SUNSPOT PENUMBRAE: FORMATION, EVOLUTION, AND FINE STRUCTURE.

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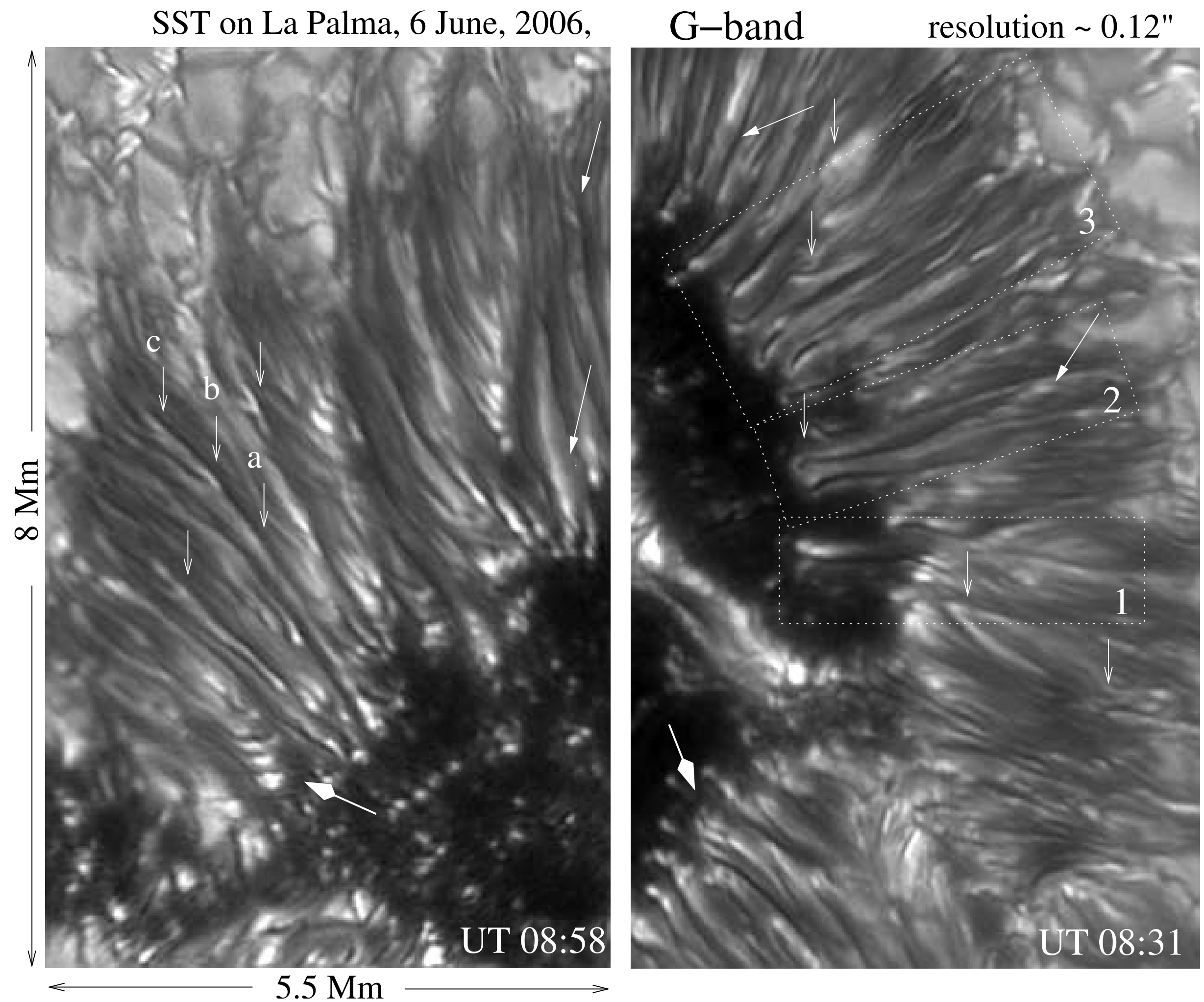
HR observations with the 1 m SST and the SOT/Hinode show new properties of penumbra and its impact on the overlying atmosphere.



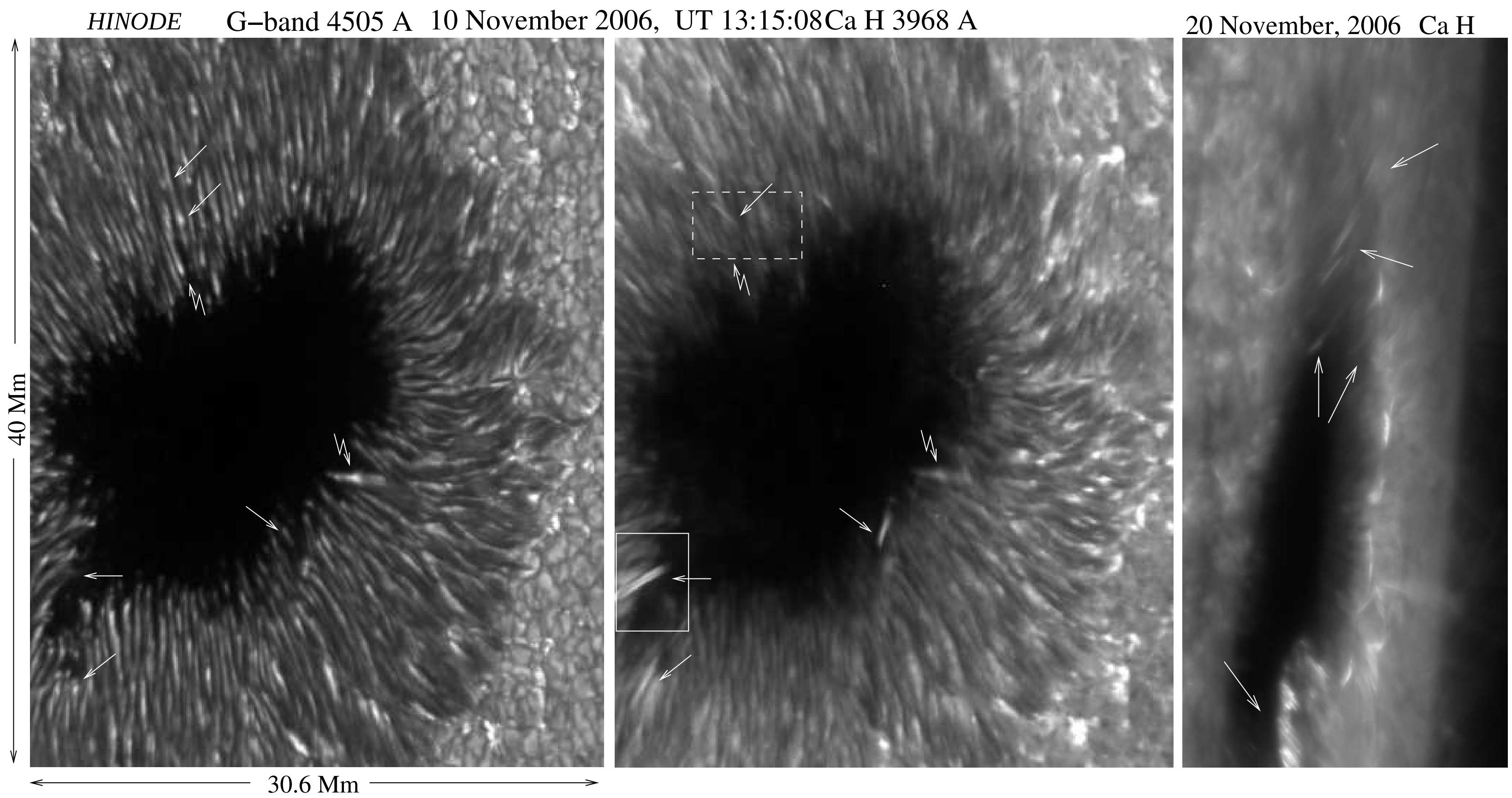
SOME PROPERTIES:

