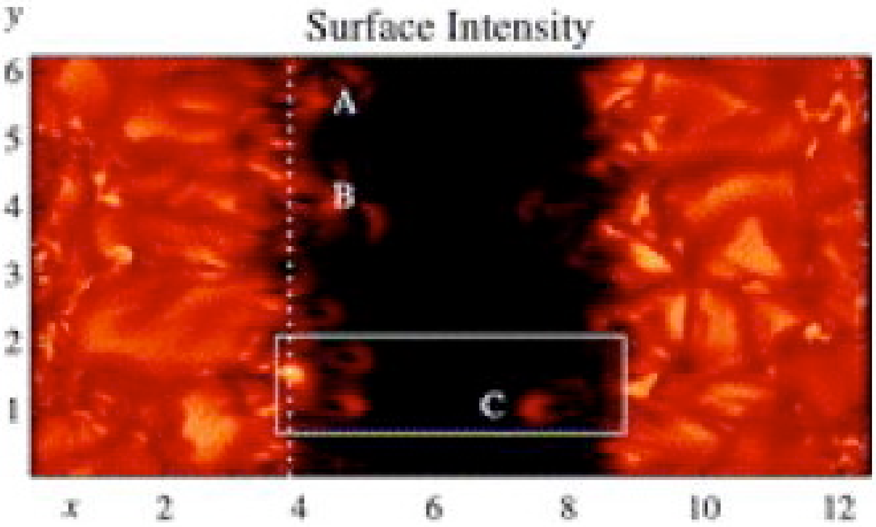
Also, Borrero and Solanki find that the vertical variation of magnetic field strength is inconsistent with field-free gaps at or just below the visible surface.

Conclusions: The gappy penumbra is inconsistent with observations.
The explanation of the dark cores is basically correct, but it doesn’t require field-free gaps intruding from the exterior plasma.

Realistic 3D compressible MHD simulations of a complete sunspot.

Simulations in a rectangular box with radiative transfer, partial ionization.

Heinemann, Nordlund, Scharmer, and Spruit 2007 →



Rempel, Schüssler, and Knölker 2008

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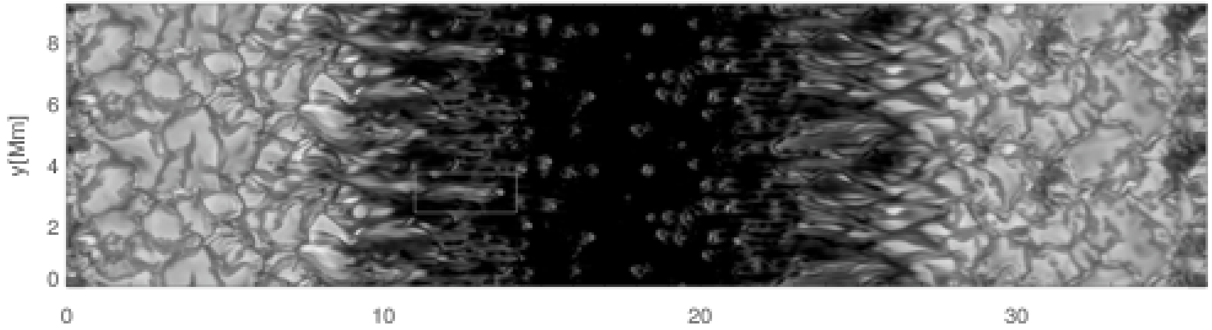
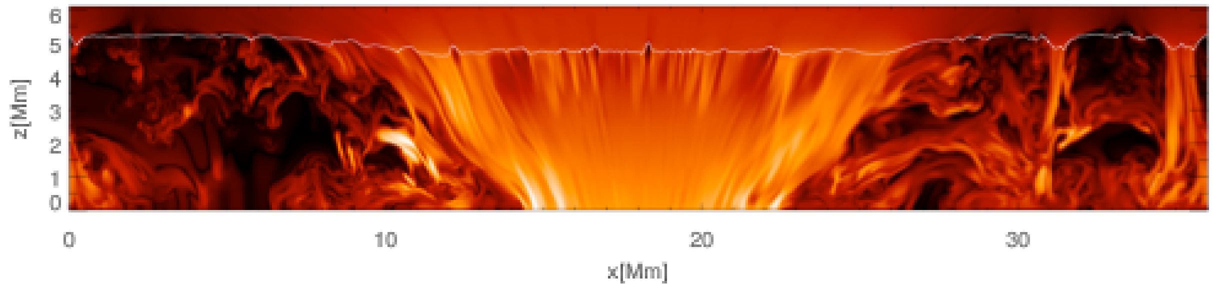


