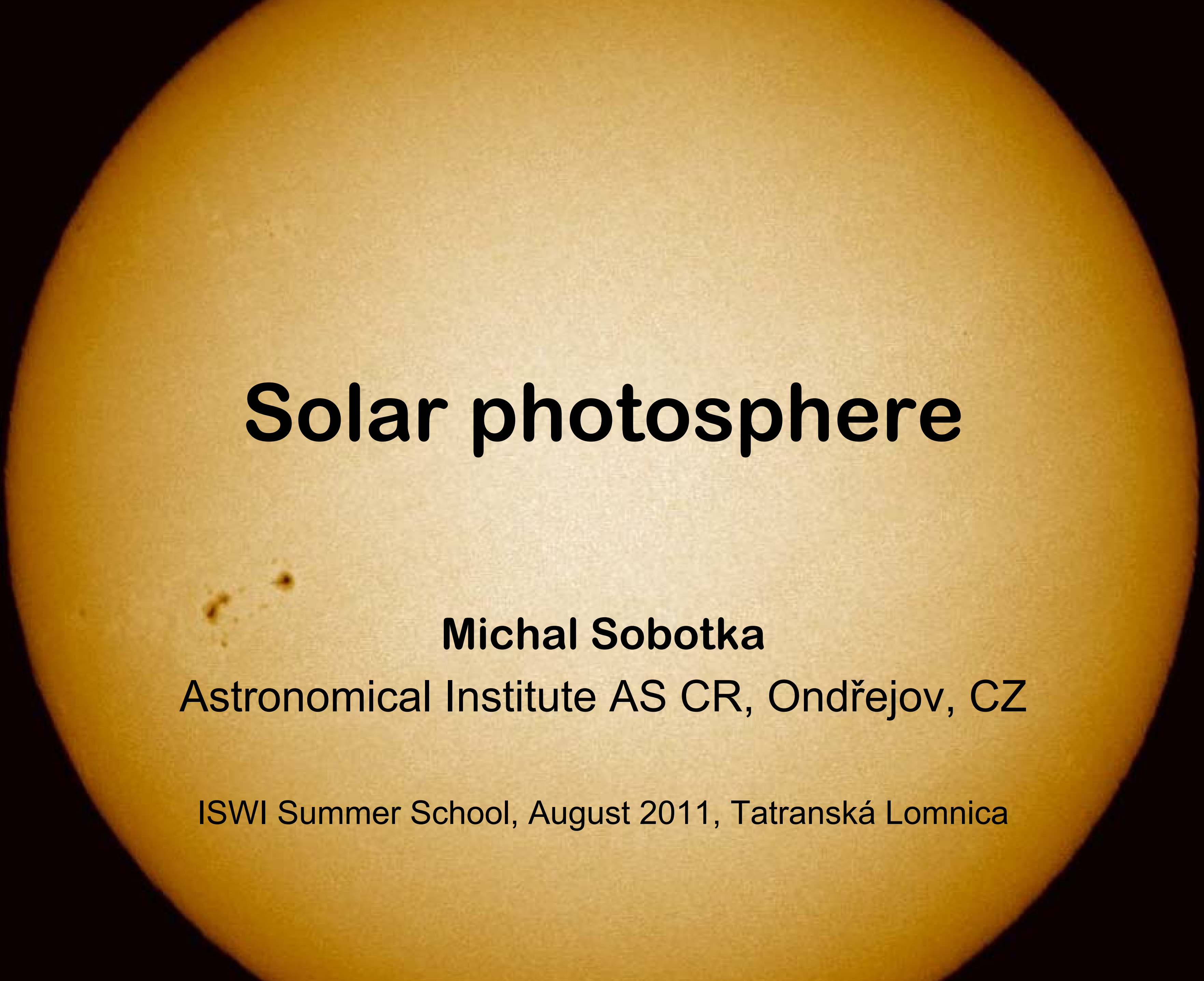

Solar photosphere

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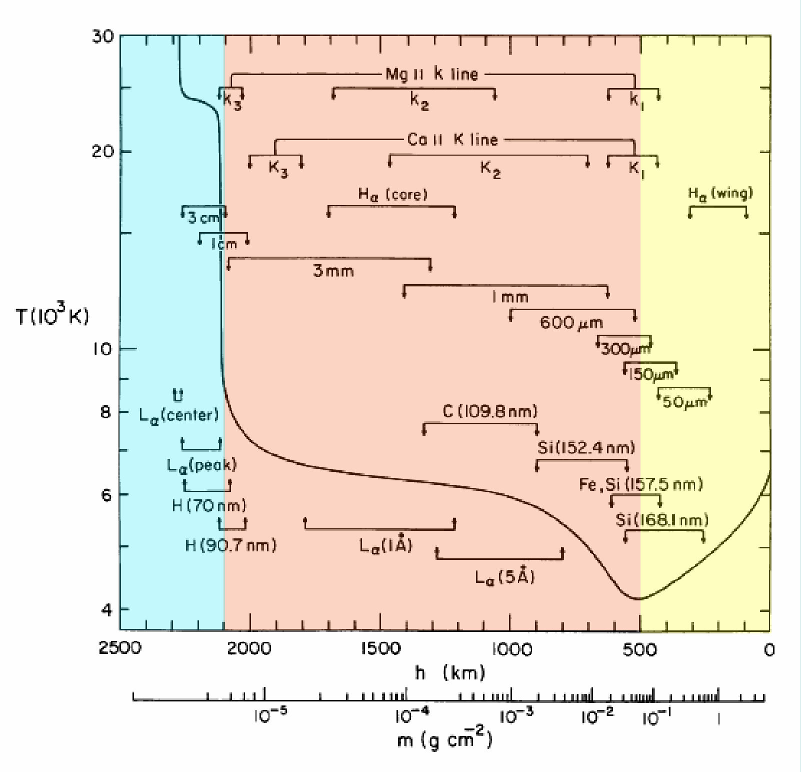
ISWI Summer School, August 2011, Tatranská Lomnica

Contents

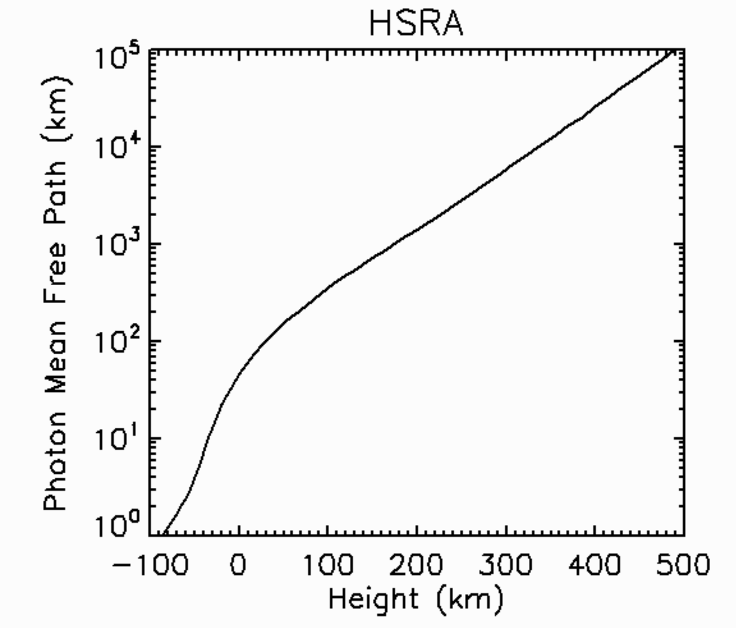
General characteristics

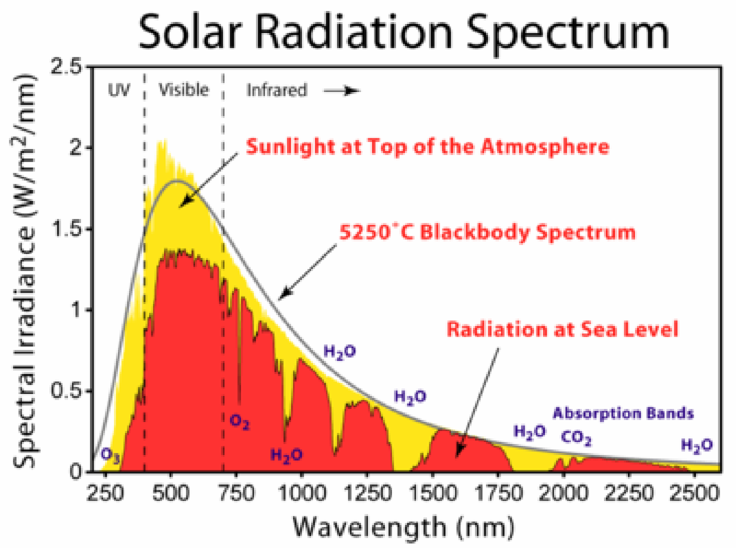
- The photosphere is the lowest part of the solar atmosphere, just above the convection zone.
- Its range is defined from $\tau_{500} = 1$ $(h = 0)$ at the bottom, to the temperature minimum at the top, so that it is about 500 km high.
- The temperature decreases with height from 6500 to 4200 K
- The density decreases from $2.7\text{x}10^{-3}$ to $4.9\text{x}10^{-6}$ kg m^{-3}



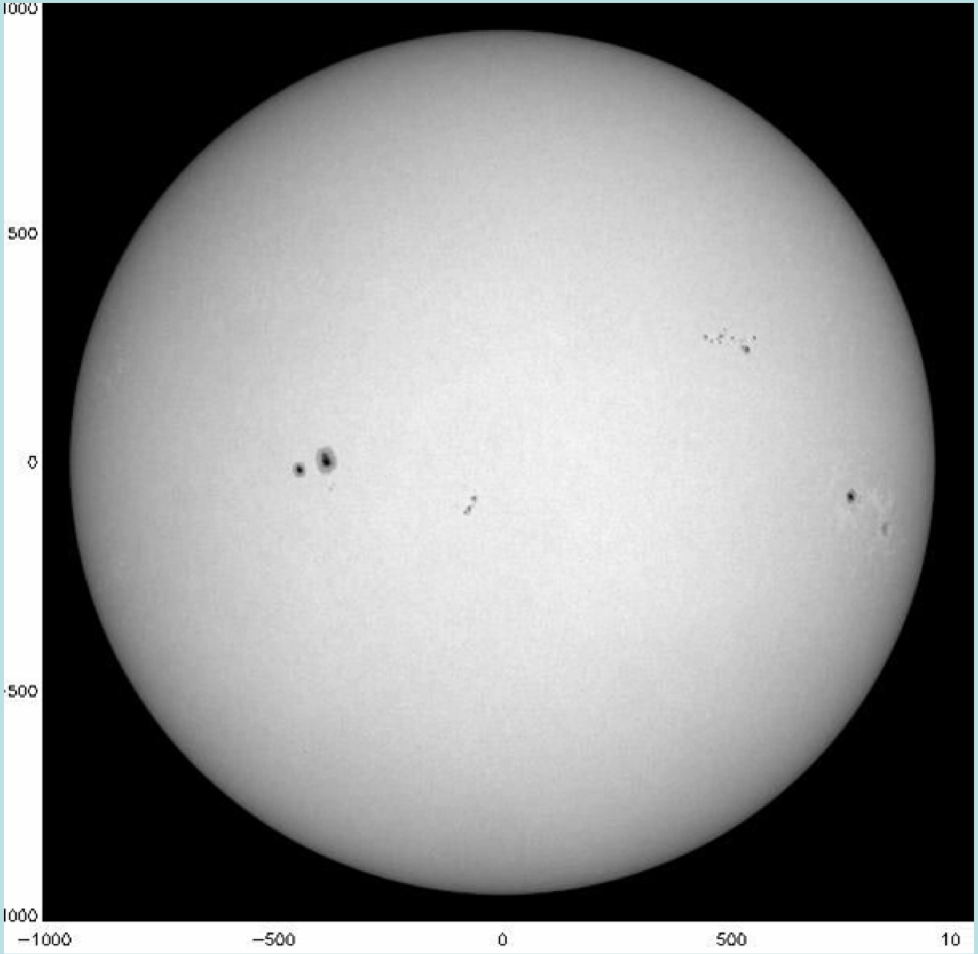
VAL 3C model (Vernazza, Avrett, Loeser, 1981)

