Single sunspot fine structures and dynamics
from SOT (Hinode) and AIA (SDO) observations

by

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Why Single Sunspots? ---> dynamo MHD "models" !

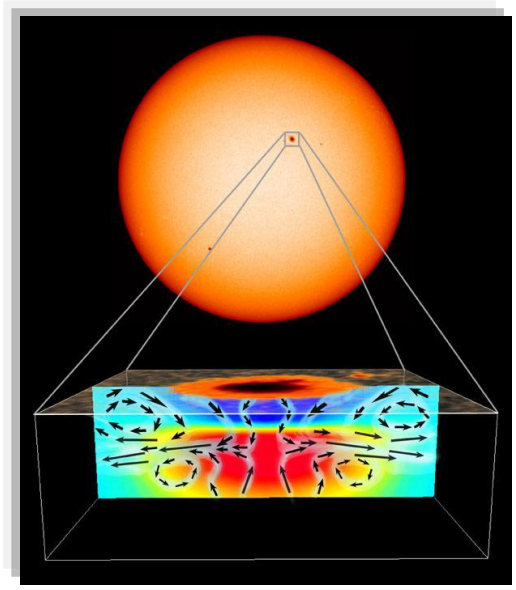
Larmor (1919) was the 1st to suggest that sunspots are due to a **self- excited dynamo**

Never perfectly axi- symmetric (Cowling 1936)

Alfven (1951) suggested they are the result of a **rising ring current or whirls**

He also suggested the relationship

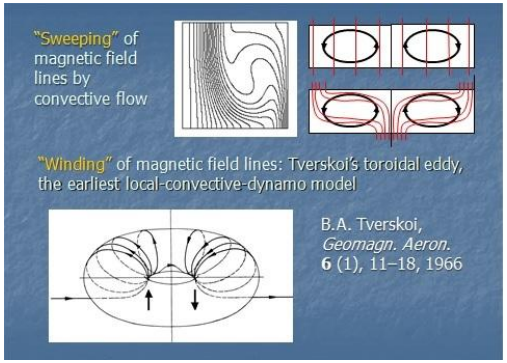
T° ↘ leads to B ↗



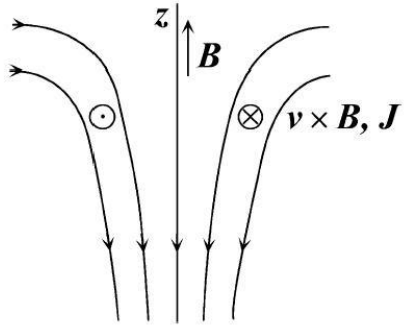
Indication of a converging flow around a sunspot

from MDI (SoHO) data/ Time- distance heliosismo

J. Zhao, A.G. Kosovichev, T.L. Duvall, Jr. 2001



also: toroidal eddy



Sketch of a self- excited dynamo in non- ideal MHD

Lorrain and Koutchmy 1998

The problem is that converging <u>inward flows</u> are needed to stabilize the system and sustain the central magnetic field although an Evershed outflow is observed and further out, a super- penumbra moat outflow

Indeed, the development of convective instability in a uniform magnetic field along gravity force and axi- symmetric converging flow leads to the formation of sunspots (MHD analytic model + numerical solutions)

A theoretical analysis with a numerical simulation of the development of nonlinear axisymmetric convective instability in a homogeneous magnetic field directed along the gravity force shows i) the development of instability leading to the concentration of the magnetic field ii) a decrease of temperature in the vicinity of the axis of symmetry. This is suggested as a possible mechanism for the formation of sunspots.