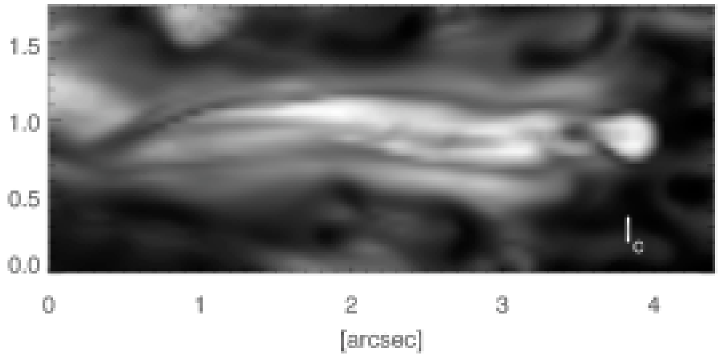
Continuum intensity



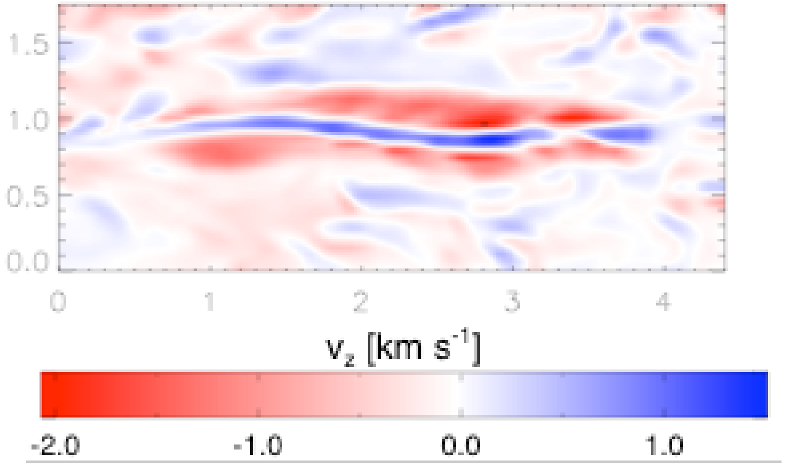
Vertical cut showing color-coded field strength

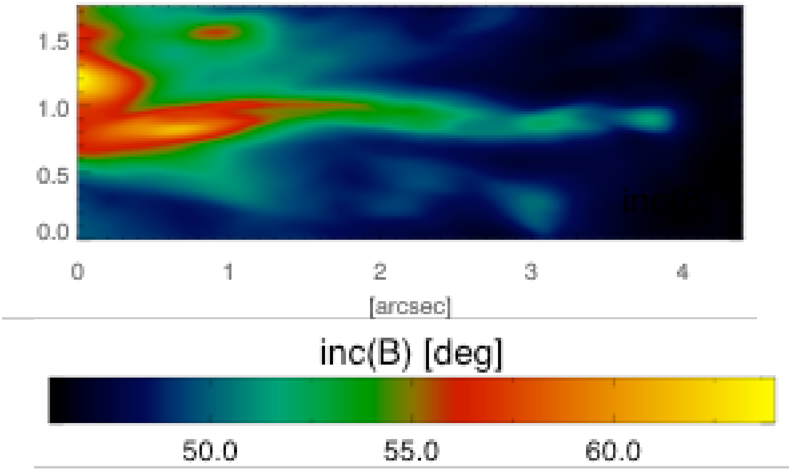
Details of the simulation of an individual bright filament with a dark core