- **The photon mean free path $= (\kappa_{500}\,\rho)^{-1}$ increases from 1 to > 100 km at the bottom of the photosphere.**
- **The energy is transferred by radiation and the convection is stopped.**
- **The continuum radiation is mostly formed by *b-f* and *f-f* transitions of the negative hydrogen ion H^-.**
- **It is very similar to the black body radiation with a maximum at $\lambda = 500$ nm.**





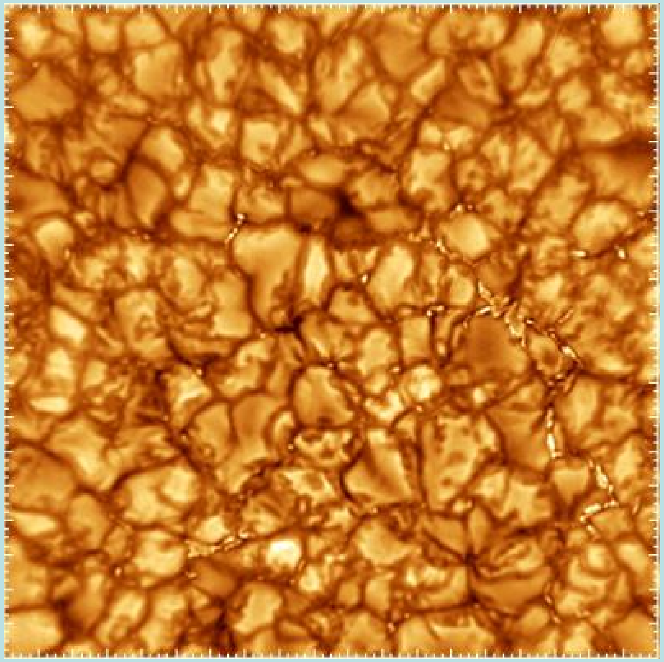
Structure

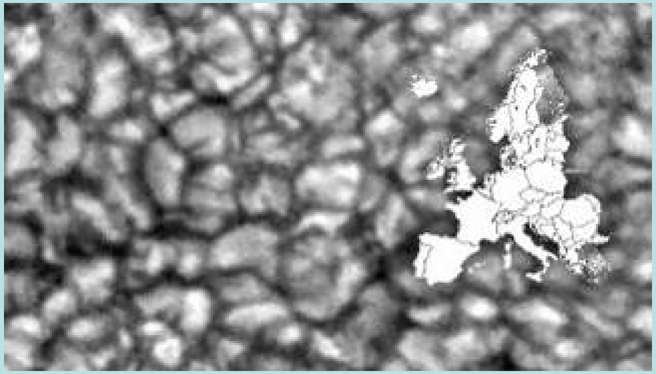


Granulation

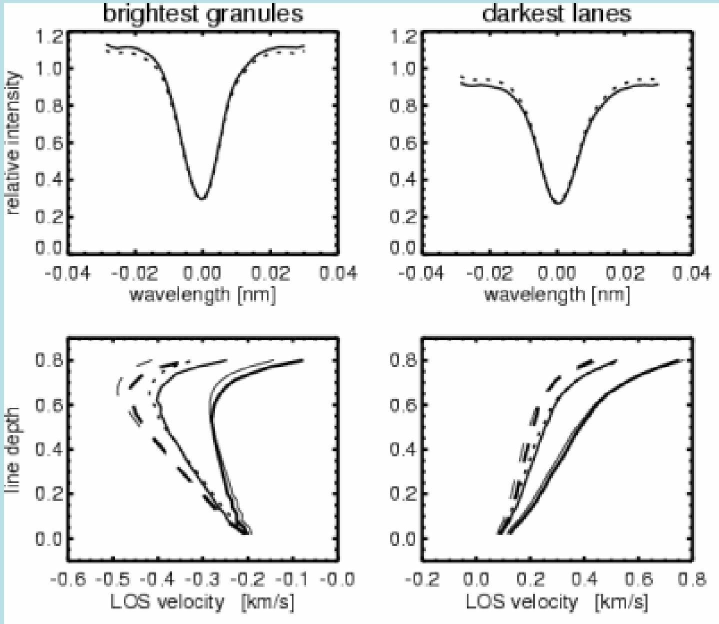
- Granules are produced by convection at the top of the convection zone.
- Size: 300–1800 km (0.4"–2.5")
- Max. area contribution by granules with size 1000 km (1.4")
- Smaller granules have a turbulent origin.
- Mean brightness of large granules: 1.1 (of the mean photospheric brightness)
- Intergranular lanes:
  width < 300 km, brightness 0.9

Image NST/BBSO

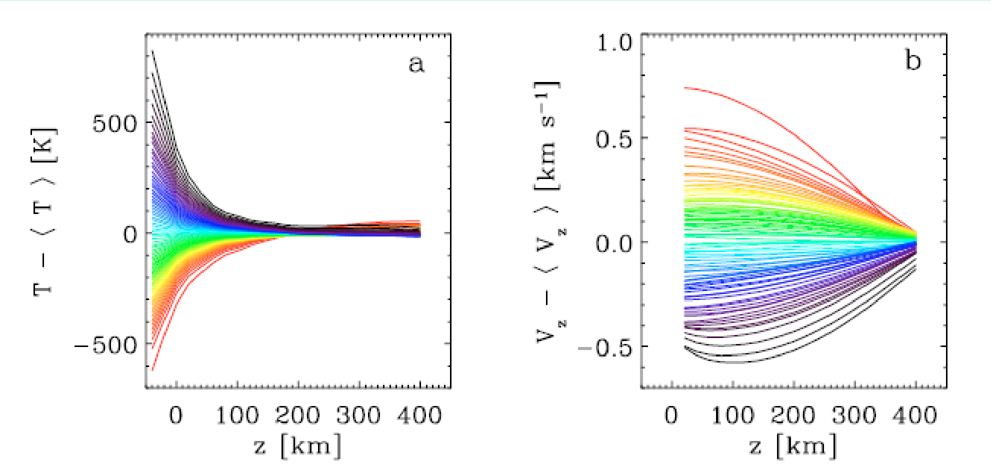




- **Line profiles in granules and intergranular lanes are asymmetric due to vertical motions (upflows in granules, downflows in intergranular lanes)**
- **Temperature difference between granules and intergranular lanes: 1000 K at h = 0; ~ 0 at h ≥ 170 km; negative at h > 300 km ("reverse granulation")**
- **Velocity differences:**
  1.4 km/s (maximum) at h ~ 50 km;
  0.4 km/s at h = 400 km

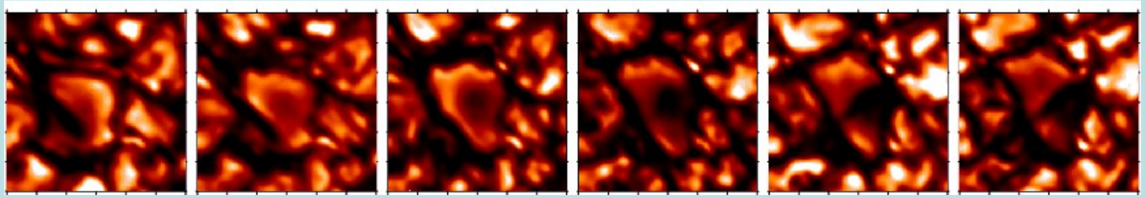


Mikurda et al. 2006



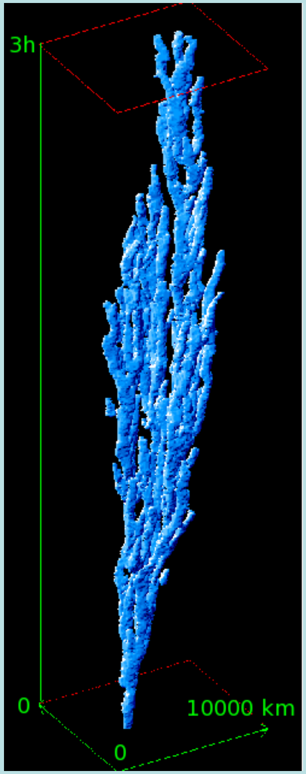
Puschmann et al. 2005

- **Lifetime: Number of granules decreases exponentially with lifetime ($N \sim \exp(-T/\tau)$), $\tau = 6$ min; maximum lifetime ~ 25 min.**
- **Typical life cycle: Birth (80% from a fragment) → growth → fragmentation (30%) or merging with other granules (50%)**
  (Hirzberger et al. 1998)
- **Exploding granules: Large granules develop a dark centre with a downflow and then fragment.**

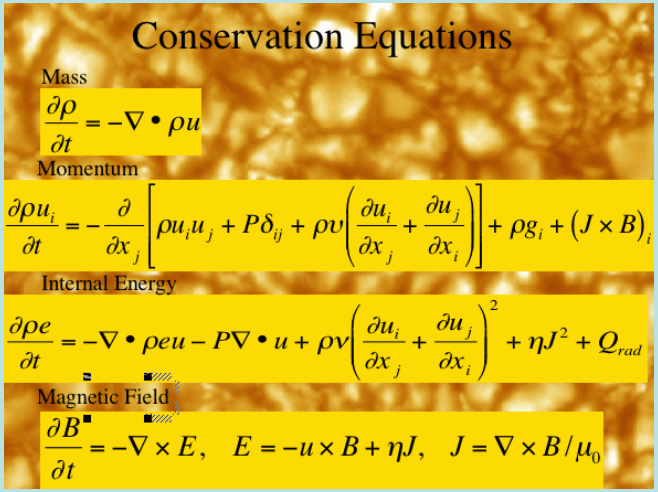


Hirzberger et al. (2001). Time step 70 s.