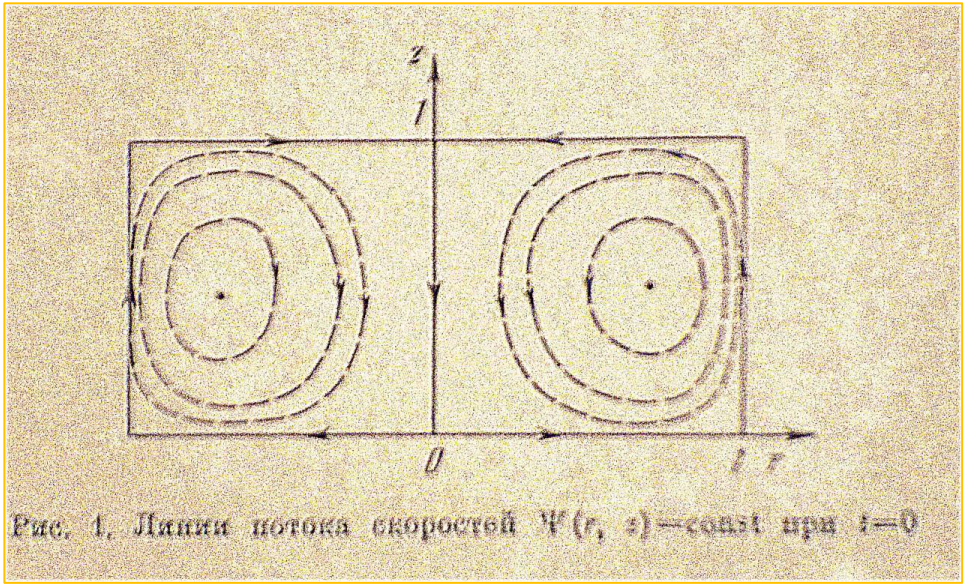
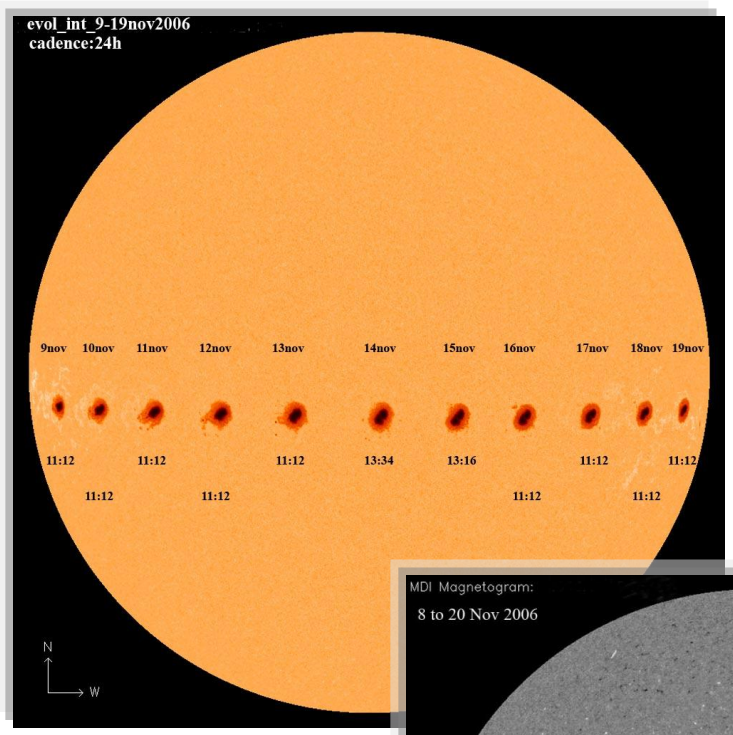
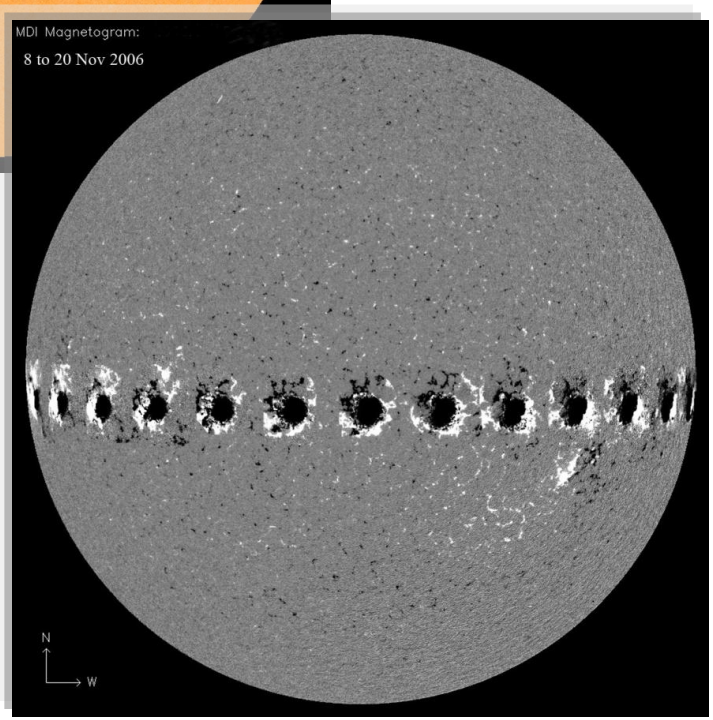