- **DARK CORES**
- $B_c < B_w$
- **ADJACENT to BP**
- **TWISTED**
- **MULTIPLE SPLITTING**
- **BRANCHING POINT, Y, IS BRIGHT**

R ~ 70 −100 km
L ~ 1000−3000 km
τ ~ 45 − 120 min

Response of the overlying chromosphere to penumbra dynamics:

At any moment of time, short living ($\sim 1\ min$) bright elongated transients are spread abundantly over the entire penumbra.



Transients are always associated with Bright Points.

True model of penumbra must et least explain:

- **Complex properties of filaments,**
- **Nature of their interaction,**
- **The very formation of penumbra, and**
- **Its impact on the overlying atmosphere.**

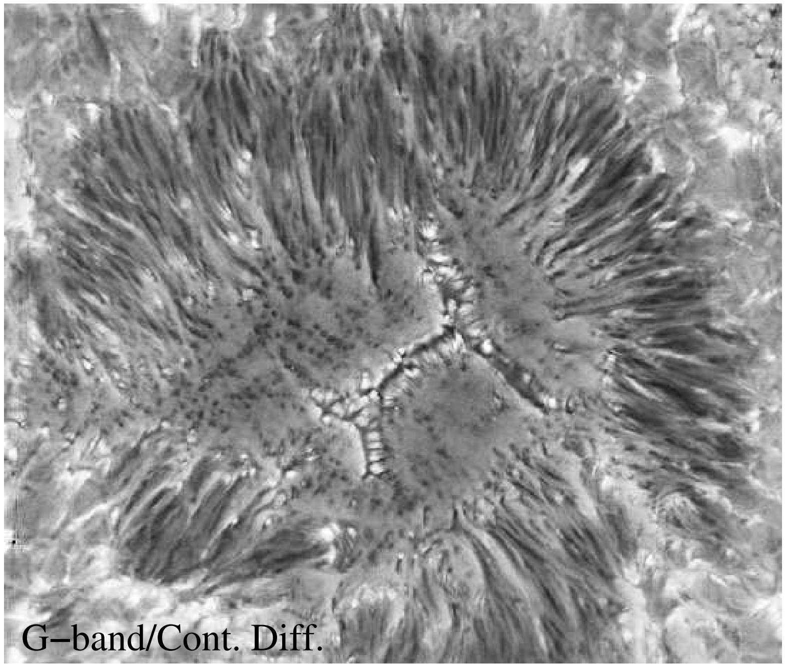
Dozens of groups are working on physics of sunspot.

But neither formation of penumbra nor the properties of interacting filaments and their association with chromospheric transients, can be understood on basis of these models.

We propose the mechanism that not only explains all the observed properties of individual filaments, but is part of the physical process that determines formation of penumbra and its impact on the overlying atmosphere.

The solution is based on the collective phenomena in a dense conglomerate of interlaced flux tubes comprising the entire sunspot, including umbra.