- **A repeated fragmenting of granules forms long-lived (hours) "families" of granules originating from a single granule.**
  (Roudier et al. 2003)



- **Numerical simulation of granulation**
- **Ingredients:**
  - **Equations for conservation of mass, momentum, internal energy, and magnetic field**
  - **Equation of state, including ionization**
  - **Radiative transfer**
  - **Diffusion**
  - **Boundary conditions**
- **Computational domain includes a part of convection zone and photosphere (e.g. 40x40x20 Mm).**



Conservation Equations

Mass

$$\frac{\partial \rho}{\partial t} = -\nabla \bullet \rho u$$

Momentum

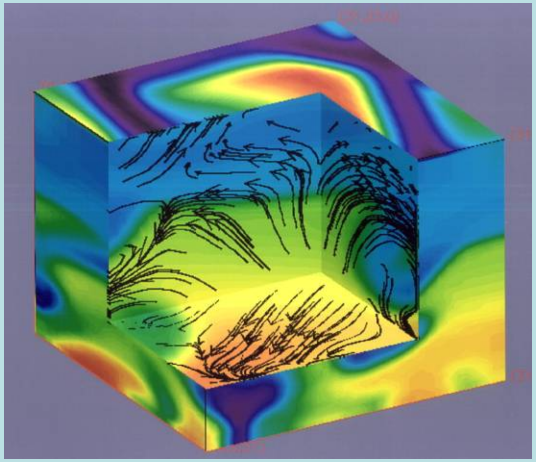
$$\frac{\partial \rho u_i}{\partial t} = -\frac{\partial}{\partial x_j}\left[\rho u_i u_j + P\delta_{ij} + \rho\upsilon\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\right] + \rho g_i + (J \times B)_i$$

Internal Energy

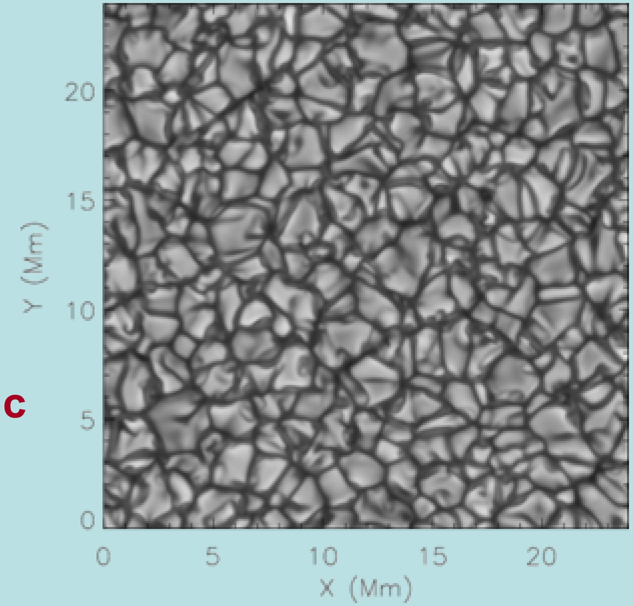
$$\frac{\partial \rho e}{\partial t} = -\nabla \bullet \rho e u - P\nabla \bullet u + \rho\upsilon\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)^2 + \eta J^2 + Q_{rad}$$

Magnetic Field

$$\frac{\partial B}{\partial t} = -\nabla \times E, \quad E = -u \times B + \eta J, \quad J = \nabla \times B / \mu_0$$



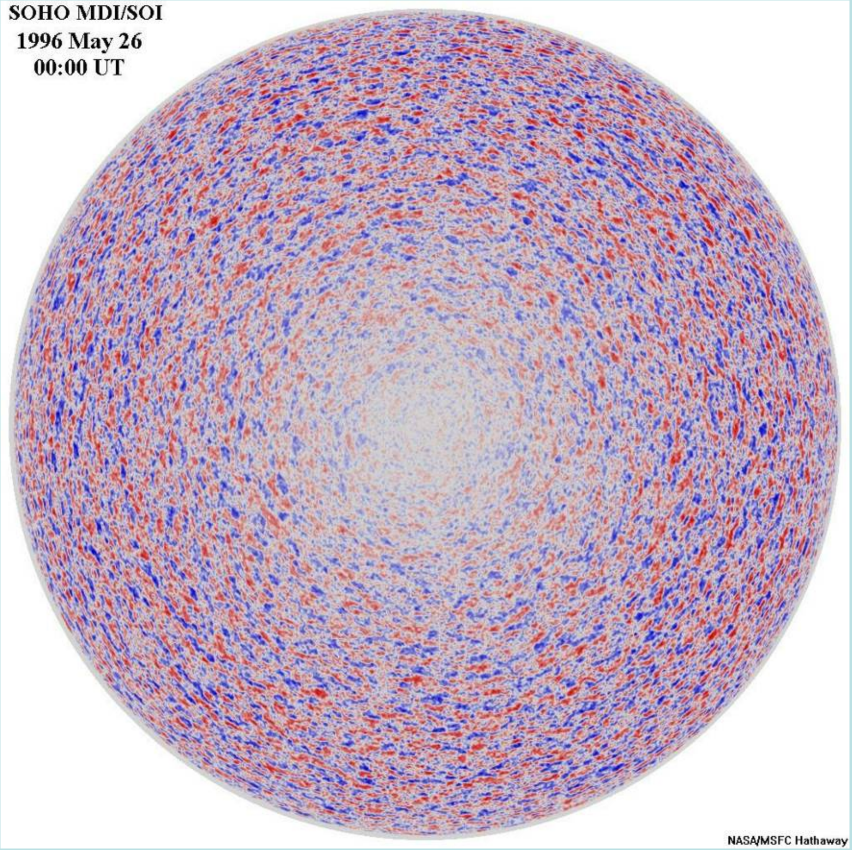
Stein & Nordlund (1998)



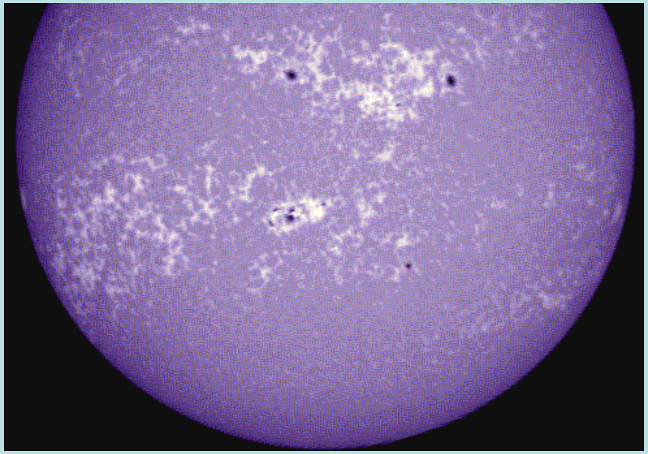
Simulated bolometric brightness (Matloch et al. 2010)

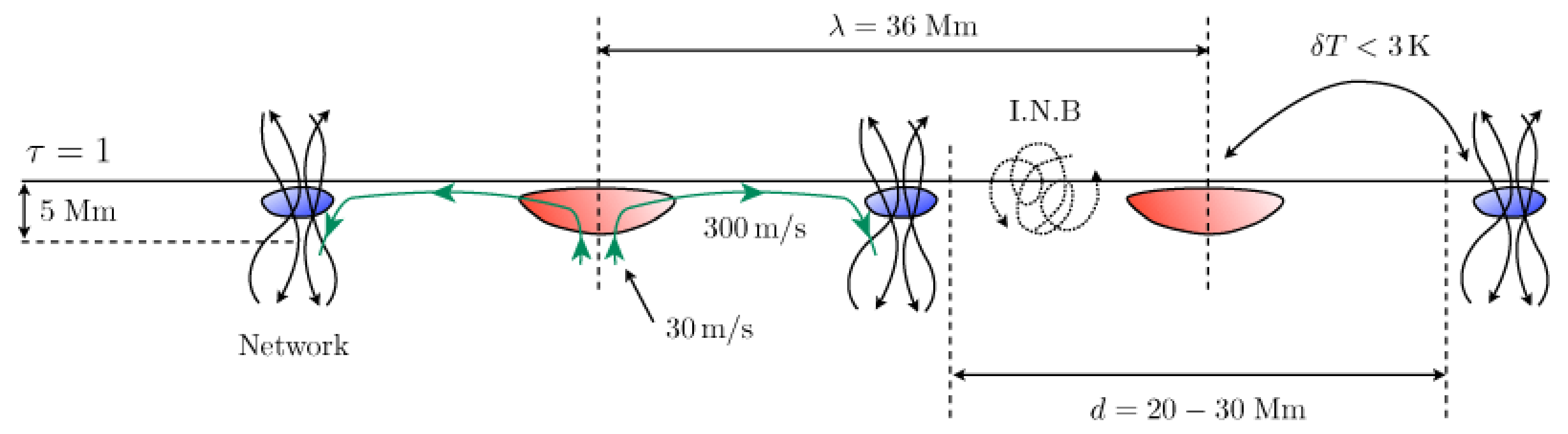
Supergranulation

- **A Doppler velocity pattern showing horizontal motions (200–300 m/s) in the photosphere. No intensity signature is observed.**
- **Typical size of a supergranule is 20–30 Mm, depth ~ 5 Mm (obtained by helioseismology), lifetime ~ 40 hours.**
- **Supergranules are expected to be produced by a large-scale convection, but the mechanism is not clear yet.**



- **Magnetic elements are advected to borders of supergranules and produce the chromospheric network seen in Ca II filtergrams.**