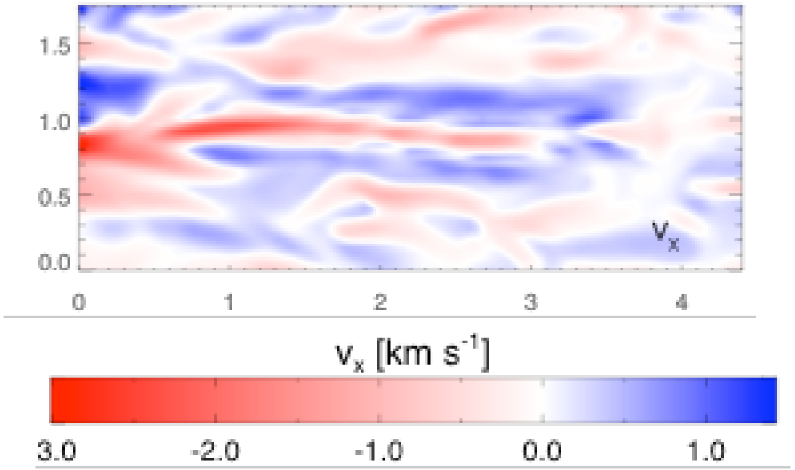
(Rempel, Schüssler, and Knölker 2008). (The umbra is to the right in the figures below.)



