ESMN School, Tatranská Lomnica, November 2004

# *Sunspot observations*

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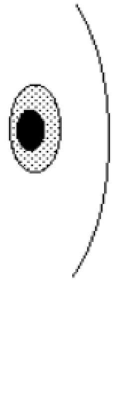
## Historical observations of sunspots

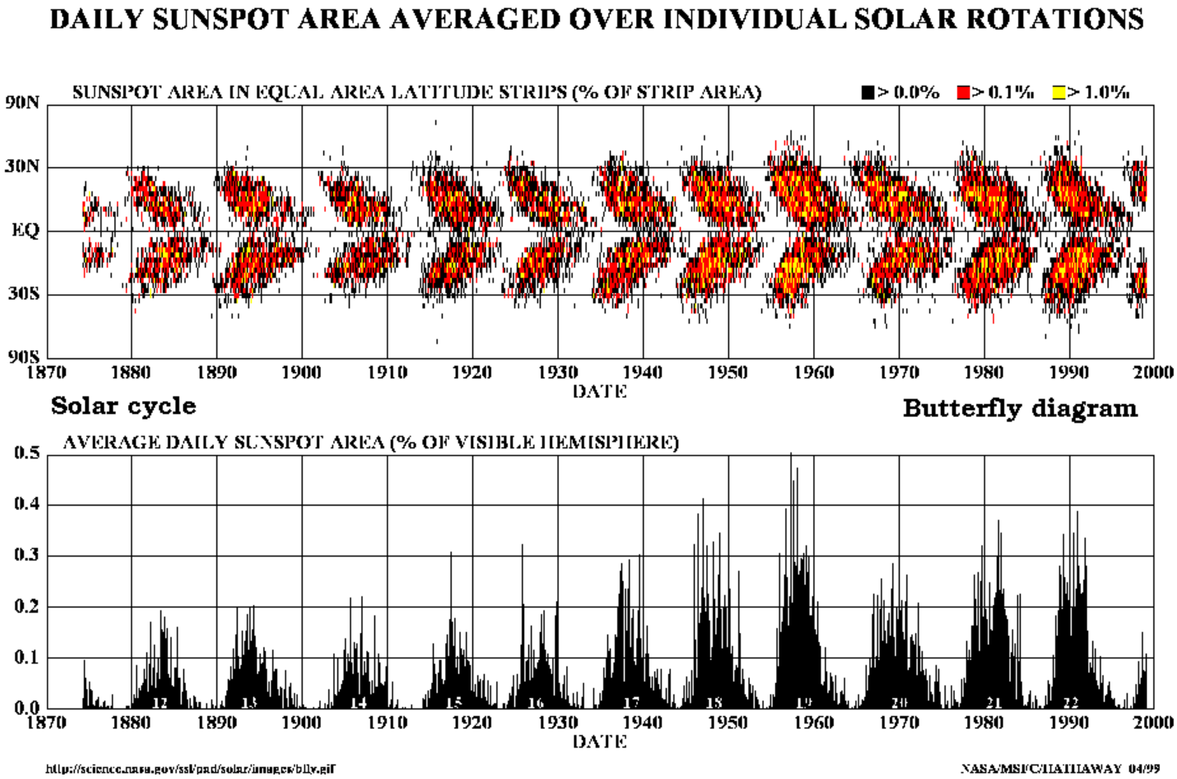
**Ocassional naked-eye observations (China)**

**First telescopic observations:**

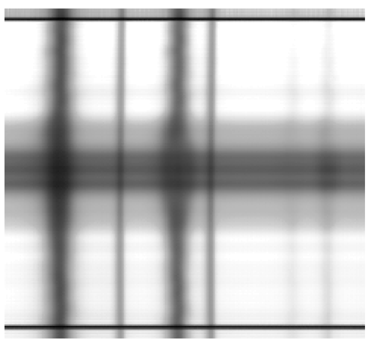
**1610 - T. Harriot**
**1611 - J. Fabricius** ***(first publication)***
**C. Scheiner**
**Galileo** ***(spots are surface phenomena)***

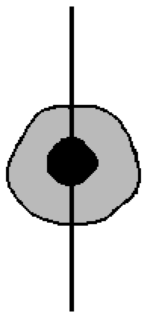
**1769 - A. Wilson**
***Wilson depression***






## Spectroscopy of sunspots



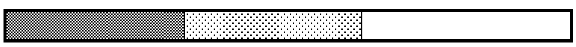


**1908 - G. E. Hale: Magnetic splitting of spectral lines**

Intensity and inclination of mag. field in large spots:

*$B \sim 3000$ G in the center of umbra*

*$\gamma \sim 0°$ 40° 70°*



**1909 - J. Evershed: Shift and asymmetry of spectral lines**

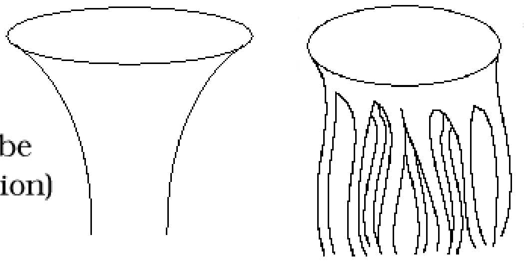
**--> a few km/s outflow in the penumbra**

**Sunspot = magnetic flux tube breaking through the solar photosphere (Cowling 1934)**

**Sunspots are cooler than their surroundings:**

- **Convective transport of heat restricted by magnetic field (Biermann 1941)**
- **Heat flux is spread over a greater area due to fanning out of field lines (Hoyle 1949)**

**Basic models**




## Magnetohydrostatic equilibrium:

Vertical magnetic field in a stratified atmosphere (Priest 1982)

Magnetic field $B(R)$ is constant with height $z$. Maximum value $B_i$ is on the vertical axis ($R = 0$) and $B \to 0$ for large $R$.
Pressure stratifications on the axis and far from it: $p_i(z)$ and $p_e(z)$.

The conditions of horizontal and vertical pressure balances are

$$p(R,z) + B^2(R)/2\mu = p_e(z) \tag{1}$$

$$\frac{\partial p}{\partial z} = -\rho(z)g, \tag{2}$$

where $\mu$, $\rho$, and $g$ are magnetical permeability, gas density, and gravitational acceleration, respectively.

Particularly, far from the axis we have

$$\frac{\mathrm{d}p_e}{\mathrm{d}z} = -\rho_e(z)g \tag{3}$$

and on the axis

$$p_i(z) + {B_i}^2/2\mu = p_e(z) \tag{4}$$

$$\frac{\mathrm{d}p_i}{\mathrm{d}z} = -\rho_i(z)g. \tag{5}$$

Differentiating (4) we see that $\mathrm{d}p_e/\mathrm{d}z = \mathrm{d}p_i/\mathrm{d}z$ and from (3) and (5) it follows that

$$\rho_i(z) = \rho_e(z). \tag{6}$$

Moreover, from (4) we see that $p_i < p_e$ and, introducing the ideal gas equation of state, we obtain the ratio of internal and external temperatures:

$$\frac{T_i(z)}{T_e(z)} = 1 - \frac{{B_i}^2}{2\mu p_e(z)}. \tag{7}$$

Usually, in the umbra at the level of the photosphere

$${B_i}^2/2\mu > p_e(z) \tag{8}$$

(magnetic pressure for $B = 3000$ G is about $2.4 \times 10^4$ N/m$^2$, while the photospheric gas pressure at $\tau_{5000} = 1$ is only $1.4 \times 10^4$ N/m$^2$). The horizontal equilibrium is perturbed and *the tube diverges, increasing its radius with height.* As a consequence,

$$\mathrm{d}B_i/\mathrm{d}z < 0 \tag{9}$$

and, since

$$p_i(z) + B_i(z)^2/2\mu = p_e(z), \tag{10}$$

the pressure gradient inside the tube is higher than the gradient outside. This results in smaller density inside the tube:

$$\rho_i(z) < \rho_e(z). \tag{11}$$

This density deficit in sunspots is partially responsible for the Wilson depression.