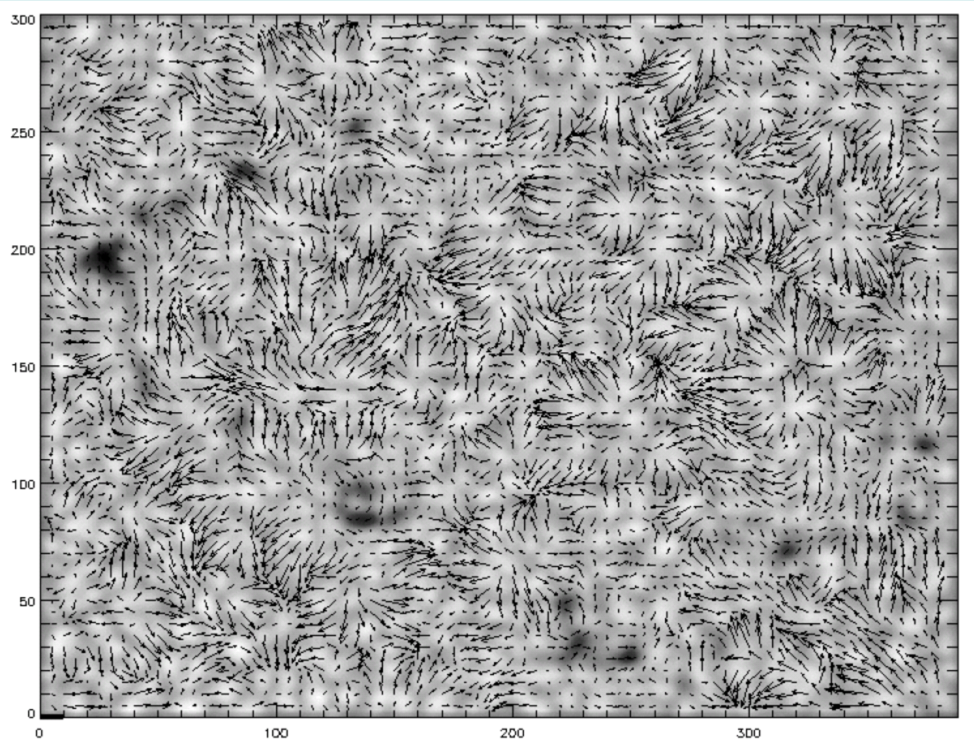




Supergranulation scheme by Rieutord & Rincon (2010), `www.livingreviews.org`

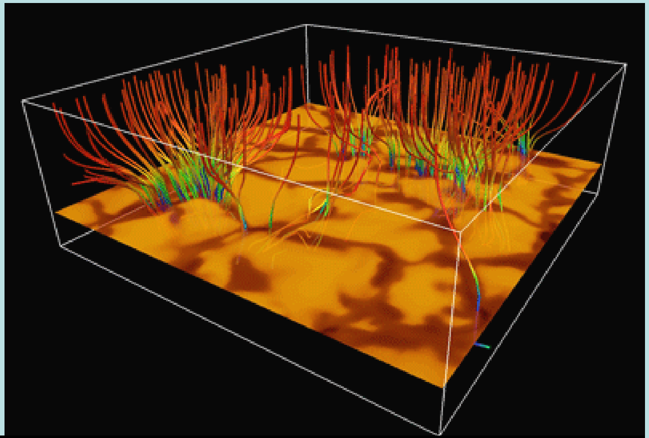
Mesogranulation

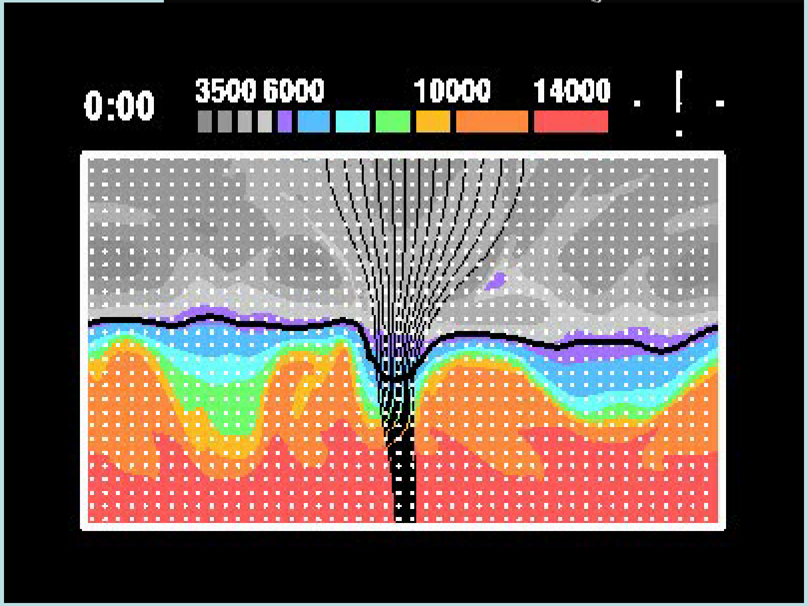
- Patterns of horizontal flows observed on scales between granulation and supergranulation.
- No typical size and lifetime are found.
- There is a discussion if mesogranules represent a distinct convective scale or if they are a mere signature of exploding granules and their families.



A flow map obtained by tracking horizontal motions of granules during 1 hour. (Sobotka et al. 2000)

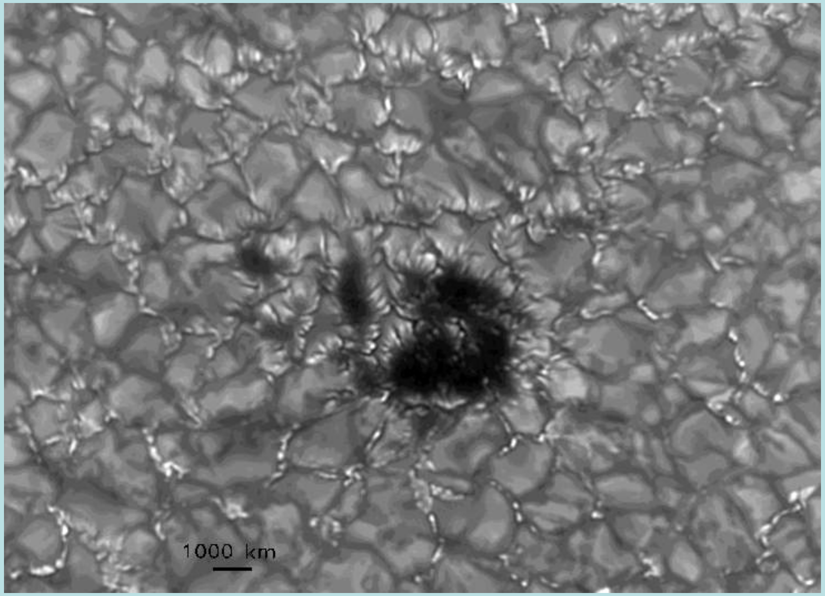
Small-scale magnetic field

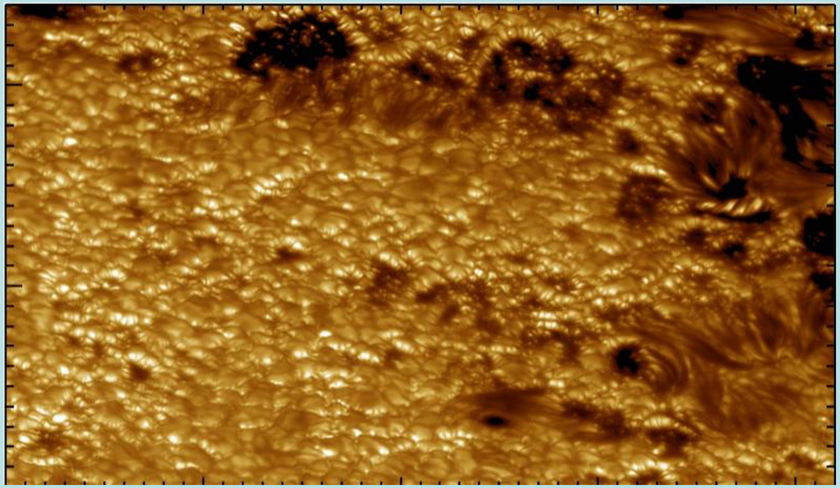




- Magnetic flux, with mixed polarity, continually emerges throughout the quiet Sun (local dynamo action).
- Diverging upflows in granules sweep magnetic flux to intergranular lanes, where it encounters existing magnetic flux with which it either cancels or augments.
- Intense (kG) vertical fields accumulate in the intergranular lanes. Resulting small-scale flux tubes are highly dynamical.

- **Flux tubes are associated with small-scale bright points visible in the continuum and especially in CH *G*-band.**
- **In the flux tubes, the opacity is reduced and we see deeper.**
- **Thin tubes are heated laterally from the hot walls of adjacent granules. Wider tubes are optically thick, cooler, and appear dark, as micropores.**
- **Near the limb, bright sides of granules are visible through the transparent flux elements, giving rise to faculae.**