continuum intensity at 630 nm



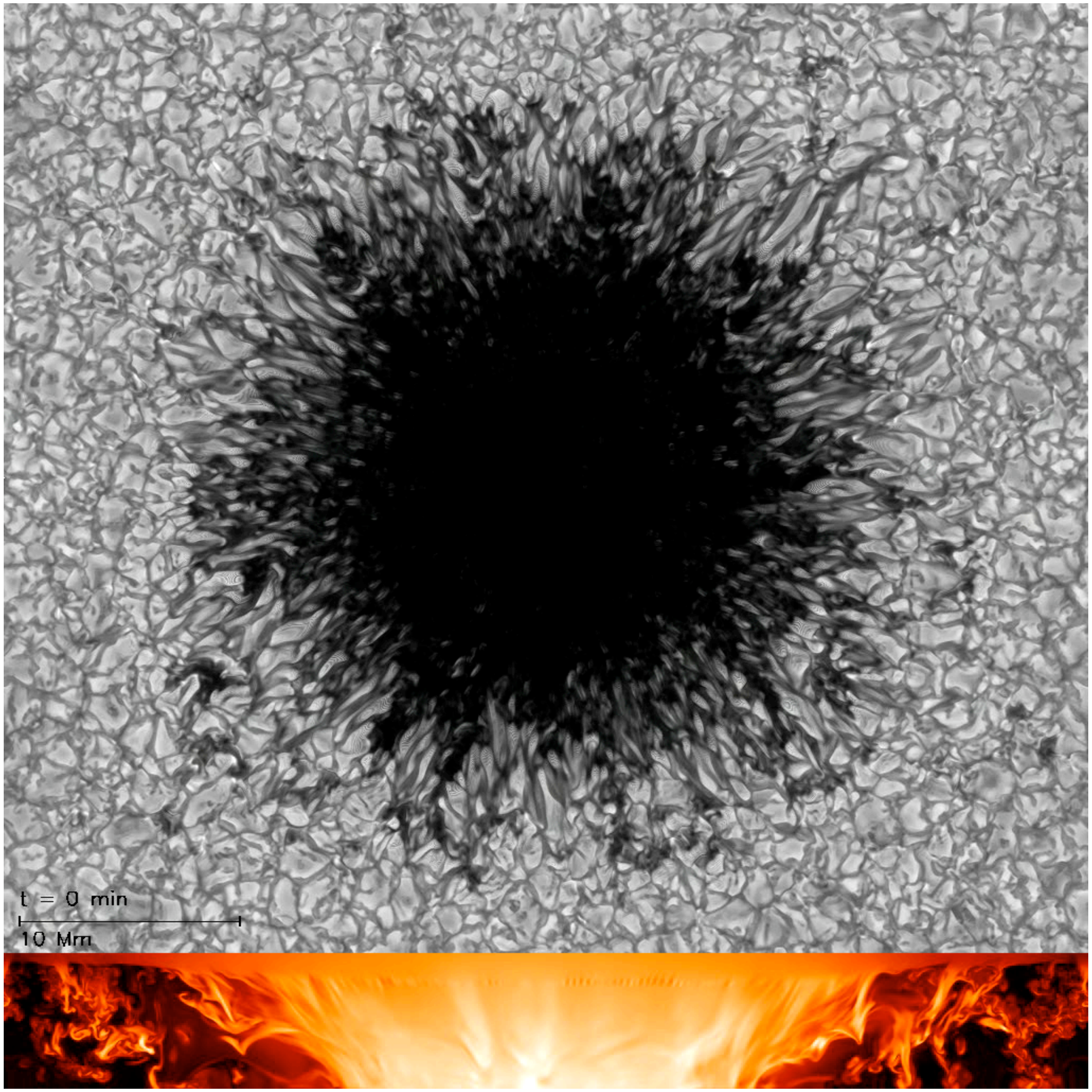




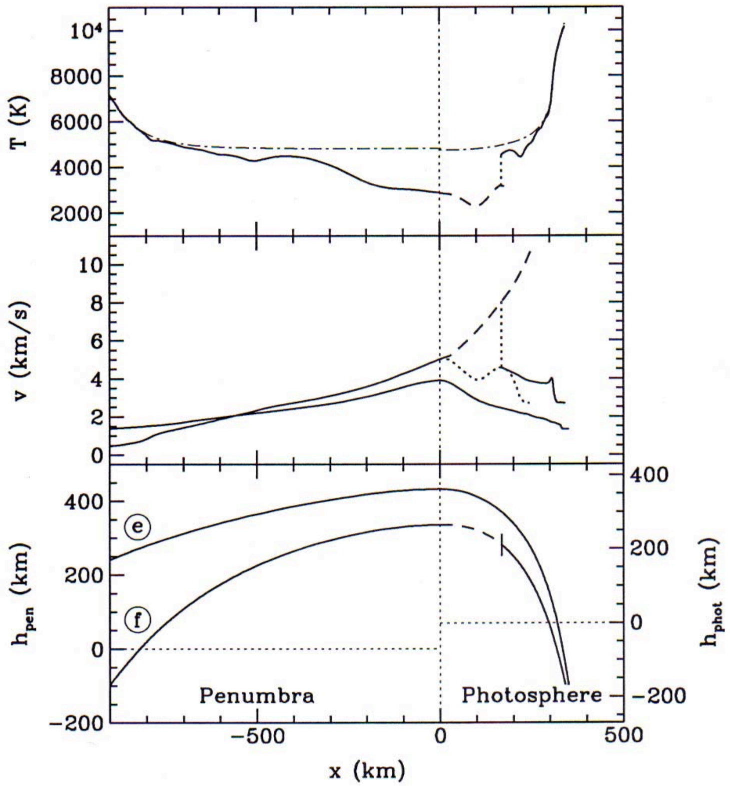
Reproduces observed features of bright filaments in the inner penumbra: elongated bright filament with dark central core (opacity effect due to buoyancy braking); bright 'head' migrates inward toward penumbra as a pattern (not bodily) motion; reduced field strength at top of plume; roll-like convection with inclined upflow in center and inclined downflow along sides, all along the plume (not interchange of individual flux tubes); horizontal (radial) component of these flows is outward along the central core, inward along the sides - average flow is outward at ~ 1 km/s.

But does not reproduce the outer penumbra: e.g. no horizontal or returning **B**, no fast Evershed flow with downflows.

New simulation by Rempel et al. of a circular sunspot in a box. (Courtesy of Matthias Rempel.)

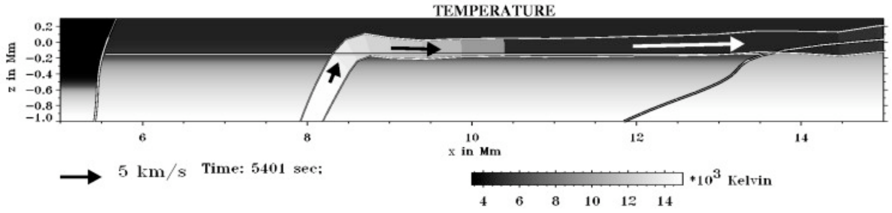


Models of the Evershed flow as flows along individual, thin flux tubes:



Siphon flow model (e.g. Montesinos and Thomas 1997)

- flow along an arched flux tube due to reduced pressure at downstream footpoint (due to flux concentration)
- steady flow (can't model transient Evershed flows)
- supersonic flows, downflows, returning flux tubes

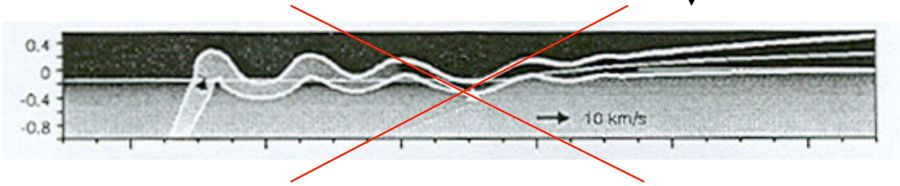


Moving tube model (Schlichenmaier, Jahn, and Schmidt 1998)