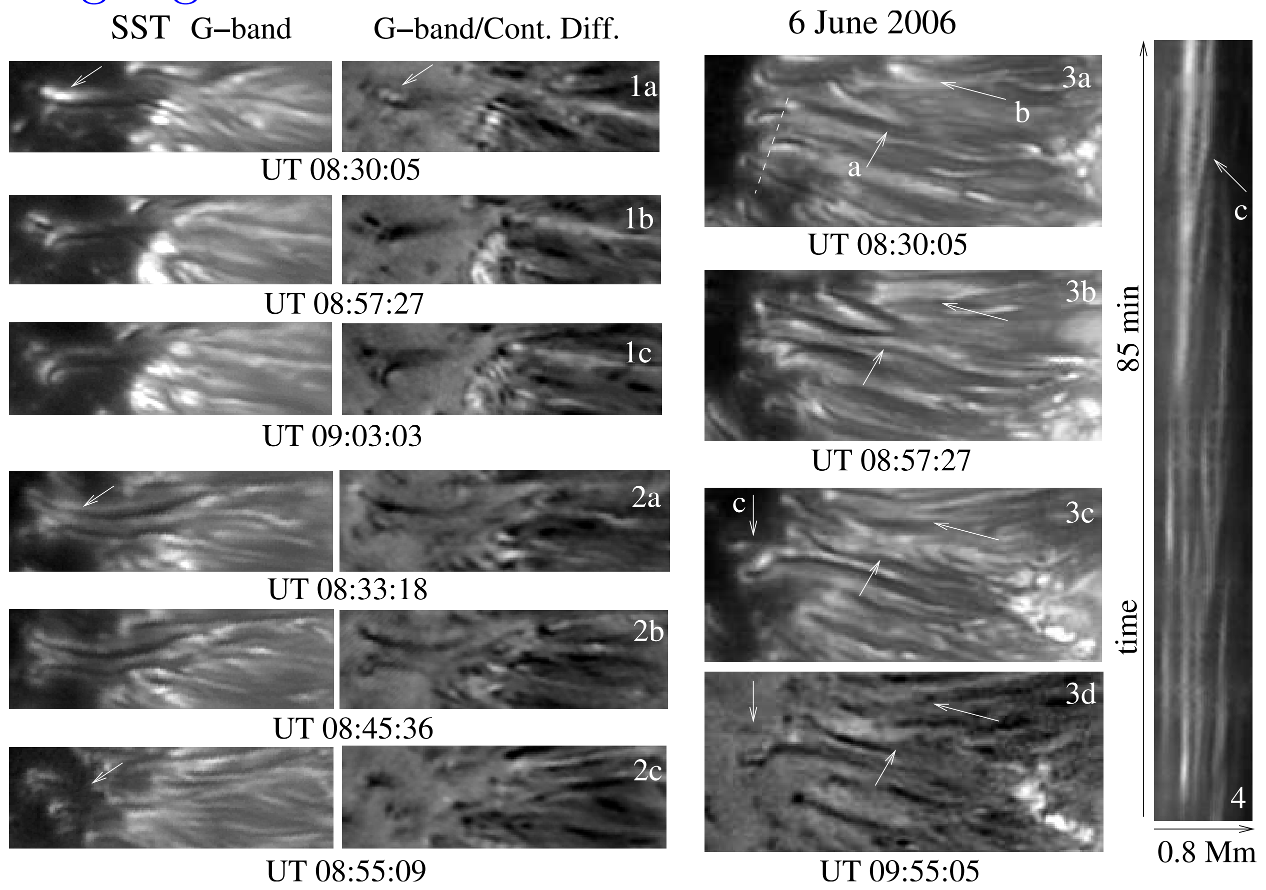
Densely packed, neighboring filaments inevitably interact.



THE FUNDAMENTAL AND UNAVOIDABLE PROCESSES IN SUCH A CONGLOMERATE ARE RECONNECTION AND POST–RECONNECTION PROCESSES

IN THE PHOTOSPHERE THESE PROCESSES ARE RADICALLY DIFFERENT FROM LOW–β CORONA.

Splitting of filaments accompanied by the enhanced brightening of splitting region is natural manifestation of the reconnection:



Examples of reconnecting filaments. Space-time image (panel 4) shows several splitting events along the dashed cut (panel 3a).

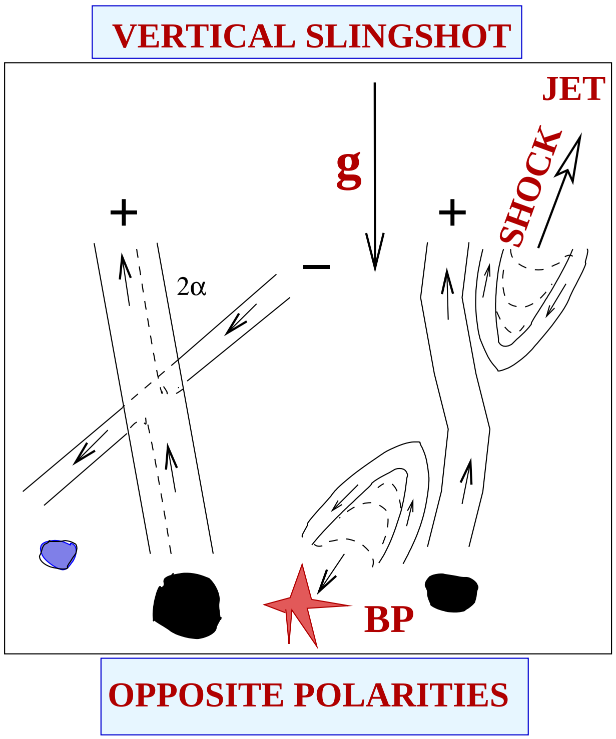
Much more comes from the post-reconnection processes!

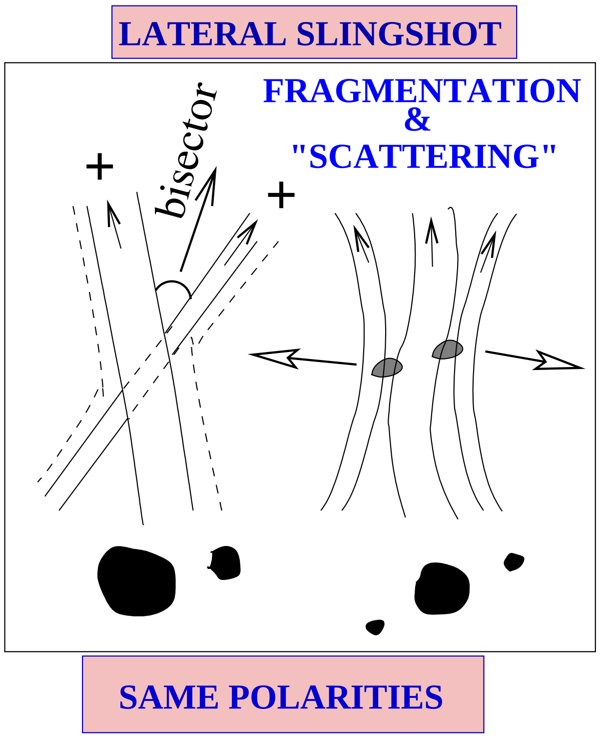
The post-reconnection specifics in the photosphere is determined by

(1) The very existence of flux tubes, being in pressure equilibrium with almost non-magnetic surrounding gaps, i.e.
$p_{ext} = p_{in} + B_{in}^2/8\pi; \quad \beta = 8\pi p_{ext}/B_{ext}^2 \gg 1; \quad \tilde{\beta} = 8\pi p_{ext}/B_{in}^2 \geq 1$