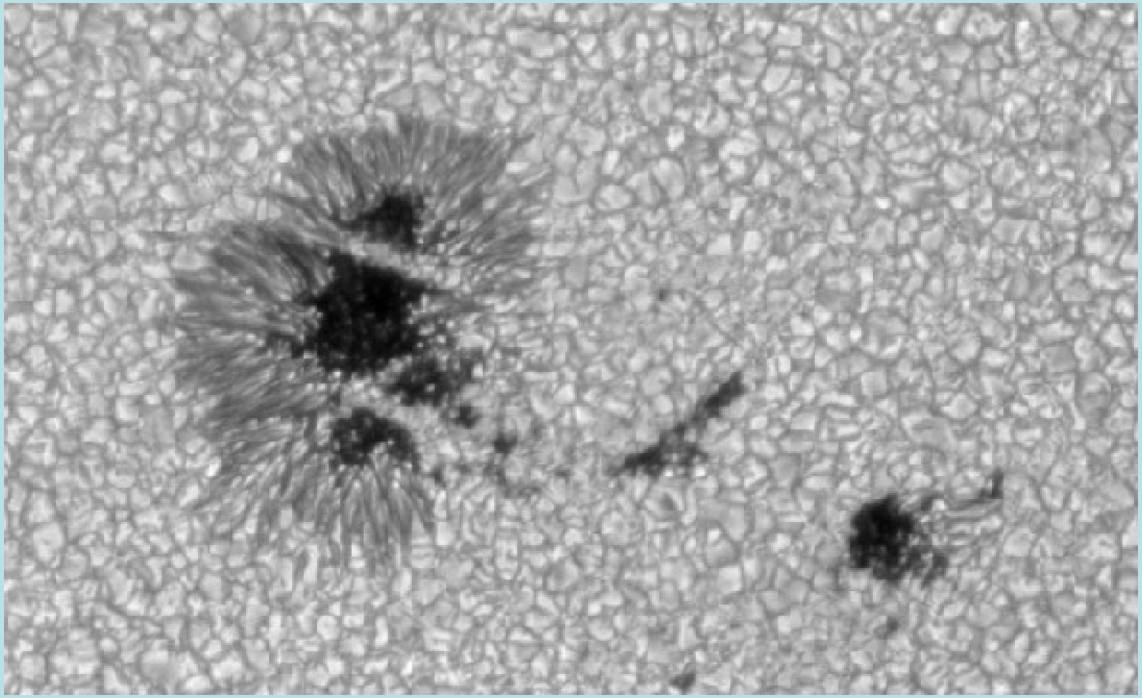




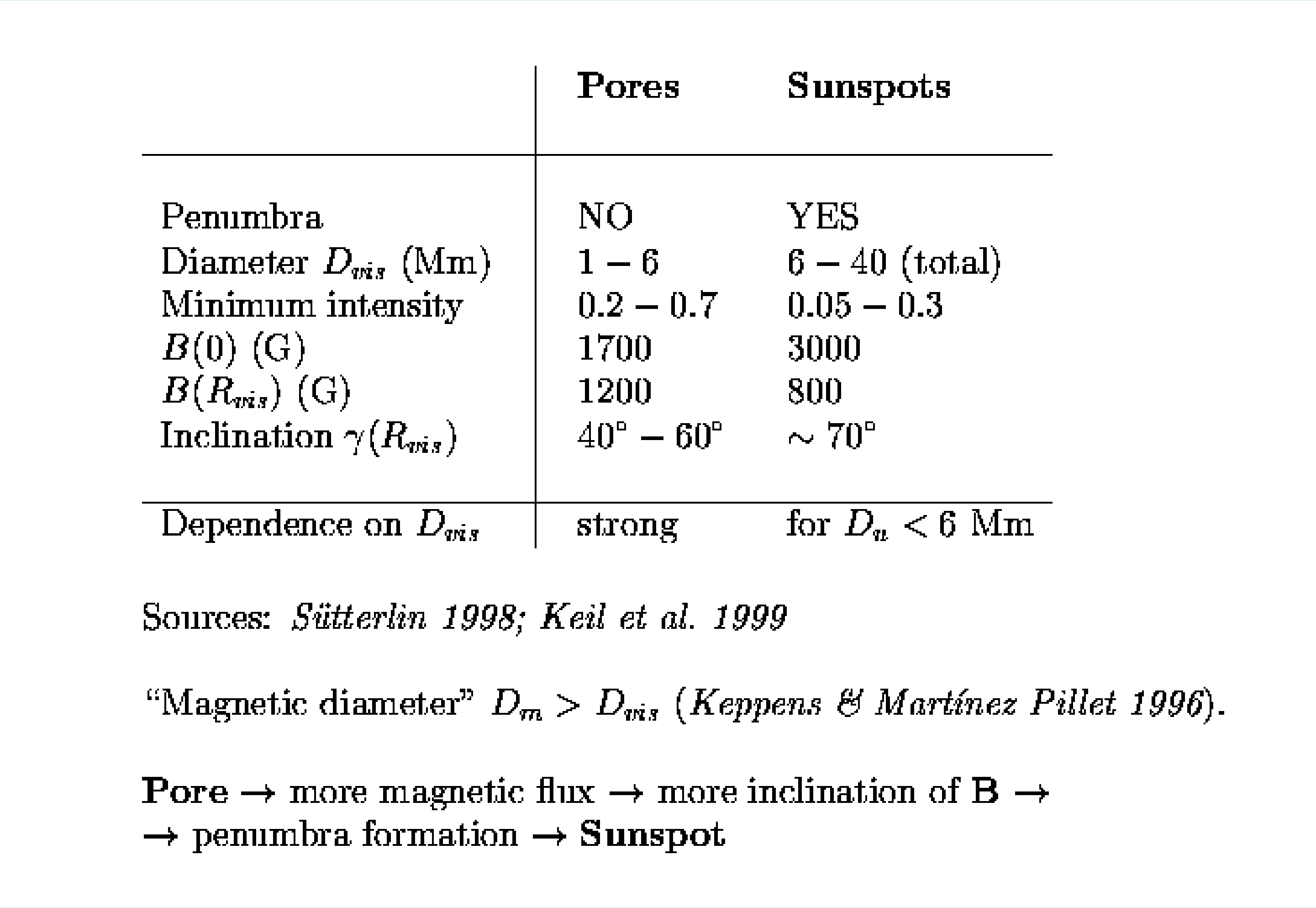
Images SST, La Palma

Sunspots and pores

- The most important solar activity phenomena in the photosphere
- Strong magnetic field reduces the convective energy transfer, giving rise to dark areas with temperature reduced by 2000 K.



General characteristics

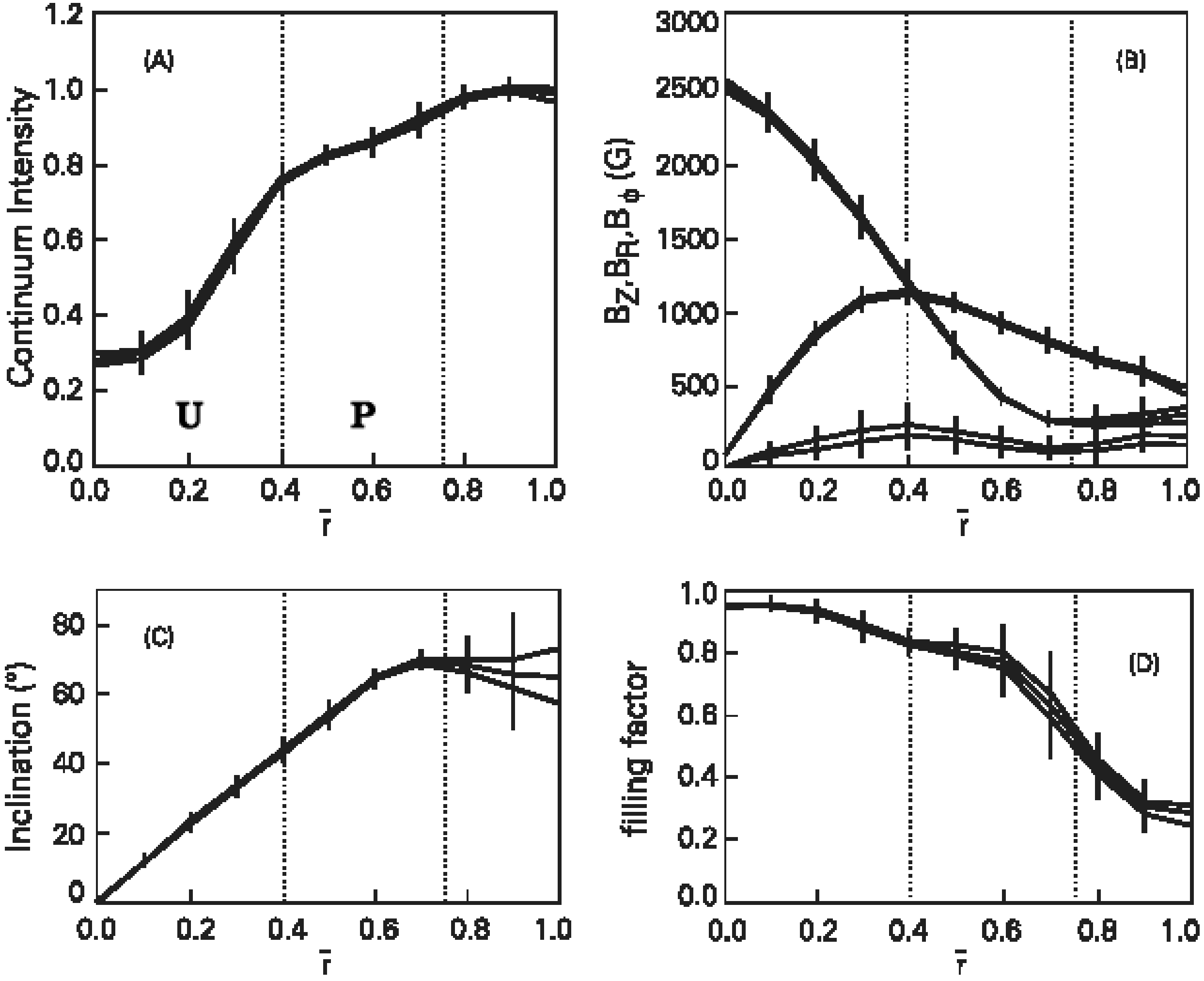


	Pores	**Sunspots**
Penumbra	NO	YES
Diameter D_{vis} (Mm)	$1-6$	$6-40$ (total)
Minimum intensity	$0.2-0.7$	$0.05-0.3$
$B(0)$ (G)	1700	3000
$B(R_{vis})$ (G)	1200	800
Inclination $\gamma(R_{vis})$	$40^\circ-60^\circ$	$\sim 70^\circ$
Dependence on D_{vis}	strong	for $D_u < 6$ Mm

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

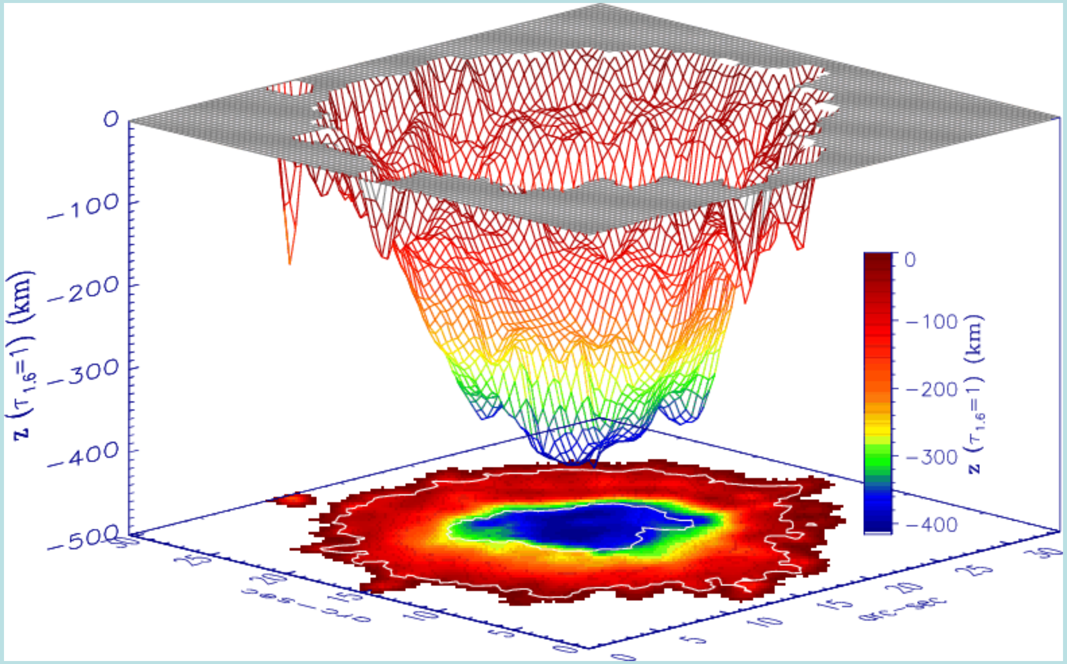
"Magnetic diameter" $D_m > D_{vis}$ (*Keppens & Martínez Pillet 1996*).

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



Magnetic field distribution (Keppens & Martínez Pillet 1996)

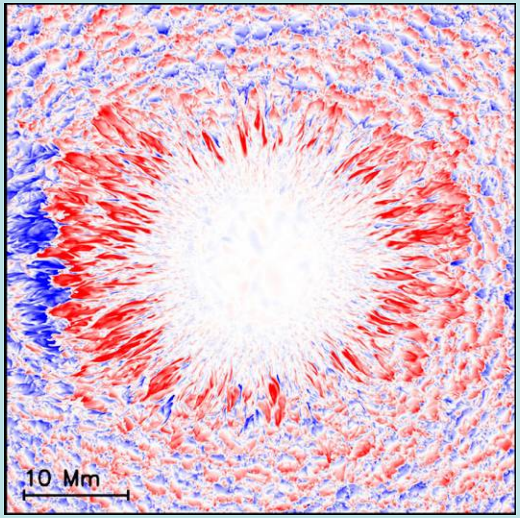
- **Approximately, sunspots are in a mechanical equilibrium with their field-free surroundings:** $P_{\mathrm{spot}}(z) = B^2(z)/2\mu + P_{\mathrm{ext}}(z)$.
- **Since the gas pressure and temperature in the sunspot are reduced, the opacity is also reduced and the** $\tau = 1$ **level inside the spot is lower that that in the surrounding photosphere.**
- **This effect is called Wilson depression.**



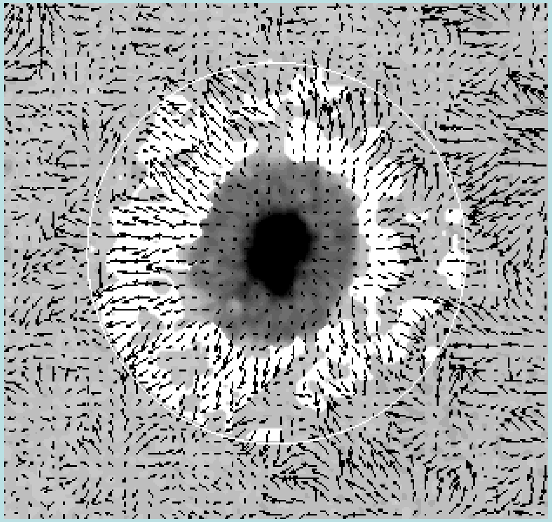
Mathew et al. 2004

Flows associated with sunspots

- **Evershed effect: radial flow of gas (1–2 km/s) in the penumbra, directed outwards.** (Evershed 1909)
- **Moat flow: horizontal motion (0.5–1 km/s) of granules and magnetic elements in an annular region (moat) around sunspots with the penumbra.** (Sheeley 1969)