# METHODS OF OBSERVATION

## IMAGING AND TIME SERIES OF IMAGES

morphology, broad-band photometric data,
evolution, horizontal motions

highest spatial and temporal resolution
correlation or sunspot trackers, adaptive optics

post-processing: speckle reconstruction
phase-diversity reconstruction

horizontal dynamics: local correlation tracking (LCT)
feature tracking

## SPECTROSCOPY AND POLARIMETRY

thermal stratification, Doppler velocities

polarimetry - I, (Q, U), V: magnetic field (vector)

moderate spatial resolution, but trackers and adaptive optics can greatly improve the results

moderate temporal resolution

highest spectral resolution

processing: inversion of profiles (I, Q, U, V) of spectral lines to obtain a semi-empirical model of the atmosphere

**2D SPECTROSCOPY AND POLARIMETRY**

**maps of thermal stratification, Doppler velocities, magnetic field**

* ***fast scanning with a slit spectrograph***

**scanning in spatial direction perpendicular to the slit**
**moderate spatial resolution (trackers, AO improve)**
**poor temporal resolution**
**spectral resolution as high as for 1D spectroscopy**

* ***Fabry-Perot spectrometers, tunable filters***

**scanning in wavelength**
**high spatial resolution (combined with speckle reconstruction)**
**moderate temporal and spectral resolution**

* ***MSDP (Multichannel Subtractive Double-Pass Spectrometer)***

**simultaneous exposures of a narrow field in several (about 10) wavelengths**
**high spatial and temporal resolution**
**moderate spectral resolution**

**LOCAL HELIOSEISMOLOGY**

**3D tomographic maps of** ***subphotospheric*** **temperature inhomogeneities, magnetic fields, flows**

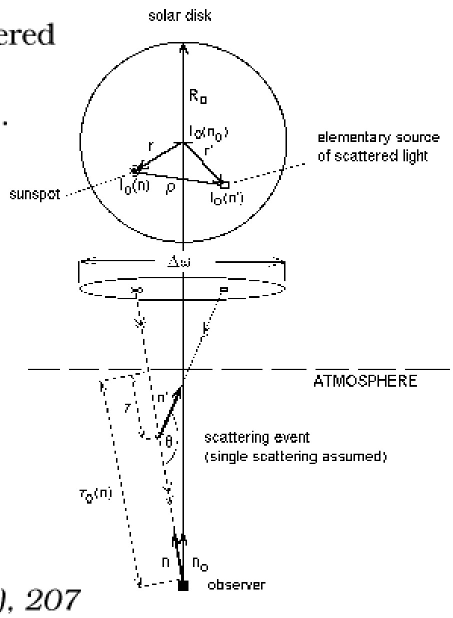
**data: long time series of dopplergrams (SOHO/MDI)**

**technique: time-distance helioseimology, based on measuring travel times of p-modes between different solar surface points**

## CORRECTION FOR SCATTERED LIGHT

In addition to the wavefront distortion in the Earth's atmosphere, light is scattered on dust and water droplets in the air, and on dust and dirt on optical surfaces.
--> bright circumsolar annulus, the **aureole**

Scattered light causes spurious enhancement of intensity in sunspots. The amount of scattered light can be obtained from aureole measurements or from polarimetric measurements, because polarized light comes mostly from the sunspot.




*V. Martinez Pillet, Solar Phys. 140 (1992), 207*

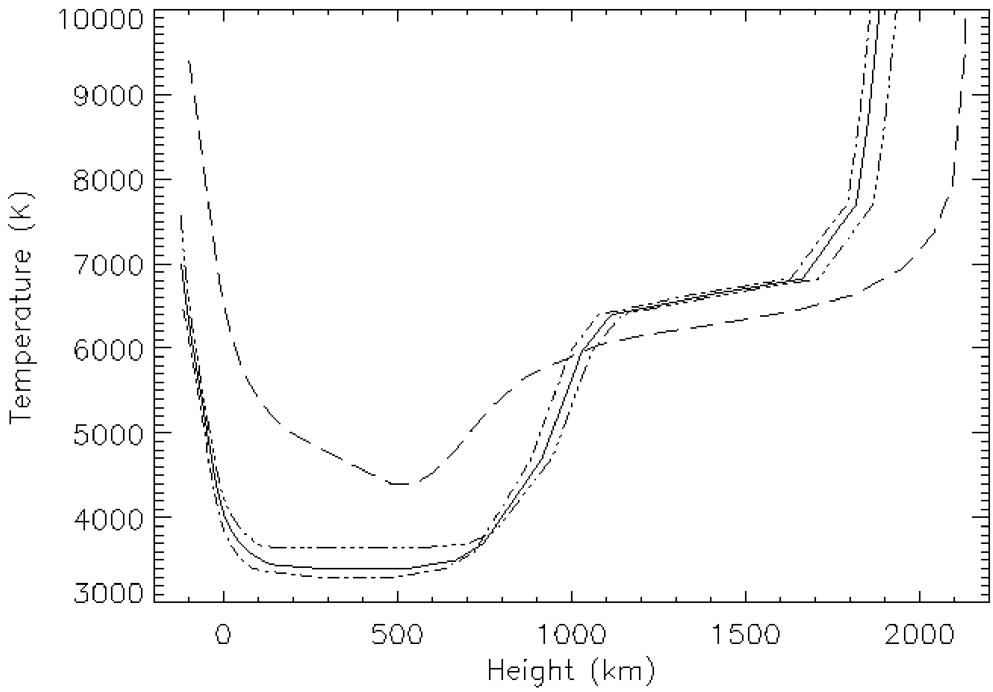
## DATA ABOUT SUNSPOTS AND PORES

| | **Pores** | **Sunspots** |
|---|---|---|
| Penumbra | NO | YES |
| Diameter $D_{vis}$ (Mm) | $1-6$ | $6-40$ (total) |
| Minimum intensity | $0.2-0.7$ | $0.05-0.3$ |
| $B(0)$ (G) | 1700 | 3000 |
| $B(R_{vis})$ (G) | 1200 | 800 |
| Inclination $\gamma(R_{vis})$ | $40^\circ - 60^\circ$ | $\sim 70^\circ$ |
| Dependence on $D_{vis}$ | strong | for $D_u < 6$ Mm |