-flow due to increased pressure at upstream footpoint (due to heating)

- time-dependent flows
- supersonic flows, but no downflows or returning flux tubes.
- all the flow goes out along the magnetic canopy (not observed)

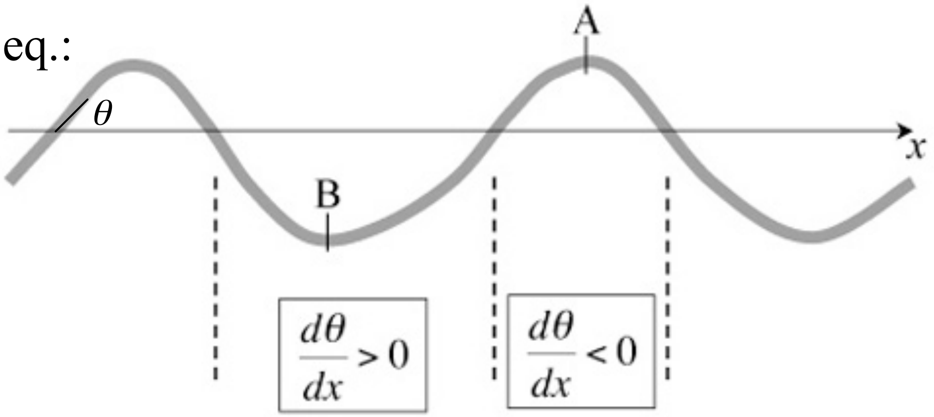
Note: super-Alfvénic, serpentine solutions (Schlichenmaier 2002) do have downflows, but these configurations are inherently unstable (Thomas 2005) so will not occur.



Gravitational instability of the serpentine configuration

Normal component of the steady momentum eq.:

$$\boxed{\left(\frac{B^2}{4\pi} - \rho v^2\right)\frac{d\theta}{dx} = (\rho - \rho_e)g}$$