Рис. 1. Линии потока скоростей $\Psi(r, z) = \text{const}$ при $t=0$

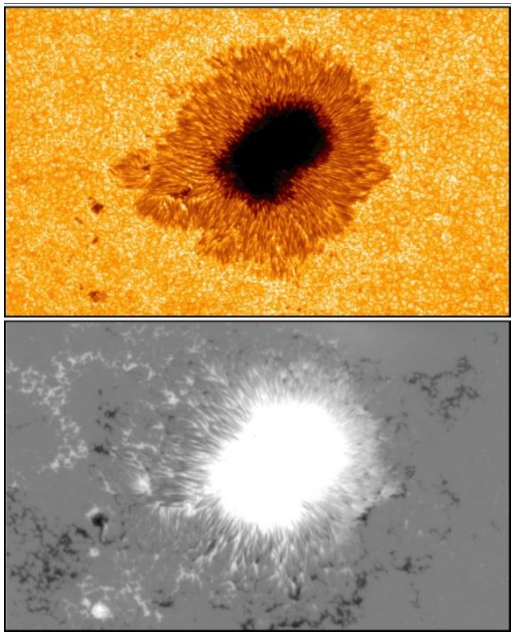
*from Gerlakh, N. I.; Zueva, N. M. and **Solov'ev, L. S.***
In Fizika Plazmy, vol. 7, Jan.-Feb. 1981, p. 177-184

Single sunspots are excellent prototype to study





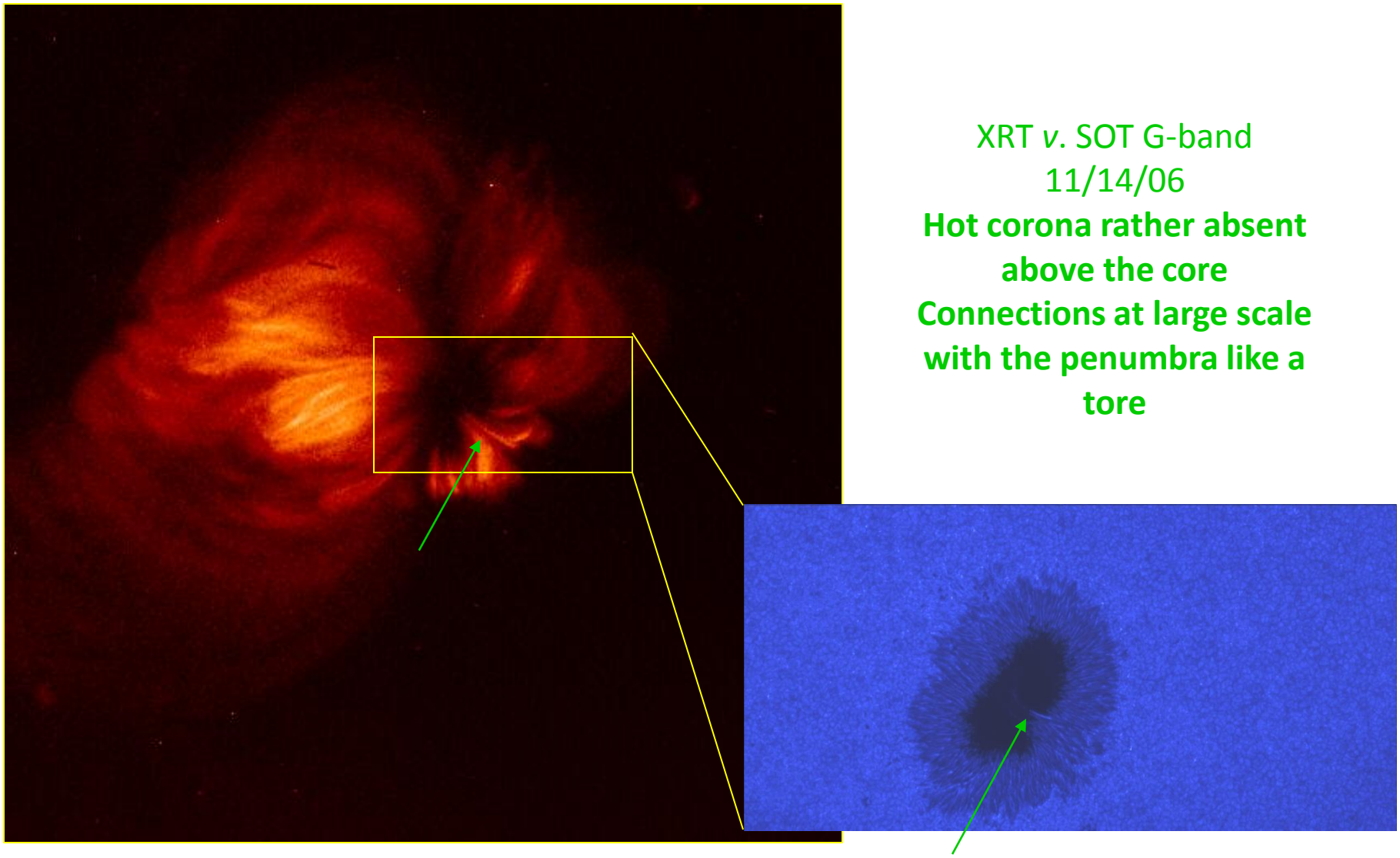
The biggest single sunspot of **Nov. 2006** (observed for >3 rotations)
From MDI (SoHO) data