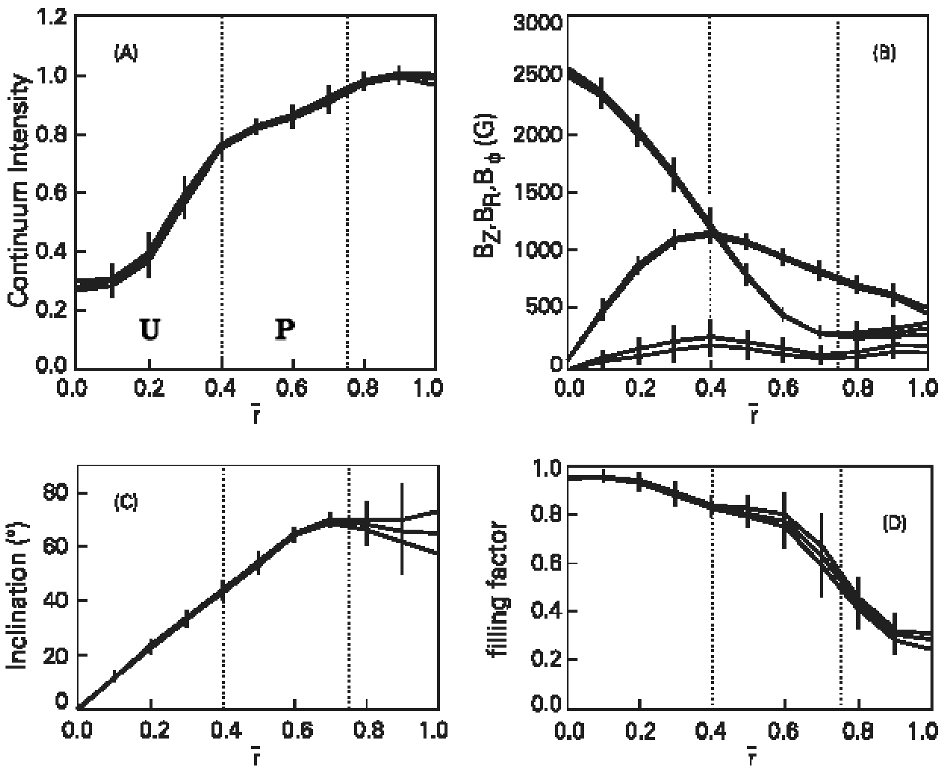
Sources: *Sütterlin 1998; Keil et al. 1999*

"Magnetic diameter" $D_m > D_{vis}$ (*Keppens & Martínez Pillet 1996*).

**Pore** → more magnetic flux → more inclination of **B** →
→ penumbra formation → **Sunspot**

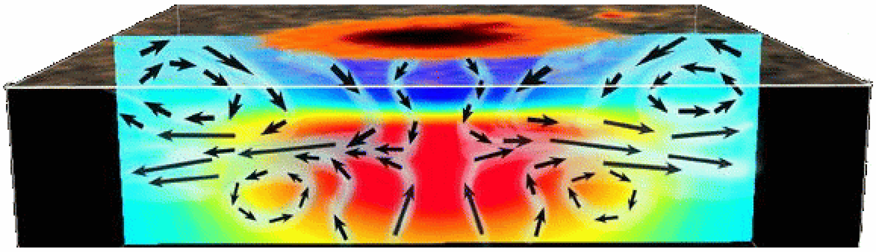



Temperature stratification in umbral models by Maltby et al. (1986). Dashed line corresponds to quiet sun.




**Magnetic field distribution (Keppens & Martínez Pillet 1996)**

**RESULTS OF HELIOSEISMOLOGY**
***(Gizon 2000, Zhao et al. 2001, Kosovichev 2002)***



* sunspot is cooler than its surroundings only to the depth of 5 Mm
* converging flows are found below 1.5 Mm, deeper changing to downflows
* strong outflows at 6 - 10 Mm

* a radial outflow of 1 km/s is found above 2 Mm (like Evershed flow)

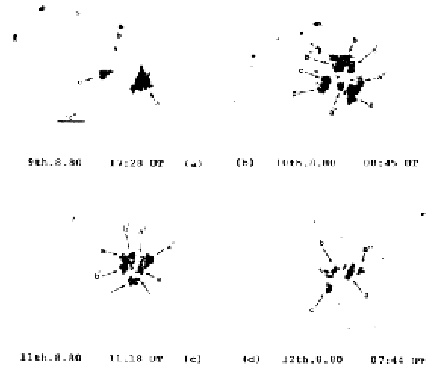
In favour of the cluster model:
* a horizontal flow across the sunspot was found at 9 - 12 Mm
* sunspot has a constant radius in deep layers (Chou et al. 1997)

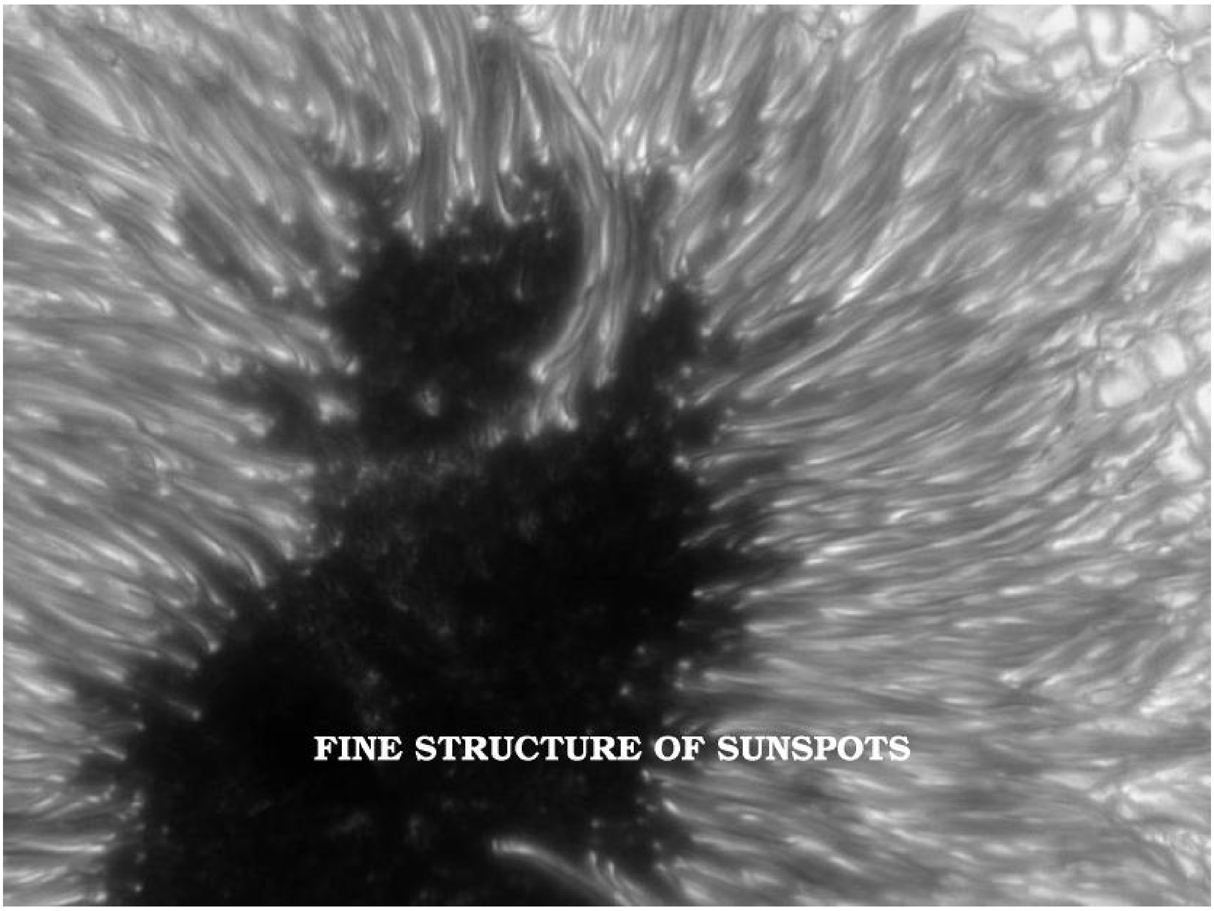
## FORMATION OF SUNSPOTS AND PORES

**Merging**, driven by supergranular and subsurface flows
(e.g. *Wang & Zirin 1992, Keil et al. 1999*):

**Small flux elements → pores and small sunspots ("fragments") →**
**→ large sunspots**

The "fragments" keep their identity during the lifetime of a sunspot (*García de la Rosa 1987*) and they are observed as umbral cores or dark nuclei in developed umbrae.
Bright small-scale structures (umbral dots, light bridges) are seen at the interstices of fragments both in sunspots and pores.