Flow is super-Alfvénic, $v > B/\sqrt{4\pi\rho}$, so

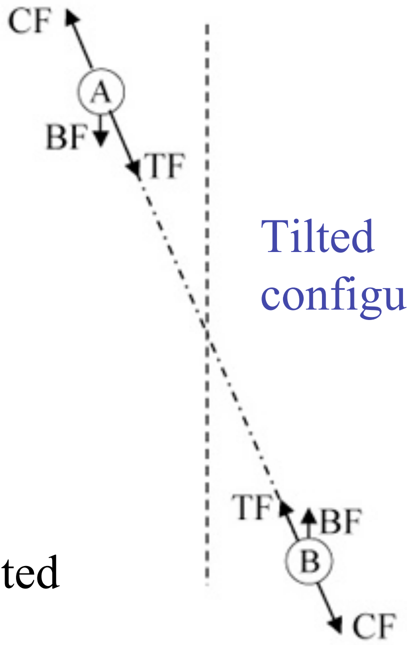
$$\frac{B^2}{4\pi} - \rho v^2 < 0$$

Therefore

$$\rho > \rho_e \text{ where } \frac{d\theta}{dx} < 0$$

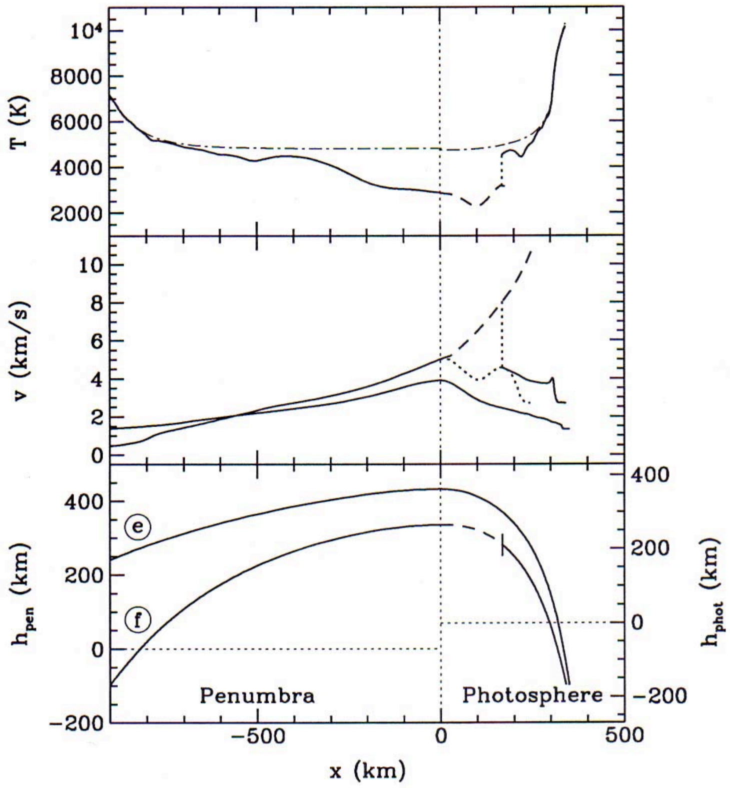
$$\rho < \rho_e \text{ where } \frac{d\theta}{dx} > 0$$

and the buoyancy force increases the displacement of the tilted configuration.



Tilted configuration

Models of the Evershed flow as flows along individual, thin flux tubes:



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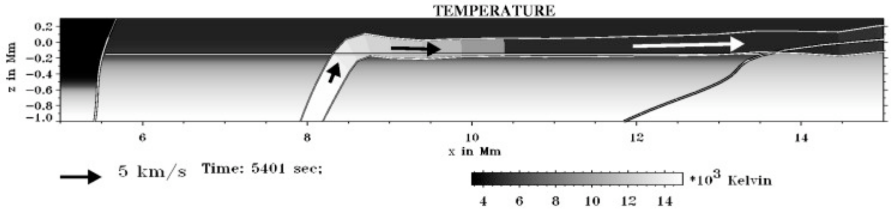

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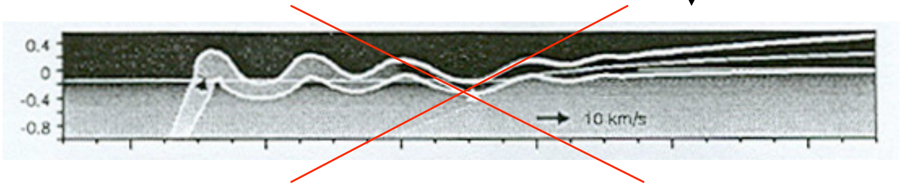

Speculation: a thin-flux-tube model combining the best features of the siphon-flow model (arched, returning flux tube; supersonic downflow) and the moving-tube model (time dependence, heating of upstream footpoint) would reproduce all the important features of the Evershed flow in the outer penumbra.

Summary

- Umbral dots are well explained by realistic simulations of magnetoconvection in a vertical, monolithic magnetic field; no need to invoke a cluster model.
- There are significant differences between the inner and outer penumbra, and it is useful to distinguish between them.
- Downward magnetic flux pumping by turbulent granular convection offers a plausible mechanism for producing the returning magnetic flux in the outer penumbra.
- The ‘uncombed’ and ‘interlocking sheet’ models of the penumbral magnetic field configuration are actually quite similar, in view of the squeezing effect on the circular flux tubes in the uncombed model.
- Observations of the penumbral magnetic field generally contradict the ‘gappy penumbra’ model.
- Realistic numerical simulations of an entire sunspot have succeeded quite well in reproducing the convective structure of the inner penumbra (but not the outer penumbra).
- Bright penumbral filaments in the inner penumbra are well reproduced in these simulations, as roll-like convection (not interchange convection). Magnetic flux is partially expelled by the plumes, but the resulting ‘gaps’ are not in contact with the exterior plasma and hence are fundamentally different from the gaps in the “gappy penumbra’ (based on the cluster model.) The central dark cores are well reproduced by the simulations, as an opacity effect due to buoyancy braking, as are the outflows along the cores.
- The simulations do not reproduce important features of the outer penumbra such as horizontal and returning magnetic fields and fast (supersonic) Evershed flows along arched channels.
- The siphon flow model still provides the best description of the Evershed flow in the outer penumbra. The moving-tube model fails to produce returning flux tubes and downflows. A thin-flux-tube model combining the best features of these two models is suggested.