From SOT Hinode data

From:
*Koutchmy, S. and Le Piouffle, V. (2008) IAUS **259** and (2012) in ESPM 12 (Fribourg)*

XRT (Hinode) combine With SOT for Photosphere/Corona Connectivity Studies



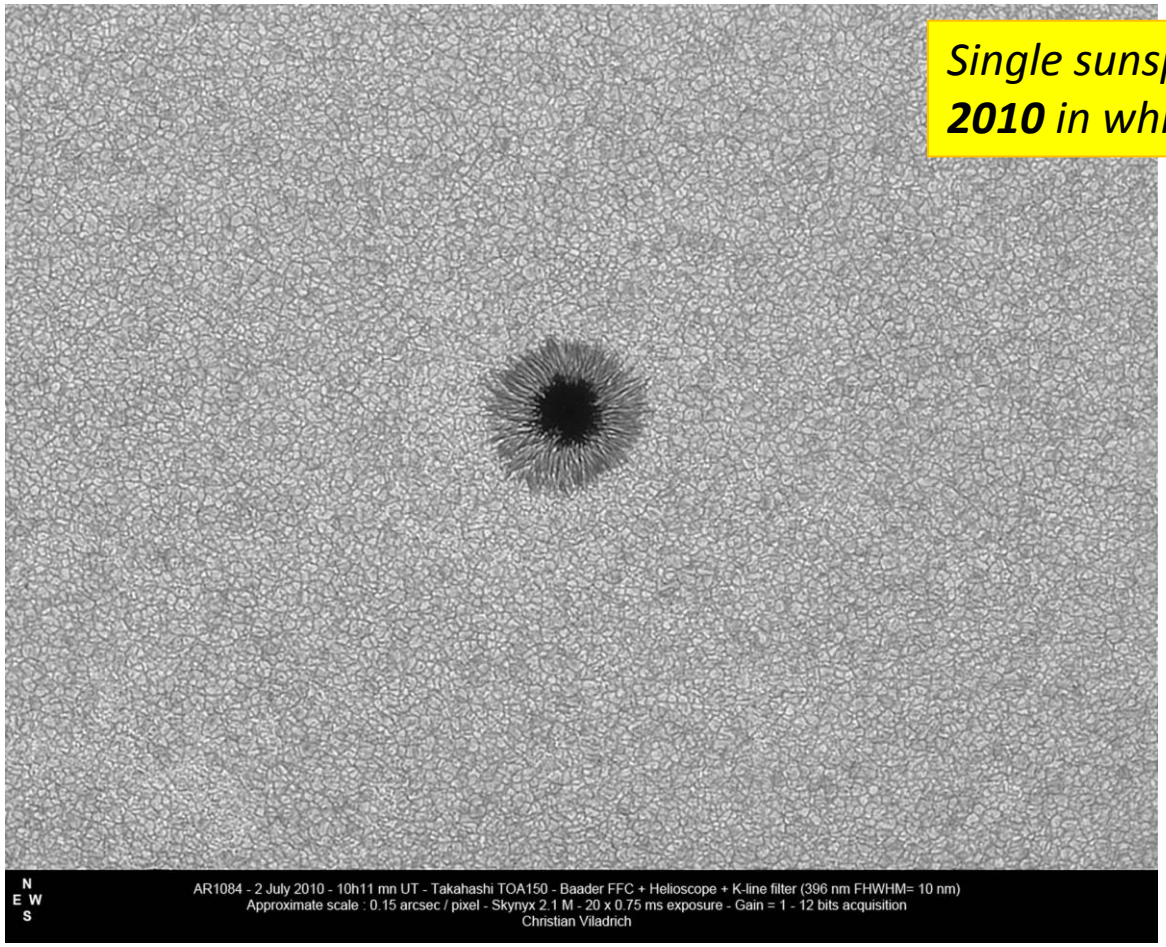
XRT *v*. SOT G-band
11/14/06

Hot corona rather absent above the core

Connections at large scale with the penumbra like a tore

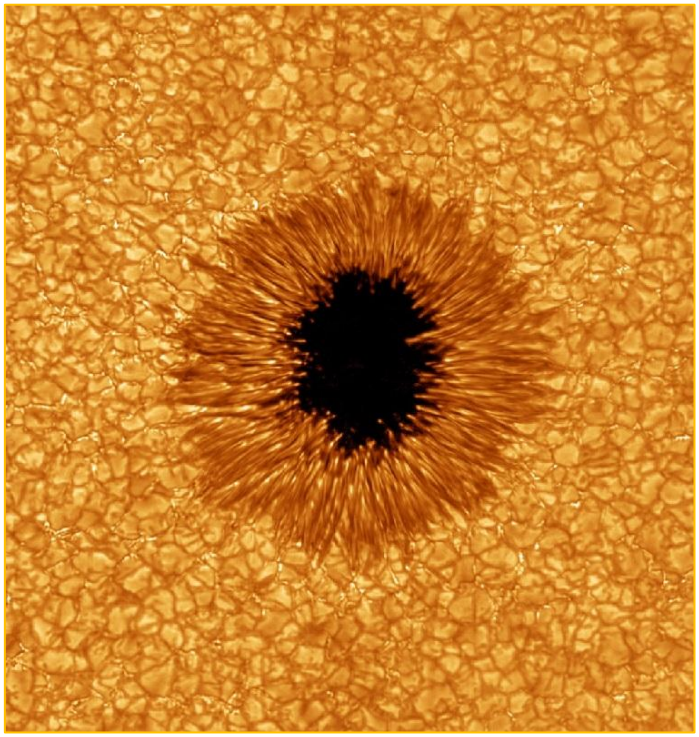
From L. Golub (2007)

We now select a single sunspot observed from SDO in July 2010

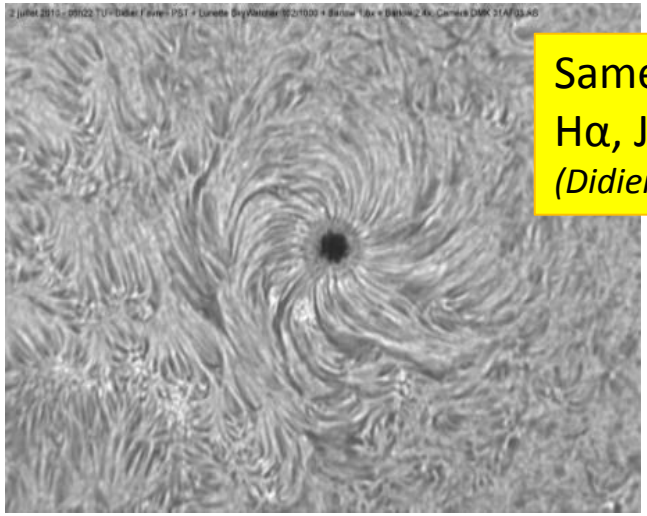


*Single sunspot observed in **July 2, 2010** in white-light (green filter)*

From Christian Viladrich (France).