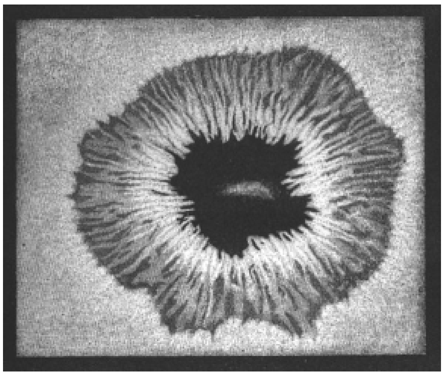





**FIRST HIGH-RESOLUTION OBSERVATIONS**

**Visual: P. A. Secchi 1870**

a drawing from the book "Le Soleil"

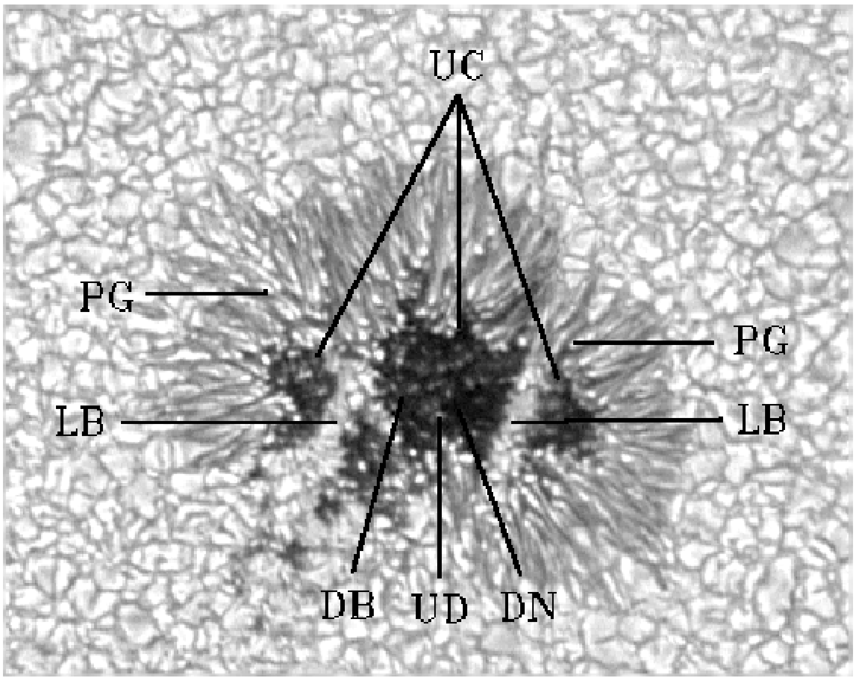


**Photographic: S. Chevalier 1916 (resolution 0".7 - 1")**

observed: filamentary structure of the penumbra
light bridges
umbral cores and dark nuclei
"umbral granulation"

**OVERVIEW OF SUNSPOT FINE STRUCTURE**

UC - umbral core, PG - penumbral grain, LB - light bridge,
UD - umbral dot, DN - dark nucleus, DB - diffuse background




## THE PENUMBRA

### PENUMBRAL FILAMENTS

* **Brightness:** On average, 1 $I_{ph}$ (bright), 0.6 $I_{ph}$ (dark)
  Terms "bright" and "dark" have only local meaning.

* **Width:** Derived from power spectra:
  - 250 km (0".35) - Balthasar et al. (2001), Sütterlin (2001)
  - unresolved ? - Sánchez Almeida & Bonet (1998)

  1-m SST, La Palma:
  - many filaments are narrower than 80 km (0".11)
  Rouppe van der Voort (2004)

* **Dark cores in bright filaments**
  best seen in the inner penumbra
  Scharmer et al. (2002, 1-m SST), Sütterlin et al. (2004, DOT)

**PENUMBRAL FILAMENTS: Magnetic and velocity fields**

Pioneering work: Beckers & Schröter (1969)
Many observations have been done, giving different results depending on examined depth in the atmosphere (spectral lines, technique).

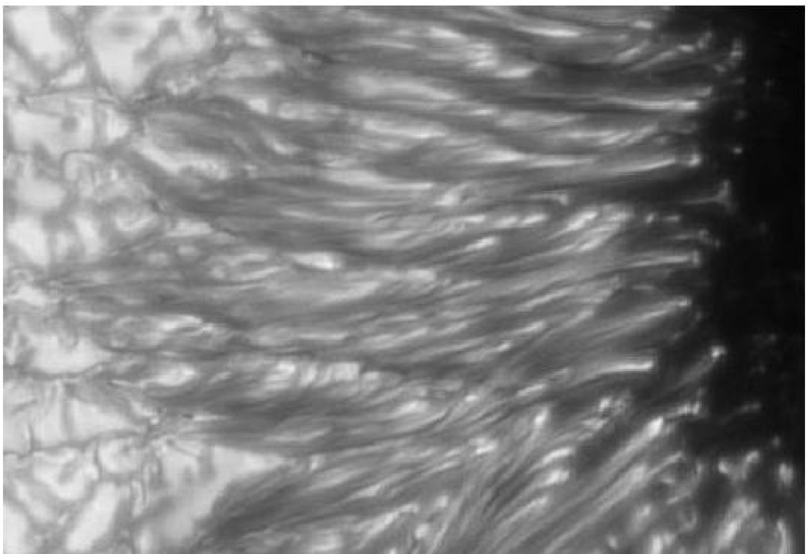
This still open problem converges to the following:

(1) Dark filaments host more inclined magnetic field (by 30° - 40°) compared to bright filaments, and possibly stronger in intensity.
Wiehr (2000), Westendorp Plaza et al. (2001), Bellot Rubio et al. (2003)

(2) Evershed flow tends to be aligned with more inclined magnetic field, i.e., with dark filaments. Its filamentary structure is seen in deep layers.
Rouppe van der Voort (2002), Bellot Rubio et al. (2003), Tritschler et al. (2004)

Upflows are observed near the umbra-penumbra border and strong downflows near the penumbra-granulation border.
Hirzberger & Kneer (2001)

**PENUMBRAL GRAINS** comet-like bright features in bright filaments

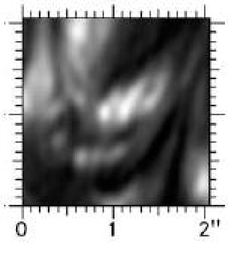


Muller (1973)

Brightness:
0.85 - 1.10 $I_{ph}$

Width: ~ 0''.5

Internal structure - dark bands
Rouppe van der Voort et al. (2004)




*SST, June 2004*

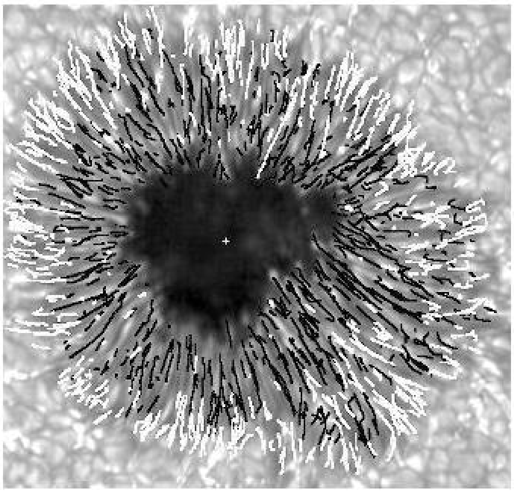
## Horizontal motions of penumbral grains

Inner penumbra:
Mostly inwards, 0.5 km/s

Outer penumbra:
Mostly outwards, 0.75 km/s

Sobotka et al. (1999)
Sobotka & Sutterlin (2001)

*trajectories*



Some inward-moving grains penetrate into the umbra (Ewell 1992).
About 1/3 of outward-moving grains cross the outer penumbral boundary, evolve into a small bright feature or a normal photospheric granule and continue to move radially avay from the spot (Bonet et al. 2004).