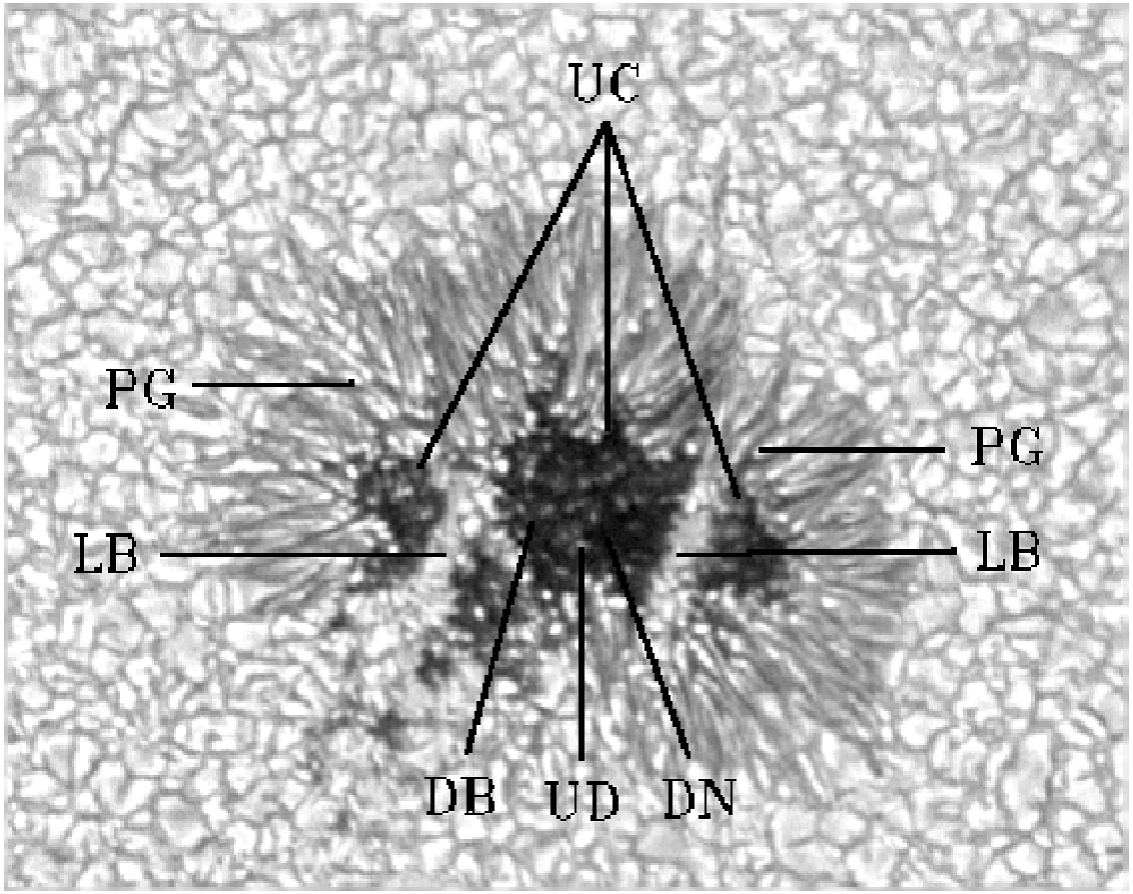
Evershed flow (red) simulated by Rempel et al. (2011)



Moat flow observed by Sobotka & Roudier (2007)

Fine structure of sunspots

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

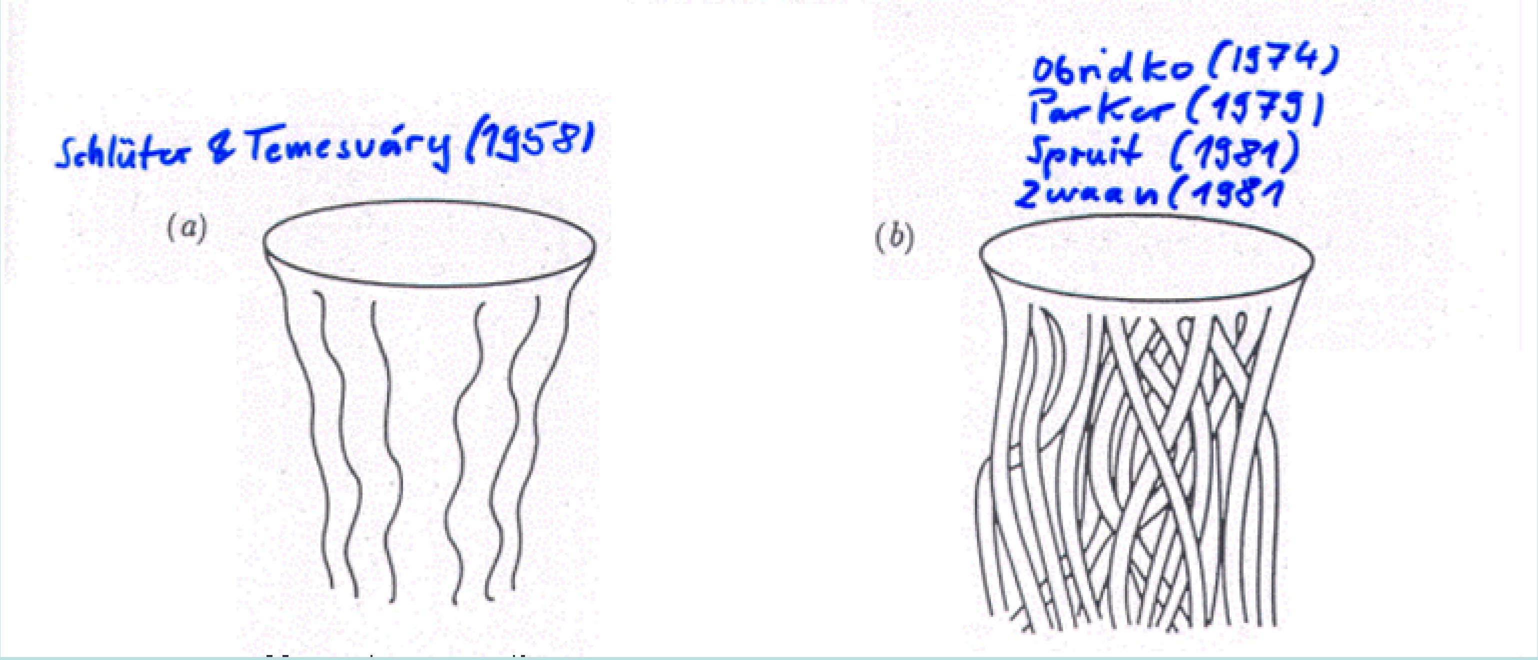


The umbra

Two possible models of the umbral magnetic structure:

- Monolithic flux tube with magnetoconvection
- Bundle of thin flux tubes (spaghetti model)

Observed fine structures can be explained by both models.



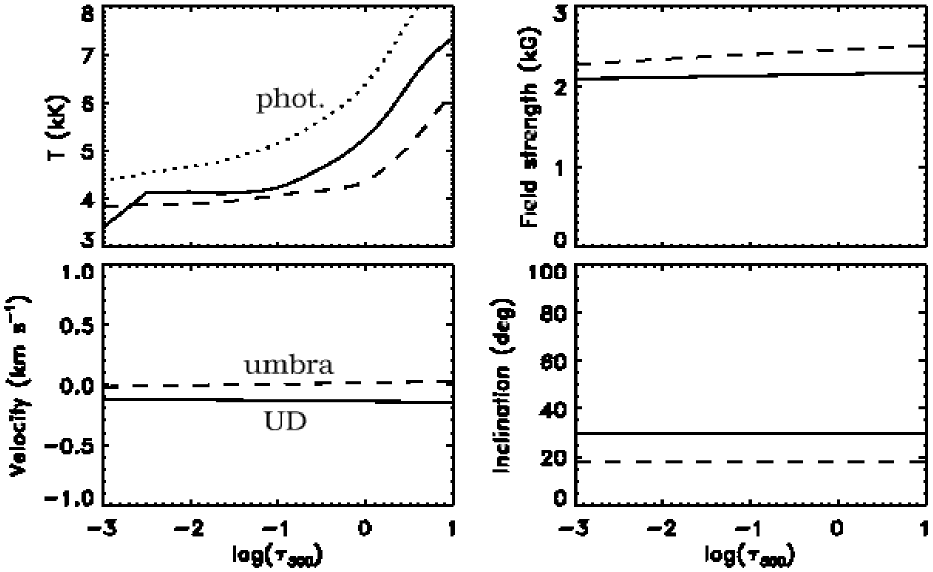
Schlüter & Temesváry (1958)

Obridko (1974)
Parker (1979)
Spruit (1981)
Zwaan (1981

Umbral dots

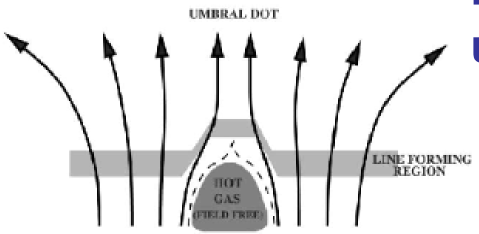
Small (~ 100 km) bright features appear inside the umbra as a consequence of magnetoconvection (monolithic flux tube model) or penetration of hot gas (spaghetti model).