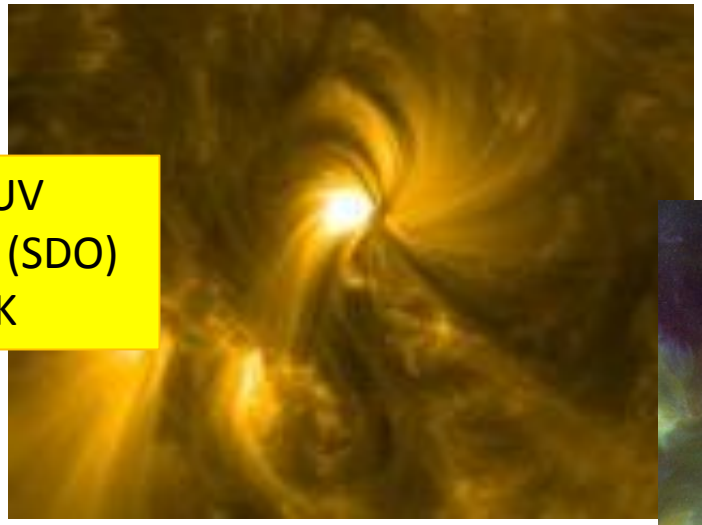


From BBSO with a TiO filter, similar to a G- band filter

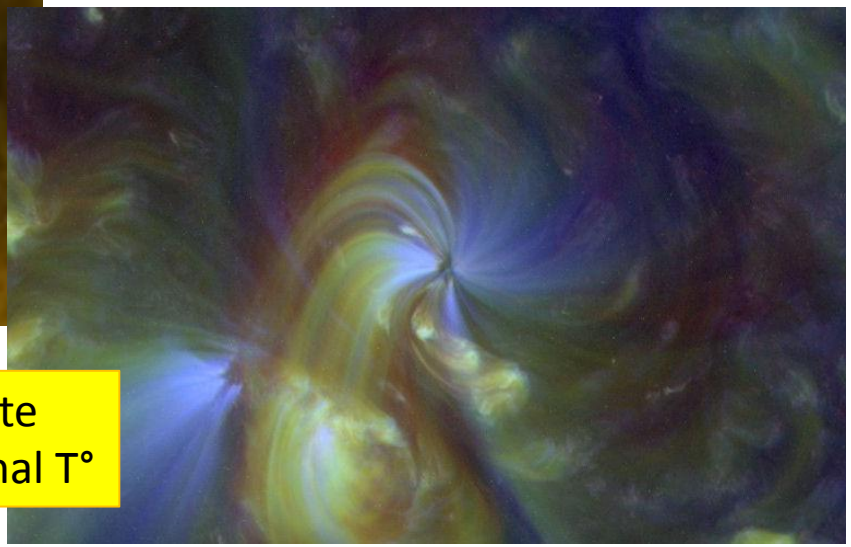


Same sunspot in Hα, July 2, 2010
(Didier Favre obs.)

“Spiral arms” develop around a single sunspot at both the chromospheric and specially the coronal levels as evidenced from stereo viewing