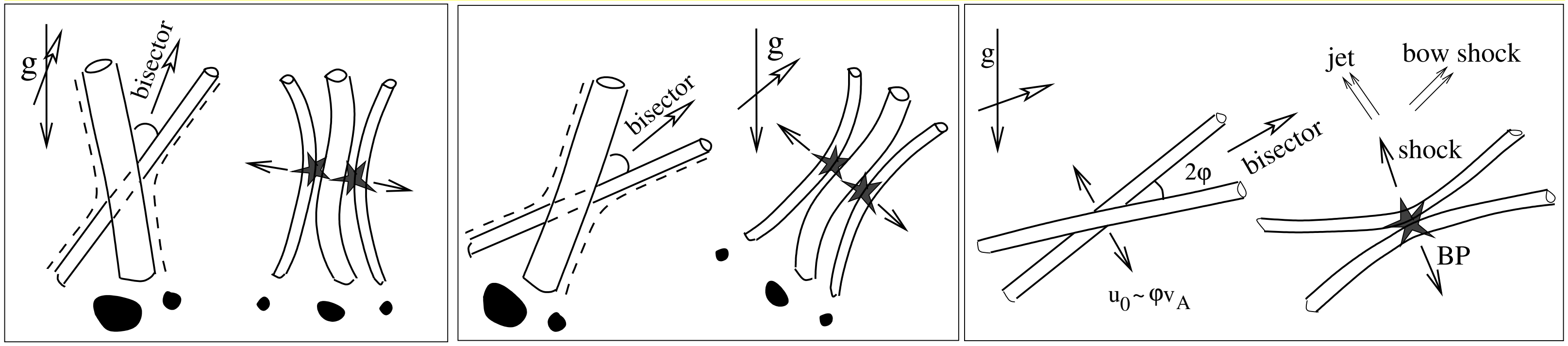
(2) Non-collinearity of flux tubes.

(3) Sharp stratification of the atmosphere.





CENTER OF SUNSPOT **TOWARD THE PERIPHERY FLUX TUBES DEVIATE FROM VERTICAL**

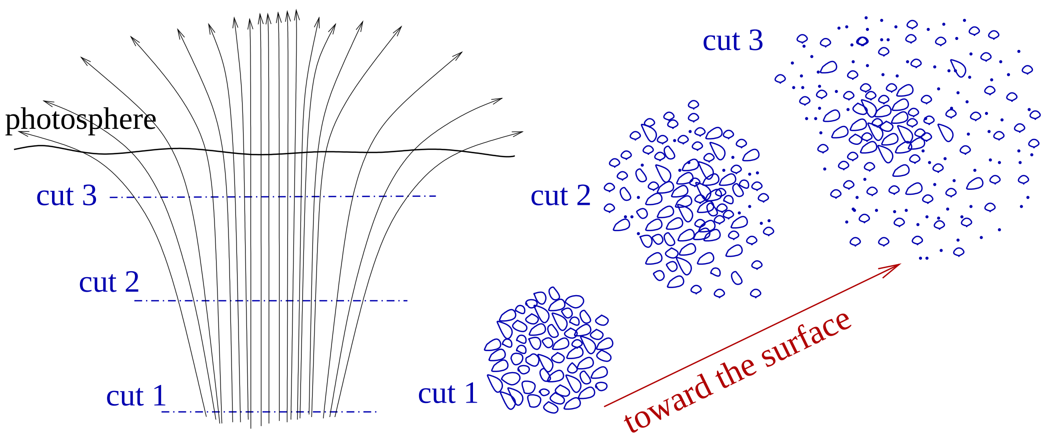


- THE RECONNECTION PRODUCTS BRANCH OUT FROM THE PARENTAL FLUX.
- THE GRAVITY TURNS ON, LEADING TO APPEARENCE OF BOW SHOCKS AND JETS.

VERY IMPORTANT:

ONLY A LIMITED PORTION OF FLUX PARTICIPATES IN EACH ELEMENTAL RECONNECTION NEAR THE PHOTOSPHERE $R_{cr} \sim 36 - 70$ km

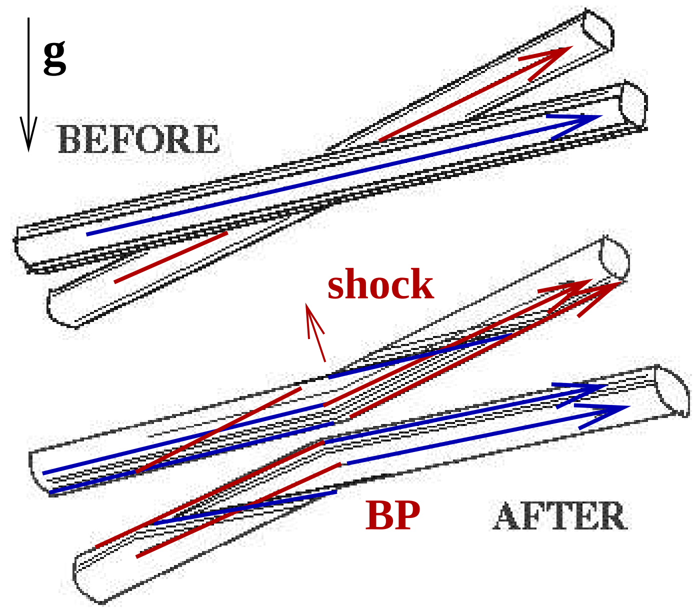
THE PROCESS OF FRAGMENTATION IN SUNSPOT AND THE BRANCHING OUT OF NEWBORN FLUX TUBES OCCURS REPITEDLY UNTIL THE RECONNECTION PRODUCTS REACH THEIR CRITICAL RADII, FORMING THUS "UNCOMBED" PENUMBRA.



MOST IMPORTANTLY:
THE RECONNECTION FACILITATES
THE ONSET OF AN ADEQUATE SCREW PINCH CONFIGURATION!