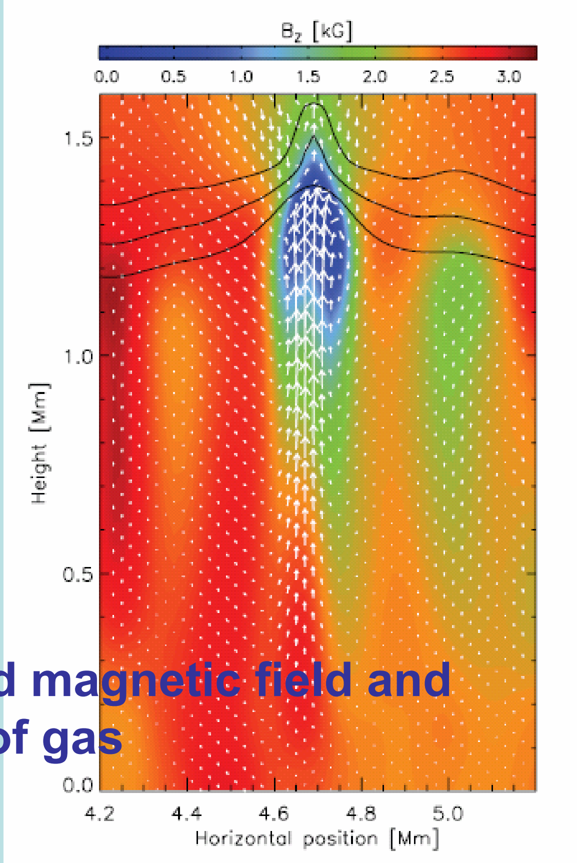
Models: **semiempirical ↓** **numerical simulation →**



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

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



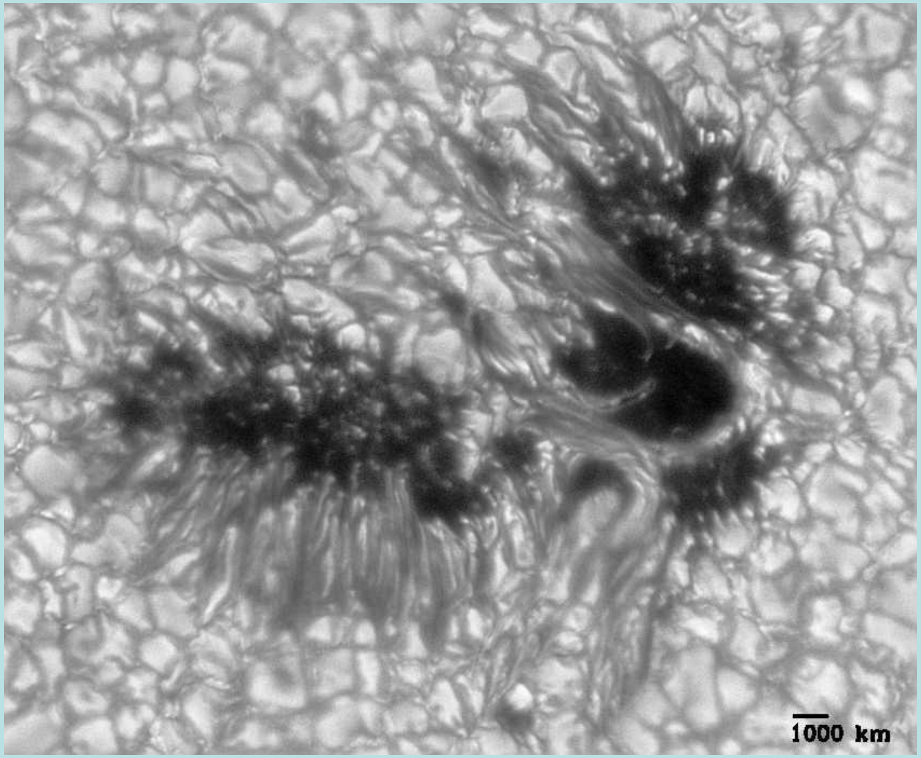


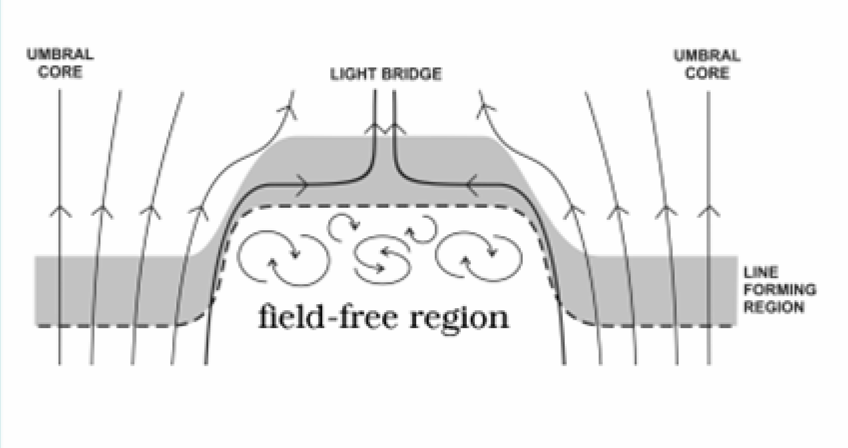
Reduced magnetic field and upflow of gas

Schüssler & Vögler (2006)

Light bridges

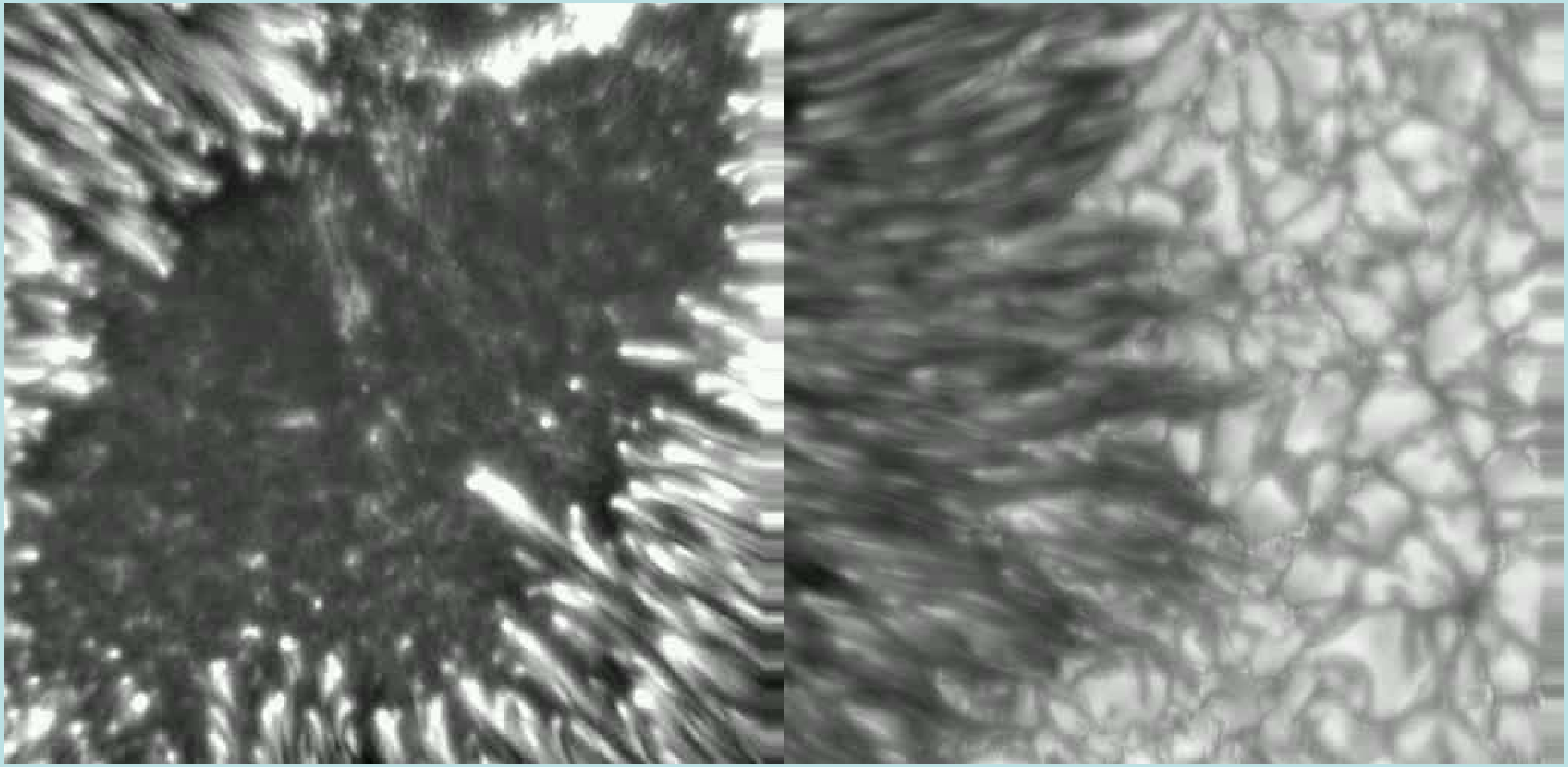
Bright elongated structures of different width with granular or filamentary structure. They separate umbral cores or intrude into the umbra. Light bridges are deep convective features with strongly reduced magnetic field and vertical gas motions.





Magnetic canopy above a light bridge (Jurčák, Martínez Pillet, & Sobotka 2006)

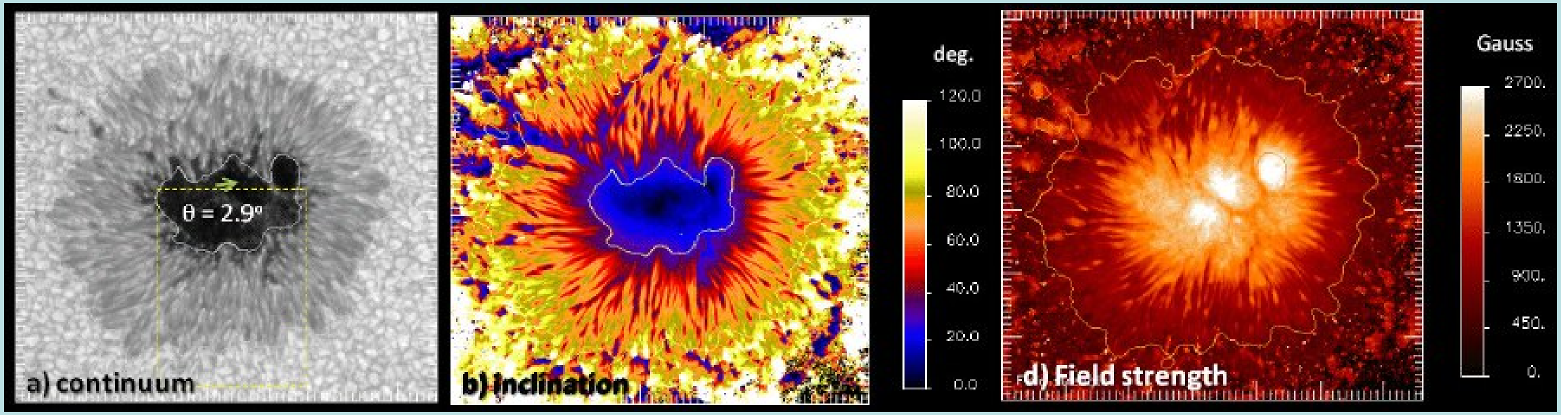
Sunspot structure dynamics



SST, La Palma, 2004; 90 minutes real time, 269 frames
Speed of the motions in the umbra ~ 400 m/s