## Lifetimes of penumbral grains

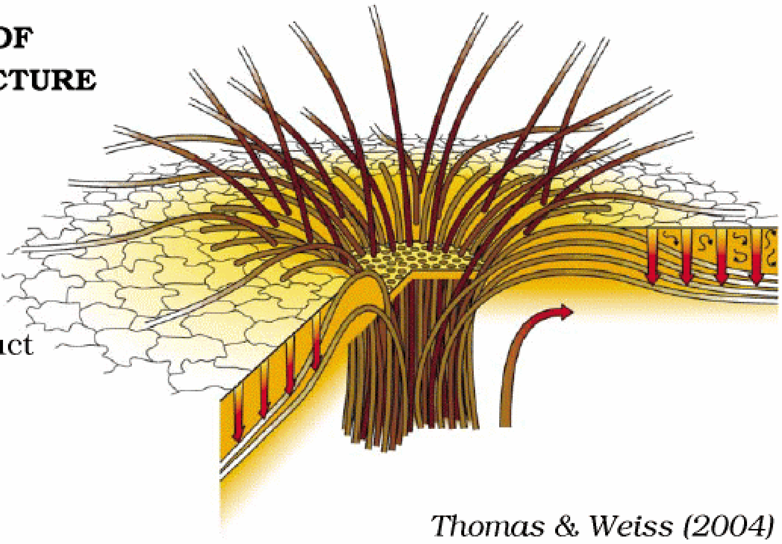
Mean: 40 min (inward-moving), 25 min (outward-moving)

## INTERPRETATION OF PENUMBRAL STRUCTURE

Two systems of flux tubes with different inclination.

Horizontal flux tubes are expected to conduct Evershed flow.

"Uncombed" penumbral model
Solanki & Montavon (1993)



*Thomas & Weiss (2004)*

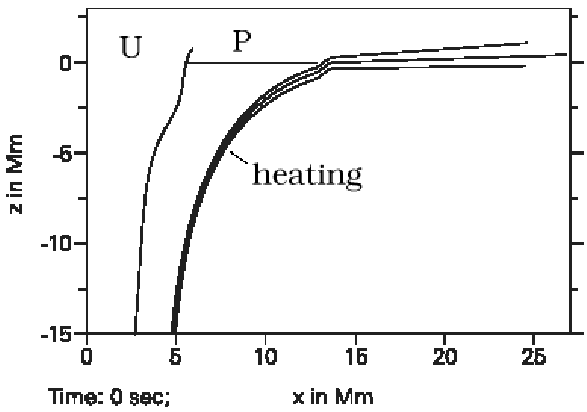
**Figure 11** Sketch showing the interlocking-comb structure of the magnetic field in the filamentary penumbra of a sunspot (after Thomas et al. 2002a). The bright radial filaments, where the magnetic field is inclined (at approximately 40° to the horizontal in the outer penumbra), alternate with dark filaments in which the field is nearly horizontal. Within the dark filaments, some magnetic flux tubes (i.e., bundles of magnetic field lines) extend radially outward beyond the penumbra along an elevated magnetic canopy, while other, "returning" flux tubes dive back below the surface. The sunspot is surrounded by a layer of small-scale granular convection (*squiggly arrows*) embedded in the radial outflow associated with a long-lived annular supergranule (the moat cell) (*large curved arrow*). The submerged parts of the returning flux tubes are held down by turbulent pumping (*vertical arrows*) by the granular convection in the moat.

**Moving tube model**

Schlichenmaier et al. (1998)

Interpretation of

- inward motion of penumbral grains
- Evershed flow



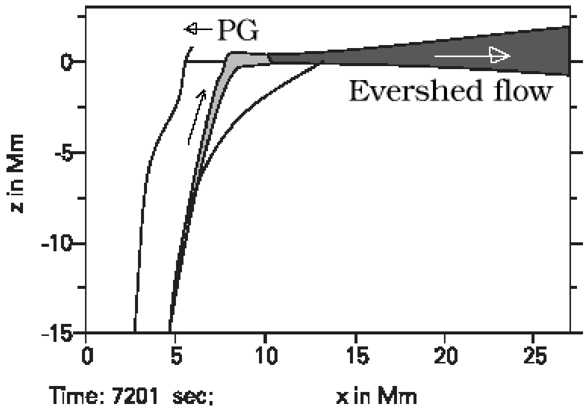

**Photospheric "serpent"**

Schlichenmaier (2002)

Flux tube, instead of lying horizontal, develops waves.

Interpretation of

- outward motion of PGs
- downflows in penumbra




## LIGHT BRIDGES

### Location in the umbra

usually at the interstices between "fragments"

* separating umbral cores - "strong" light bridges
* embedded in the umbra - "faint" light bridges

### Structure

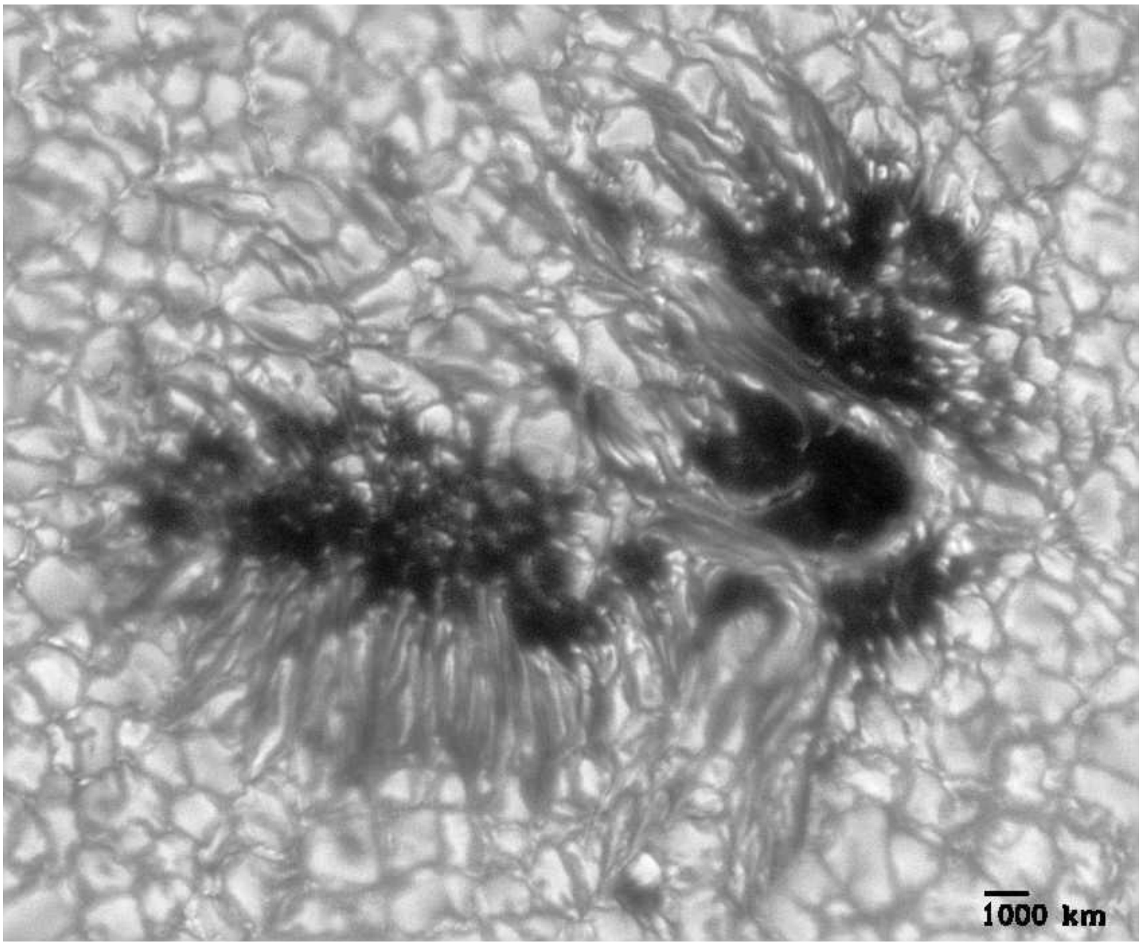
* granular, size of grains from 0".2 to 1".2
  sometimes, a central dark lane is observed
* filamentary, penumbra-like bright filaments
* mixed