KRUSKAL–SHAFRANOV THEOREM:
LONG CYLINDRICAL FLUX TUBES ARE INTRINSICALLY UNSTABLE AND TWIST INTO A KINKED HELICAL SHAPE WITH THE PITCH ANGLE

$$\theta = B_\varphi / B_Z$$



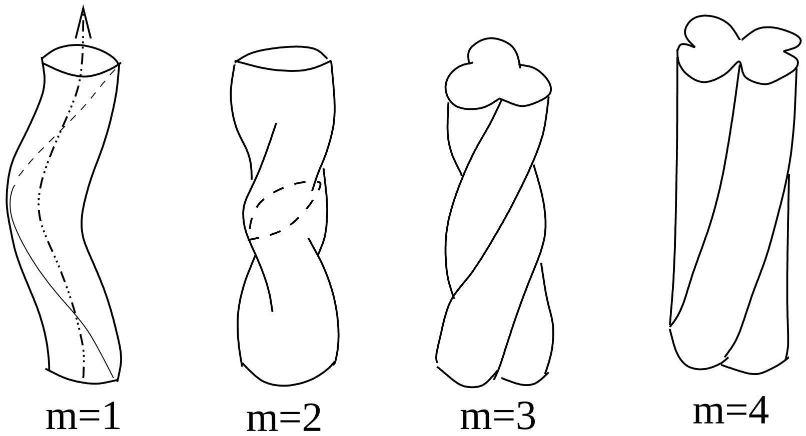
Screw pinch configuration is dynamically stable if the safety factor

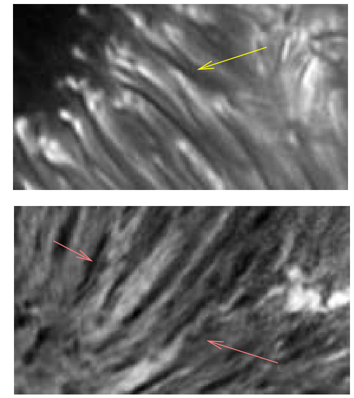
$$q \equiv \frac{h}{L} < 1$$

L is the length of flux tube, h is the pitch:

$$h(R) \equiv \frac{2\pi R}{\tan\theta} = \frac{2\pi R B_z}{B_\phi}$$

This determines profiles of magnetic field, current and temperature inside flux tube depending on the mode, m of helical perturbation.

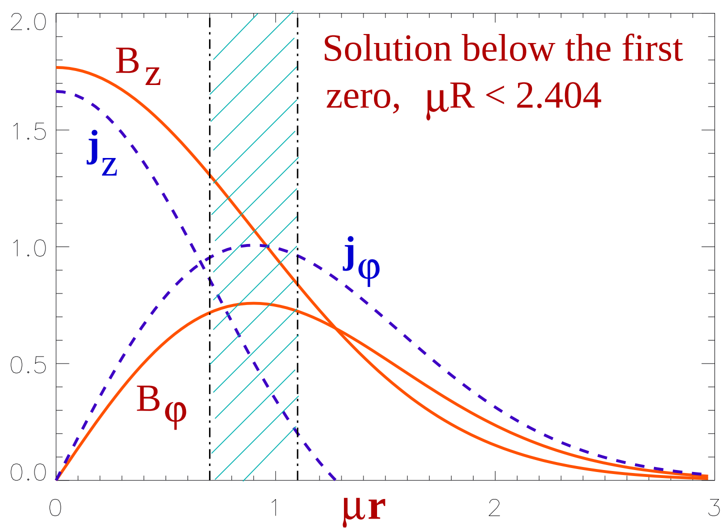




Solution for $m = \pm 1$ is the Lundquist field:

$$B_z(r) = B_0 J_0(\mu r), \qquad B_\phi(r) = B_0 J_1(\mu r); \qquad \mu \equiv \frac{2\pi}{h}$$

$$j_z(r) = \frac{B_0 c}{2\pi} \mu J_0(\mu r), \qquad j_\phi(r) = \frac{B_0 c}{2\pi} \mu J_1(\mu r); \qquad h \equiv \frac{2\pi r B_z}{B_\phi}$$



$\mu R = 2\pi R/h = 0.523$

$R = 5\ 10^6$ cm

$h = 6\ 10^7$ cm

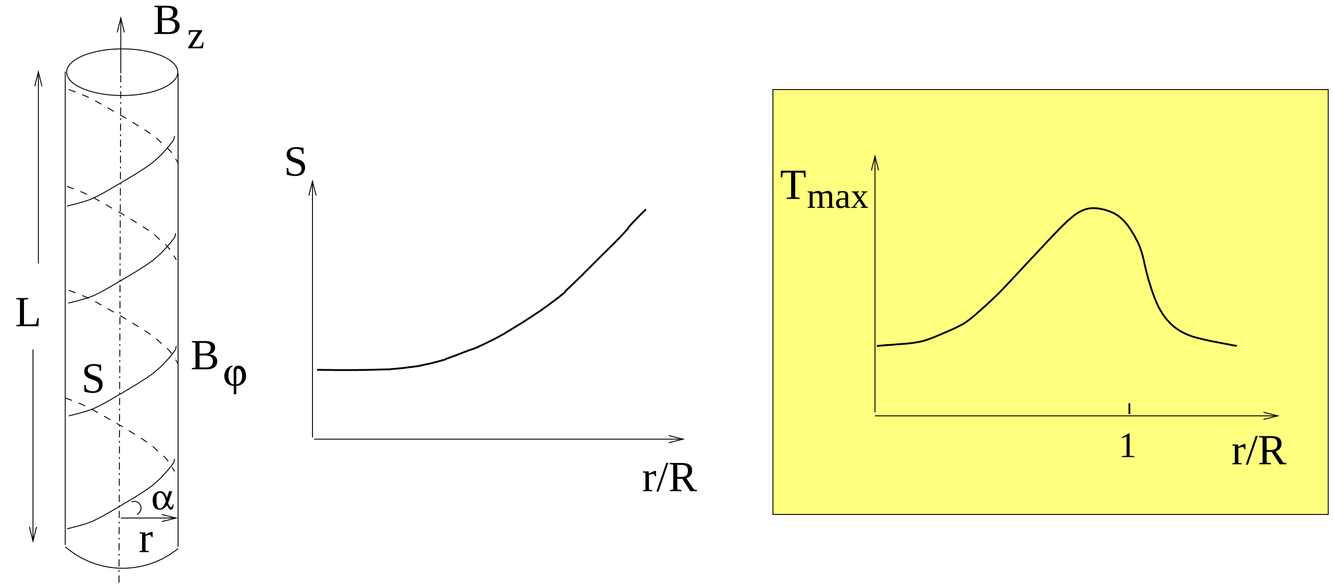
$B_z = 1000$ G

THE SHADED AREA IS WHERE THE ENHANCED HEATING OCCURS, PROVIDING COOLER INTERIOR & HOTTER WALLS

Temperature profile across the twisted flux tube is:

$$T_{max}(r) \simeq S^2(r)\ j^2(r)/(8\sigma\kappa_{\|}),$$

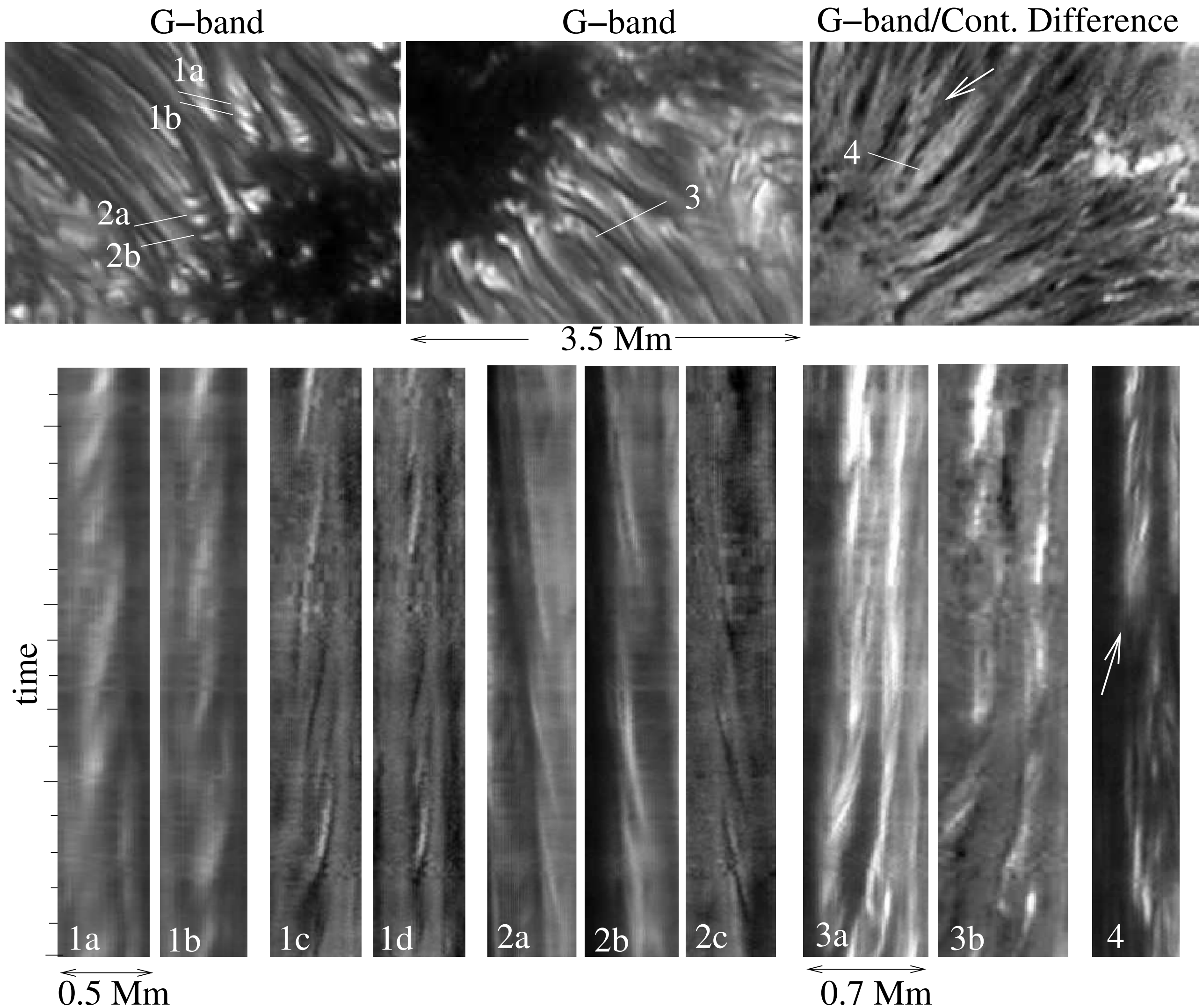
$S(r)$ is the length of helical magnetic line, $S(r) = L\sqrt{1 + B_\phi^2/B_z^2}$.
S is minimum at the axis, and rapidly grows toward periphery.



Presence of the factor $S^2(r)$ leads to hollow temperature profiles.

Pitch: $h \equiv \frac{2\pi R B_z}{B_\phi}$, **Radius, Magnetic fields, Safety factor -** $q \equiv \frac{h}{L}$, **are directly and independently measurable.**

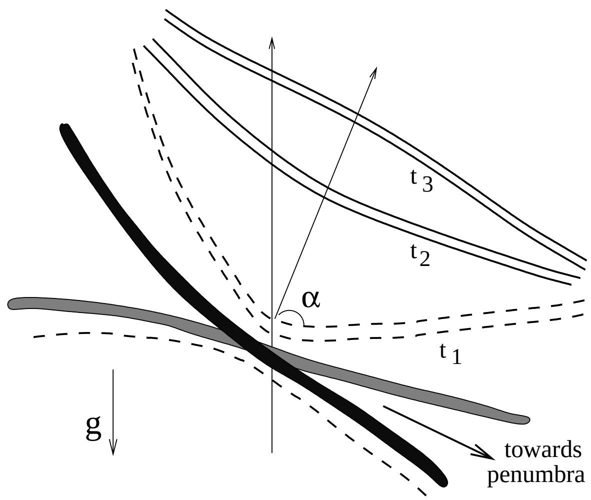
Space-time images allow to measure the pitch, $h = \Delta x(T/\Delta t)$:

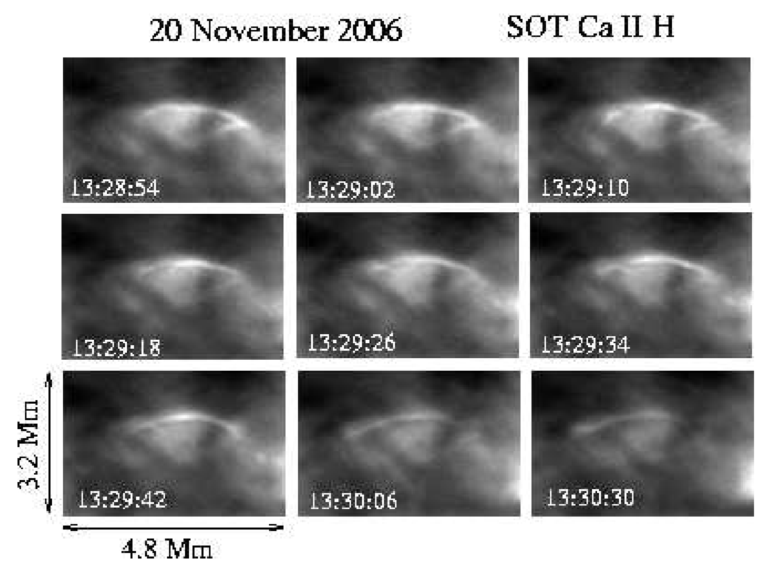


e.g. (1) $h \simeq 550\ km$; (2) $h \simeq 700$ km; (3) $h \simeq 400$ km.

Impact on the overlying atmosphere.

Under action of gravity ⋃-shaped reconnection product accelerates. At transonic velocities in front of it a bow (*detached*) shock is formed as it usually occurs in cases of blunt bodies moving with supersonic velocities.





Under a certain angle bow shock should appear as a double bright structure, moving in direction perpendicular to its long axis.

This is exactly what we observe in vast majority of cases!

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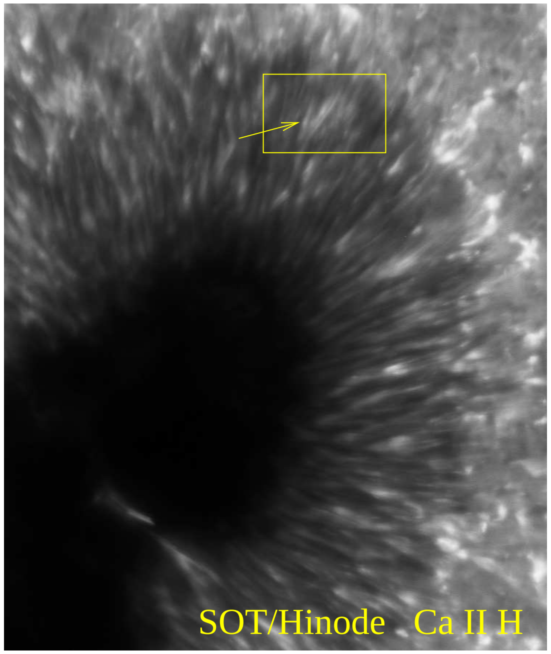

SIMPLE THOERY OF BOW SHOCKS ALLOWS FULL QUANTITATIVE ANALYSIS

	$h = 800\ km$			$h = 1000\ km$		
α	60°	50°	40°	60°	50°	40°
M	1.35	1.42	1.5	1.9	2	2.1
ϵ	0.662	0.622	0.583	0458	0.437	0.420
$\Delta\ (km)$	370	379	386	489	487	485
$h_{bow}\ (km)$	1170	1179	1186	1489	1487	1485
$L_{bow}\ (km)$	2770	1910	1343	3464	2384	1678
$T_1\ (K)$	9645	10000	10500	13200	14000	15000
$T_2\ (K)$	12900	14100	15700	25800	29000	33000
$u_{bow}\ (km\ s^{-1})$	10.8	11.36	12	15.2	16	16.8

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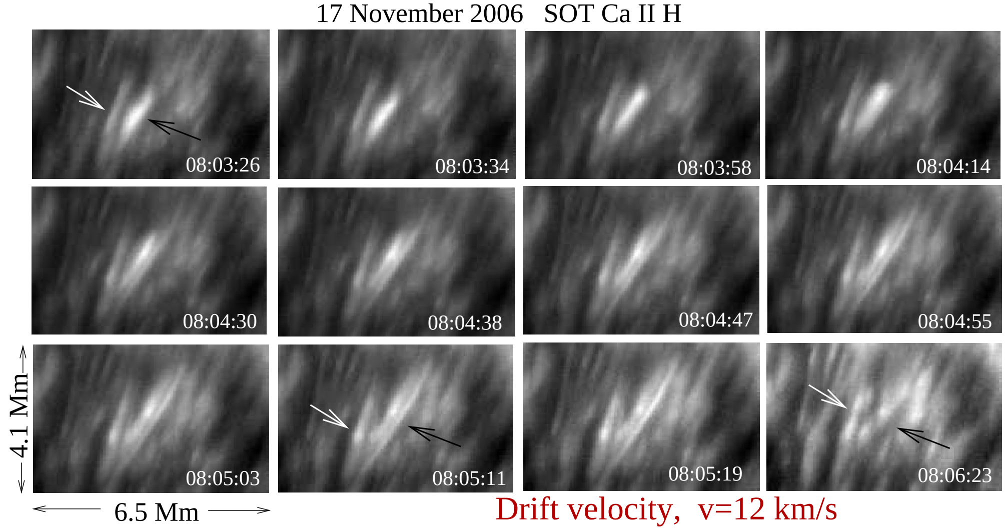
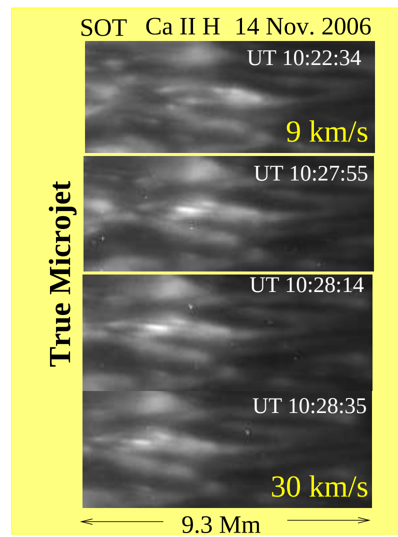


Drift velocity, v=12 km/s



Summary

All the observed properties of penumbra and and its impact on the overlying atmosphere are the natural consequences of the ongoing reconnection processes.