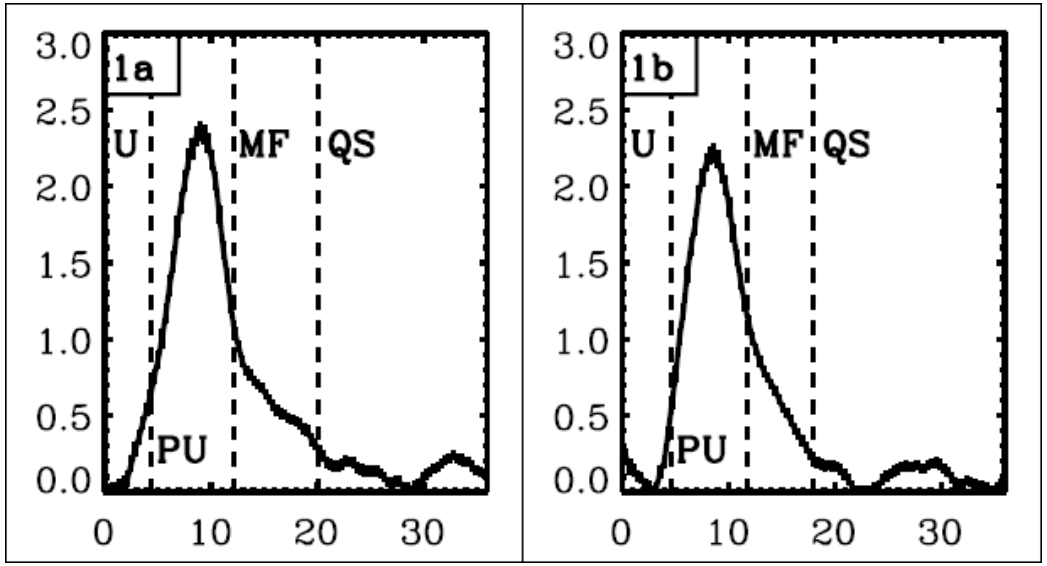


In 171 EUV with AIA (SDO) T° # 1 MK

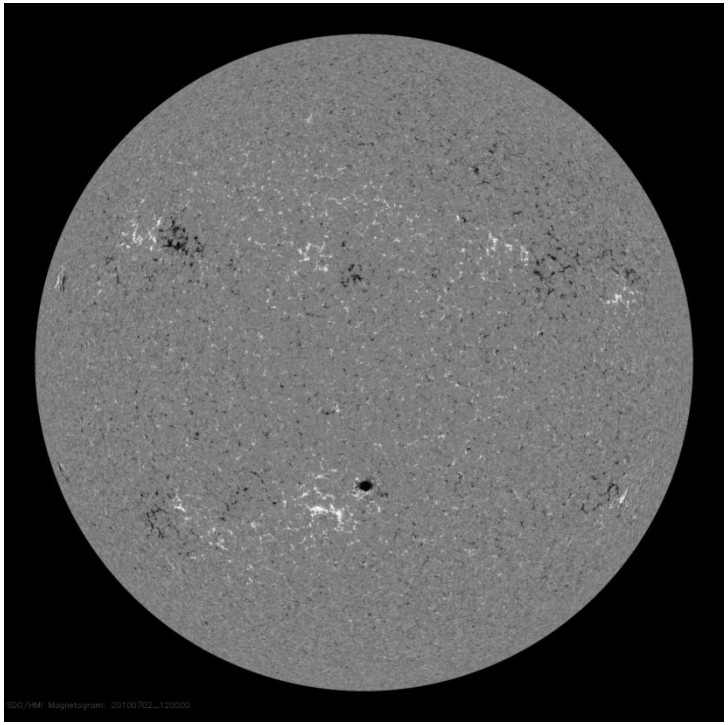


AIA (SDO) composite For different coronal T°

This sunspot was analyzed by Löhner-Böttcher J. and R. Schlichenmaier (2013) in **Doppler Shifts** (outside the disk centre) for the flows around (penumbra and super-penumbra);
Results confirm the continuity with the Evershd flow.

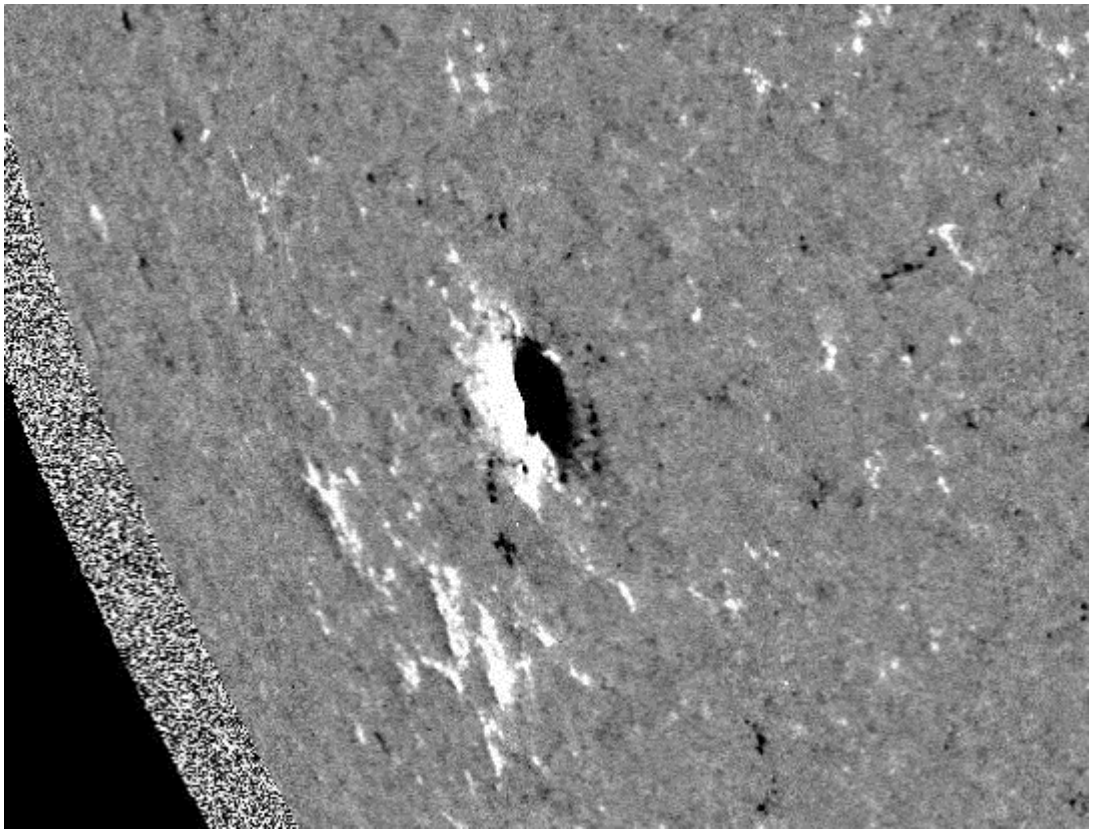


Radial extension of the flows (ordinates are horizontal velocities in km/s) deduced from observed around the sunspot of July 2, 2010 (NOAO region 11084). ***Doppler shifts*** *measured with the HMI (SDO) experiment. Abscissa are in Mm. U- umbra; MF- moving features; QS- quiet Sun.*
1a is for June 29, 2010 (S19 E45) and 1b for July 6, 2010 (S19 W47). Dashed lines are the boundaries defined by the authors:
Löhner-Böttcher J. and R. Schlichenmaier (2013) in AA