### Evolution

*Sunspot formation:*

granulation --> light bridge --> chain of umbral dots

*Sunspot decay:* A reverse scenario

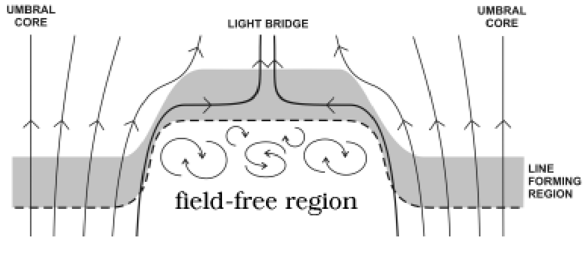



**Magnetic field and velocities in light bridges**

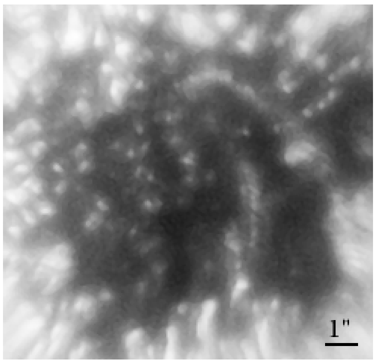
B is reduced by 500 - 1200 G vith respect to the surrounding umbra.
Magnetic field is inclined, but less than in penumbra. (Leka 1997)
Possible existence of magnetic canopy above light bridges.
Upflows and downflows (max. 400 m/s) indicating convective motions.

In granular LBs, convective elements with upflows in bright grains and downflows in dark lanes are observed. Velocities and cell sizes are smaller, lifetimes longer than in photospheric granulation. (Rimmele 1997)
Irregular horizontal motions of grains (300 m/s, Hirzberger et al. 2002)
Steady horizontal flow (900 m/s) along LB (Berger & Berdyugina 2003)

**LBs are deep-rooted structures of convective origin.**



# UMBRAL DOTS




## BRIGHTNESS AND SIZE

Restricted by telescope aperture, seeing, signal-to-noise ratio.

Many UDs are spatially unresolved.

Indirect methods to find "true" brightness and size:

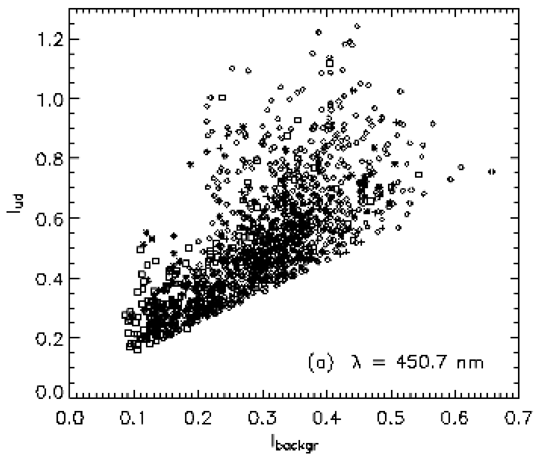
- two-color photometry (Beckers & Schröter 1968)
- two-component thermal models (Sobotka et al. 1993)

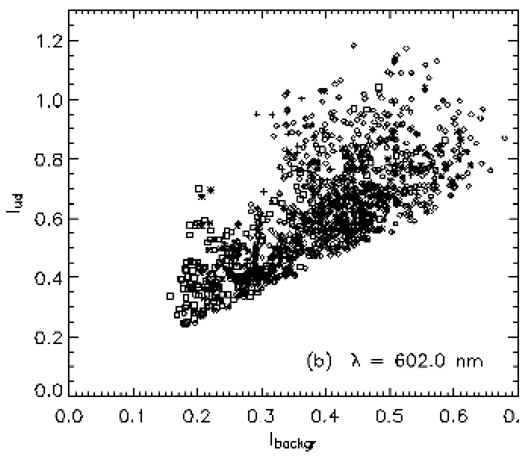
**Brightness:** Observed in the range 0.2 - 0.7 $I_{ph}$
Peripheral UDs are brighter than central UDs
Brightness is related to local background intensity

$I_{ud} \cong 1.5\, I_b$ (observed)

"True" brightness: $I_{ud} \cong 3\, I_b$

Sobotka & Hanslmeier (in preparation) - 1-m SST, 2003

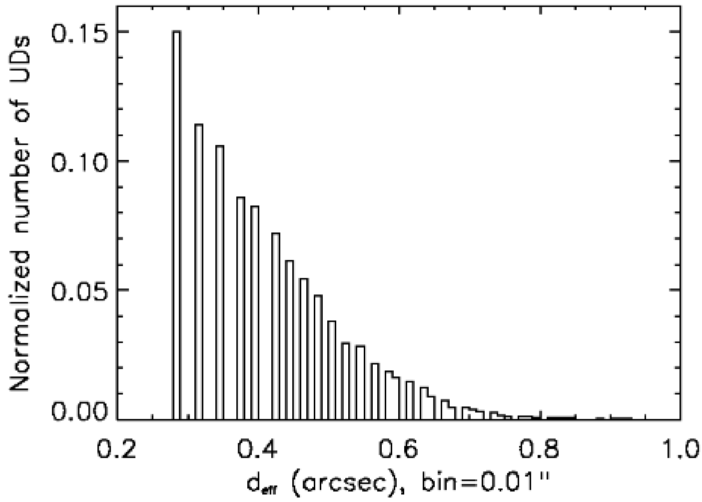



Observed UDs vs. background intensities

blue: $I_{ud} / I_{db} \sim 1.8$ red: $I_{ud} / I_{db} \sim 1.6$

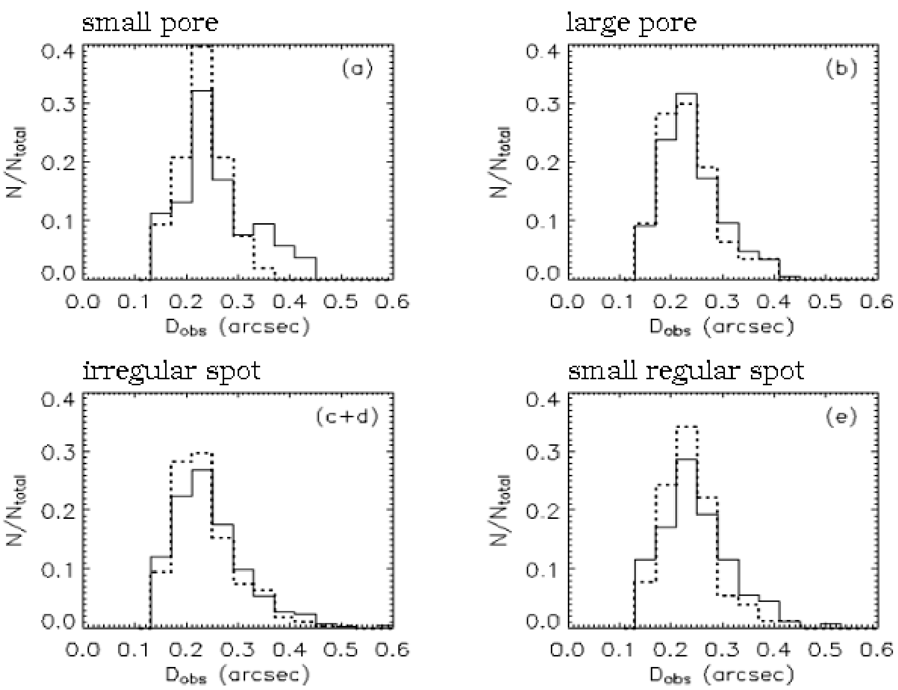
**Observed size:**




observed diameter

Sobotka et al. (1997): Number of UDs increases with decreasing D, i.e., smallest UDs are not spatially resolved (0.5 m telescope)

Tritschler & Schmidt (2002): The same result, with 0.7 m telescope and phase−diversity image restoration




Observed diameters: Most of UDs are spatially resolved !