- The very formation of filamentary penumbra.
- Multiple splitting of individual filaments.
- Enhanced brightening of footpoints (region of reconnection).
- Presence of dark cores in the filaments.
- Intrinsic twist of filaments with safety factor $q = h/L < 1$.
- Resulted dynamic stability (long lifetimes) of filaments.
- Generation of electric currents and flows that mimic a screw pinch configuration.

For details and quantitative analysis see our poster $P6 - 6$.

Thank you.

Magnetic cylinder in dynamic environment is subject of inevitable fragmentation process due to nonlinear instabilities.

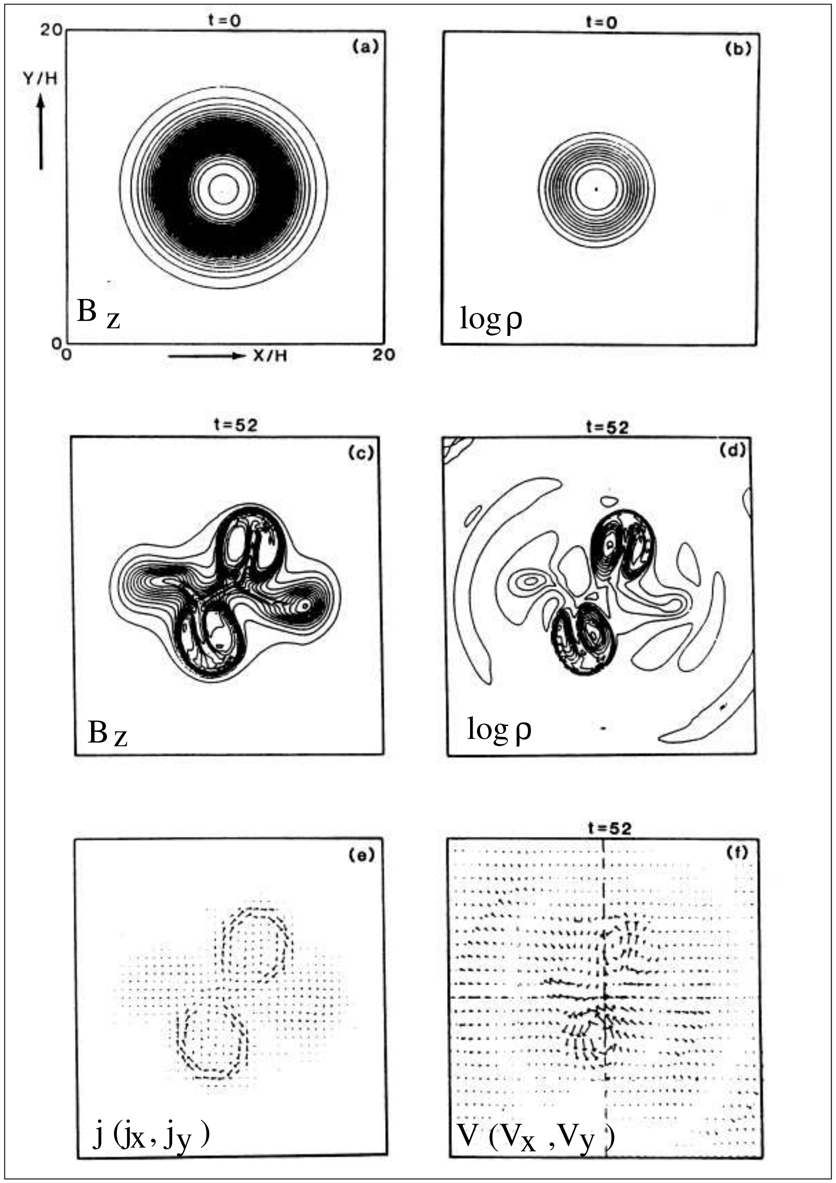
Interaction of flux tube with wave fields and/or convection leads to "Magnetosonic Streaming" (Ryutova, Kaisig & Tajima, 1996, Theory and numerical simulations):

- Absorption of the momentum leads to the generation of *upward* and *downward* mass flows **along the filament**.
- Absorption of the angular momentum leads to the generation of rotational mass flows **across the filament**.

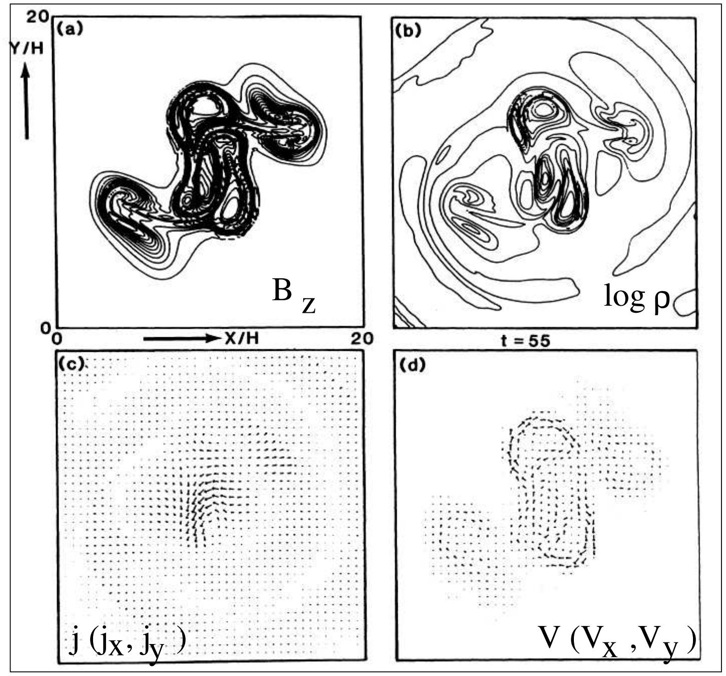
Most importantly the induced flows lead to redistribution of magnetic field and density inside flux tube causing fragmentation and appearance of the inner sub-structure.

Illustrated area in numerical simulations (of a single box) is 20×20 in units H, characteristic width between neighboring filaments.

m=1



Final state of the evolution in case of higher modes



$Re_m = 10^3$, $H = 300$ km, $B_z = 1000$ G

$\rho = 2 \; 10^{-7}$ g/cm^3, R = 50 km ,

helical pitch, h = 400 km, T=6000 K,

Generated currents range:

$j = 2.1 \; 10^{-2}$ A/m^2 – 1.7 A/m^2

Generated flows:

v = 0.5 km/s – 7 km/s