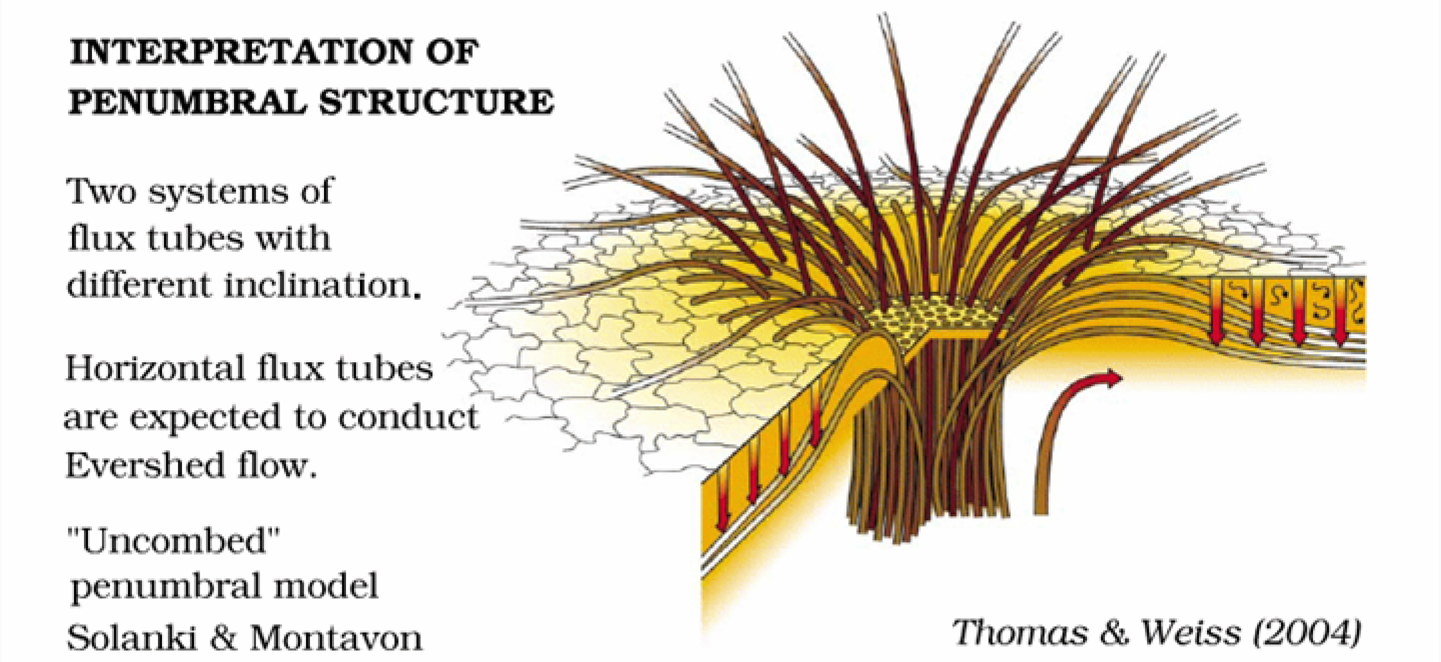
The penumbra

- **Filamentary structure, composed of bright and dark filaments. Penumbral grains move along the bright filaments.**
- **The magnetic field has also a filamentary structure, which is not completely correlated with the intensity structure:**
- **Spines – stronger and more vertical magnetic field; correlated with bright filaments in outer penumbra**
- **Intraspines – weaker and more horizontal field, containing the Evershed flow. Correlated with bright filaments in inner penumbra and dark filaments in outer penumbra.**



Borrero & Ichimoto (2011)

- **There are two systems of magnetic flux tubes in the penumbra: a more vertical in spines and nearly horizontal in intraspines. “Uncombed magnetic field” (Solanki & Montavon, 1993)**



INTERPRETATION OF PENUMBRAL STRUCTURE

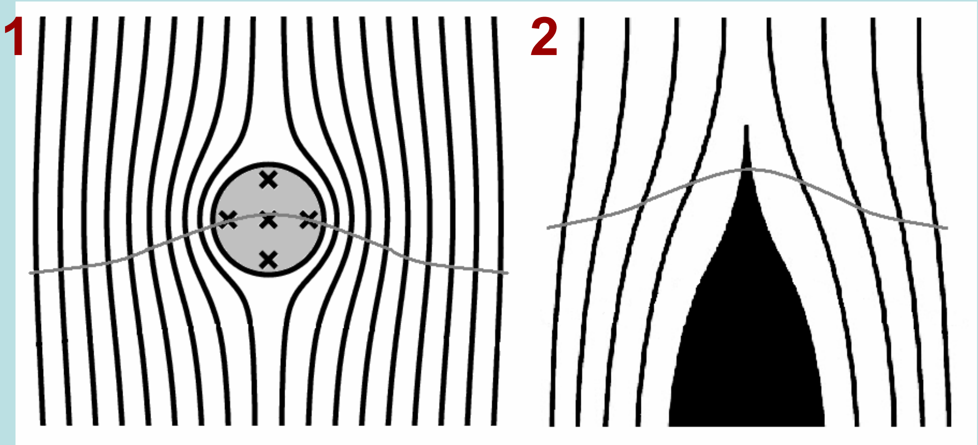
Two systems of flux tubes with different inclination.

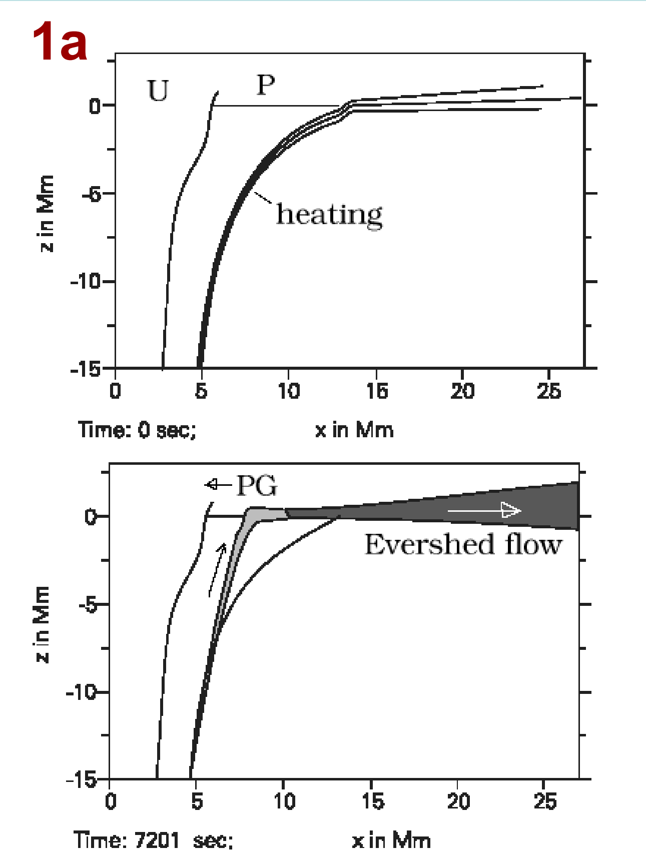
Horizontal flux tubes are expected to conduct Evershed flow.

"Uncombed" penumbral model
Solanki & Montavon

Thomas & Weiss (2004)

Two possible models of penumbral magnetic structure





Rising flux-tube model

Schlichenmaier et al. 1998

(1) Embedded flux-tube model

(Solanki & Montavon, Schlichenmaier)

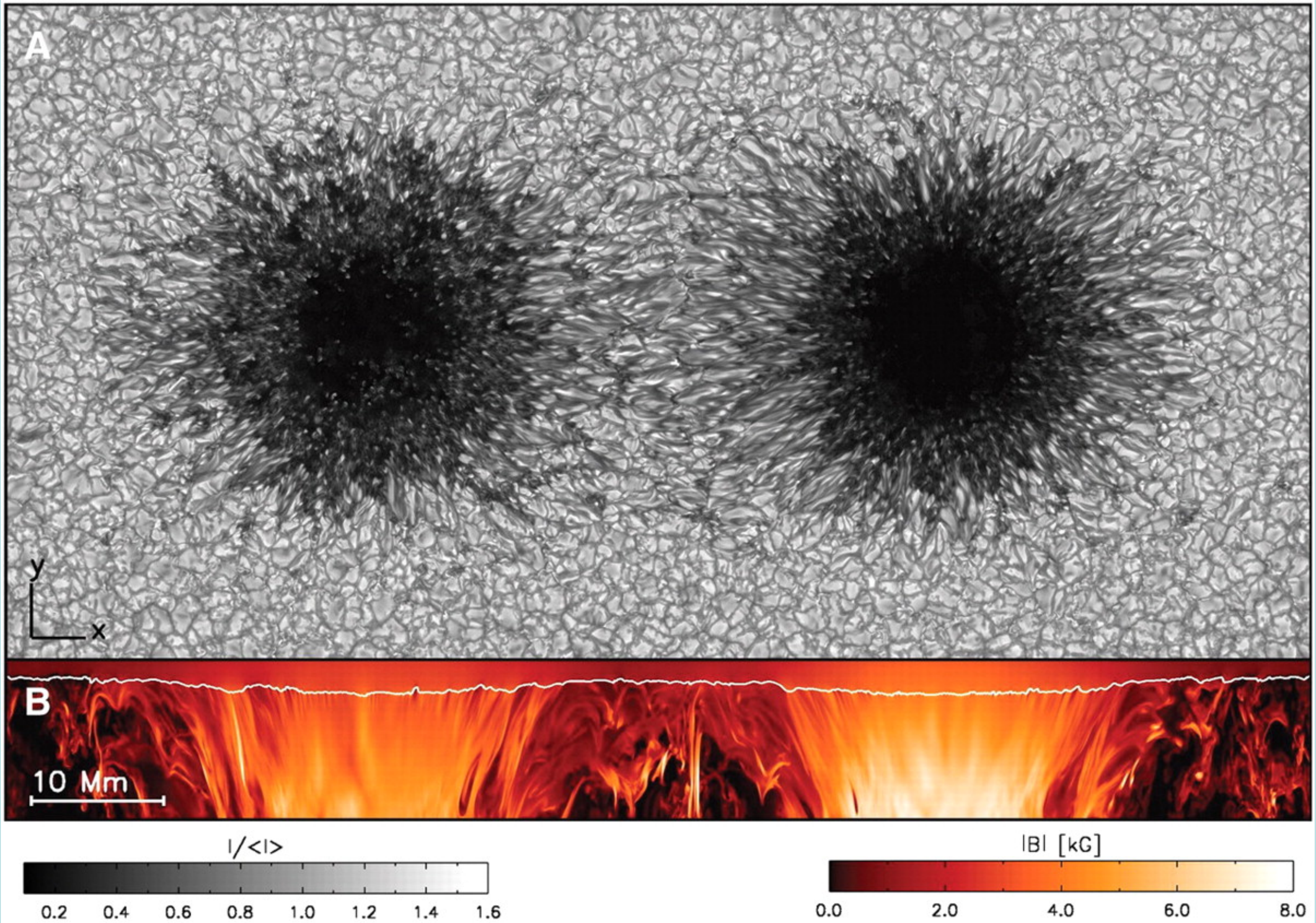
explains the Evershed flow and the motion of penumbral grains

(2) Field-free gap model

(Spruit & Scharmer 2006)

Convection in radially directed gaps explains the penumbral brightness.

Numerical simulation of sunspots



Rempel et al., 2009, Science, 325:171-174

Conclusions

- From the photosphere we receive information about the subsurface convection and magnetic field, important to explain effects in the chromosphere and corona.
- In the photosphere we can study interactions between moving dense plasma and strong (10^2 – 10^3 kG) magnetic field.
- These interactions produce phenomena on spatial scales from 10^1 to 10^4 km.
- High spatial resolution is necessary to observe the photosphere. The following instruments are most appropriate:

HINODE satellite	180 km resolution
SST La Palma	90 km
NST/BBSO and GREGOR	60 km
ATST and EST in future	25 km

Thanks for attention

☺