**Typical observed diameter: 0".23 (165 km)**

Sobotka & Hanslmeier, in preparation

## Two–colour photometry technique: "True" intensities and sizes

Beckers & Schröter (1968)

$$I_\lambda = I_\lambda^{db} + \Delta I_\lambda, \quad J_\lambda = J_\lambda^{db} + \Delta J_\lambda, \quad J_\lambda^{db} \sim I_\lambda^{db} \quad \lambda = blue,\ red$$

The flux is not influenced by image degradation

(*) $$\Delta I_\lambda D_\lambda^2 = \Delta J_\lambda d_\lambda^2, \qquad d_{blue} = d_{red}$$

colour index $c$ : calculated from observed values

$$\Delta J_{blue} = c \Delta J_{red}, \qquad c = \frac{\Delta I_{blue} D_{blue}^2}{\Delta I_{red} D_{red}^2}$$

Obtaining colour temperature T from colour index c by fitting Planck curve
– a system of two equations for $\Delta J_{red}$ and T

$$J_{blue} = \quad J_{blue}^{db} + c\Delta J_{red} = B_{blue}(T)/I_{blue}^{ph}$$

$$J_{red} = \quad J_{red}^{db} + \Delta J_{red} = B_{red}(T)/I_{red}^{ph}$$

and d from (*)

## Calculated intensities and sizes of UDs

Results of two–colour photometry (Sobotka & Hanslmeier, in prep.)

About 50 % of UDs are brighter and hotter than the mean quiet photosphere

Calculated diameters of UDs

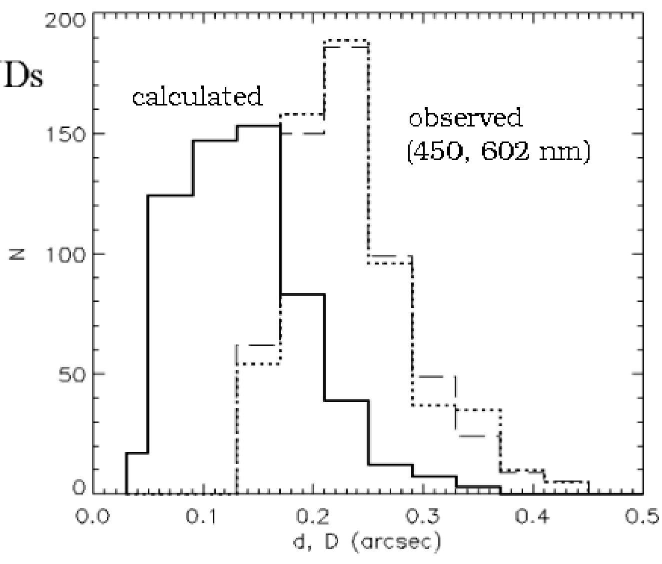
average d = 0.14" (100 km)

median d = 0.13" (95 km)

**Mean free photon path (500 nm continuum)**

**umbra: ~ 70 km**

**photosphere: ~ 90 km**



**SPATIAL DISTRIBUTION OF UMBRAL DOTS**

Non-uniform, preferred locations, clusters and chains.

Nearest-neighbour distance (0".4 - 0".7) decreases and observed filling factor (6 - 15 %) increases with increasing brightness of the umbral background (Sobotka et al. 1993).

**Is the umbra heated by umbral dots?**

At the visible surface, UDs contribute only by 10 - 20 % of the total flux, so that the umbral brightness is influenced mainly by the brightness of the umbral background.

However, the umbral background can be heated by lateral radiation of UDs below the visible surface.

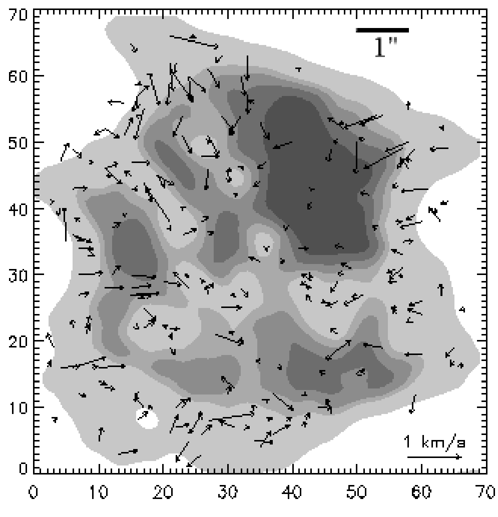
**LIFETIME OF UMBRAL DOTS**

66 % : t < 10 min
27 % : 10 < t < 40 min
1 % : t > 2 hours

**HORIZONTAL MOTIONS**

Velocities 0 - 800 m/s
On average, UDs are faster in peripheral parts of umbra, where inward motions prevail.

Relation to inward-moving penumbral grains?



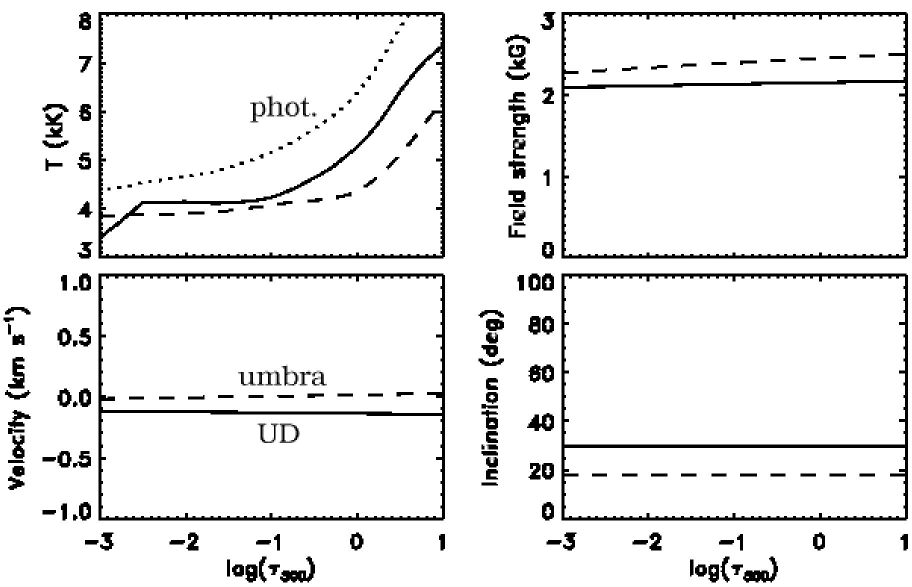

Sobotka et al. (1997)

**MAGNETIC FIELD AND LINE-OF-SIGHT VELOCITY**

Hard to detect, because

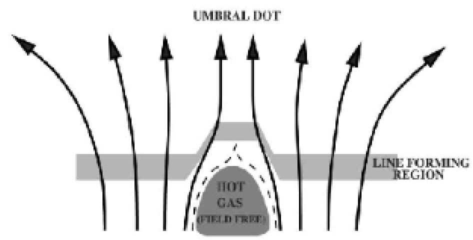
1. UDs are deep-formed structures and their magnetic and velocity signatures are weak at heights of formation of spectral lines. (Degenhardt & Lites 1993)
2. Lines are formed at different heights in UDs and in the umbra.

- Magnetic field in umbral dots is weaker by 10 %
  (Schmidt & Balthasar 1994; Socas Navarro et al. 2004)
- Upflows of 200 - 1000 m/s are observed in deepest layers
  (Socas Navarro et al. 2004; Rimmele 2004)
- UDs are hotter than the surrounding umbra only below z = 100 km
- Magnetic field in UDs is inclined 30° - 40° to the normal
  (Socas Navarro et al. 2004)



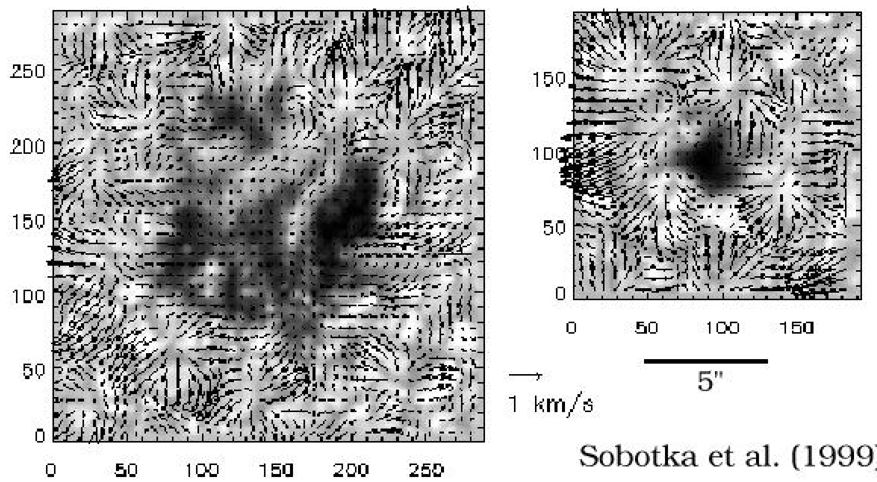

Socas Navarro, Martínez Pillet, Sobotka, Vázquez (2004)

2D (scanning) spectroscopy, 0.5-m SVST, LPSP



## HORIZONTAL MOTIONS AROUND SUNSPOTS AND PORES

**PORES**

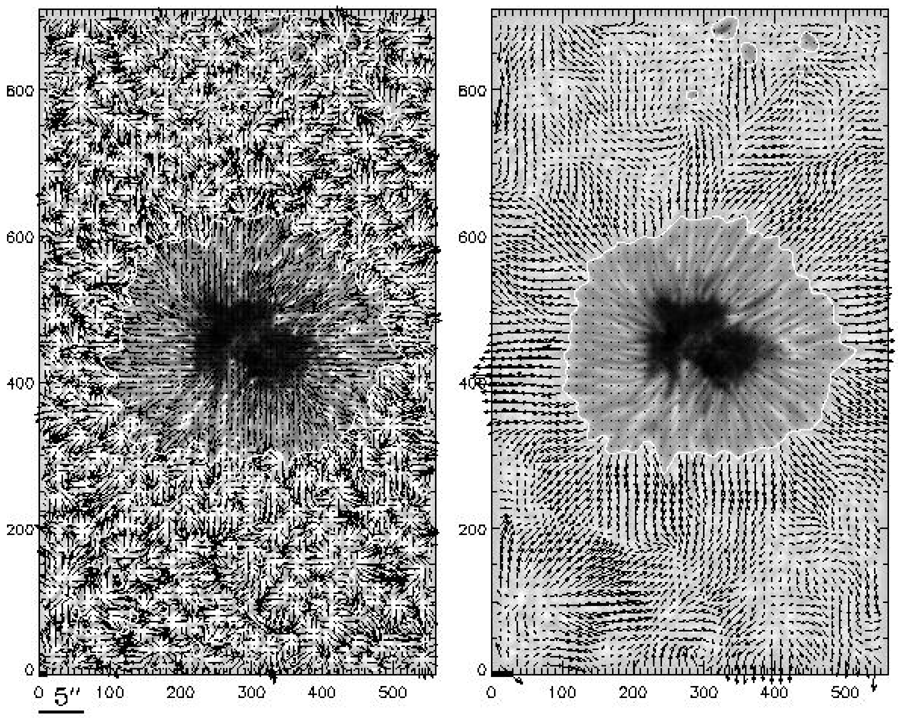



Sobotka et al. (1999)

* Granules in a 1500 km wide zone around the pore are directed toward the pore. These motions are driven by exploding granules and mesogranules.
* Some granules (or their fragments) penetrate into the umbra.

**SUNSPOTS**

* Local divergent motions (~3") - exploding granules
* Regular outflow (500 m/s) in the ***sunspot moat***



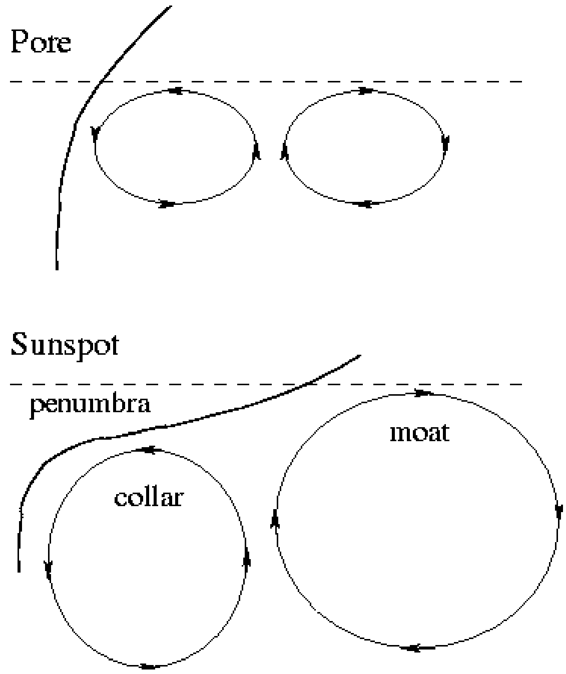

Bonet et al. (2004)

**RESULTS OF NUMERICAL SIMULATIONS**

Hurlburt & Rucklidge (2000)

Plasma neighbouring with the flux tube is cooled --> downflows.
Inflows help to stabilize the pore / sunspot.

Discrepancies with the results of helioseismology.




## SOME CONCLUSIONS

* We have now a fairly good picture on sunspot structure and dynamics on scales down to 0".2.
* We have also some glimpses on the structure at 0".1.
* This knowledge gives a good input for modelling magnetoconvective and other dynamical processes in sunspots.
* Helioseismology is promissing in revealing sunspots' subsurface structure and needs further development.
* Cluster ("spaghetti") model of sunspots, supported by some results of helioseimology, needs a deeper elaboration.
* We still do not know exactly how sunspots are formed and what is the reason for the formation of penumbra.

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***Recommended review papers:***

Solanki, S.K., 2003, "Sunspots: An overview", The Astronomy and Astrophysics Review, 11, 153-286

Thomas, J.H. & Weiss, N.O., 2004, "Fine Structure in Sunspots", Annual Review of Astronomy and Astrophysics, 42, 517-548.