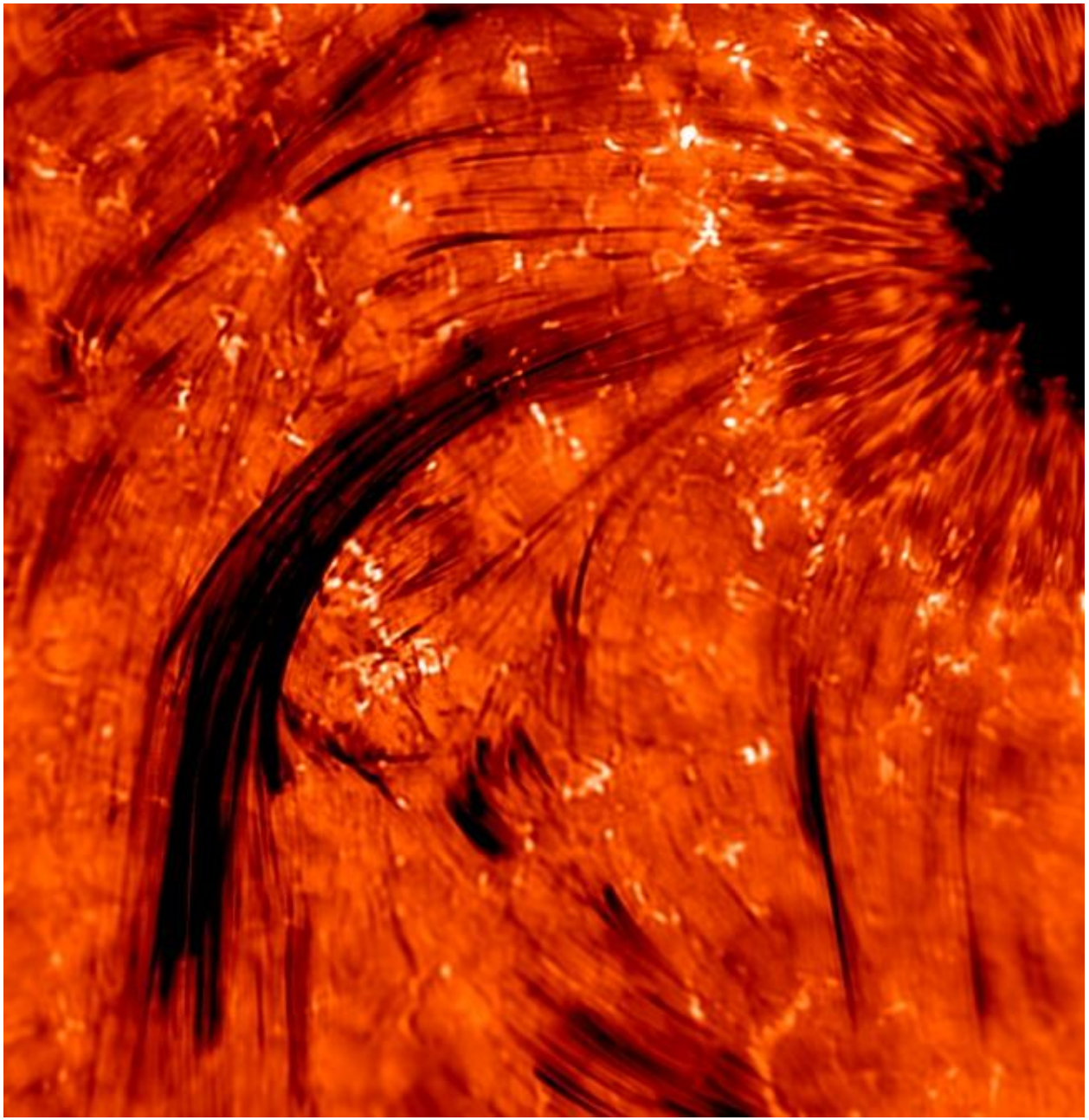
HMI magnetogram
of July, 1 2010

See the Movie with
time interval 3 hours,
from 28 June 2010 (00:39:33)
until 5 July 2010 (23:44:03)



8 days Movie using HMI (SDO) magnetograms with
time interval 3 hours, starting from 28 June 2010 (00:39:33) until 5 July 2010

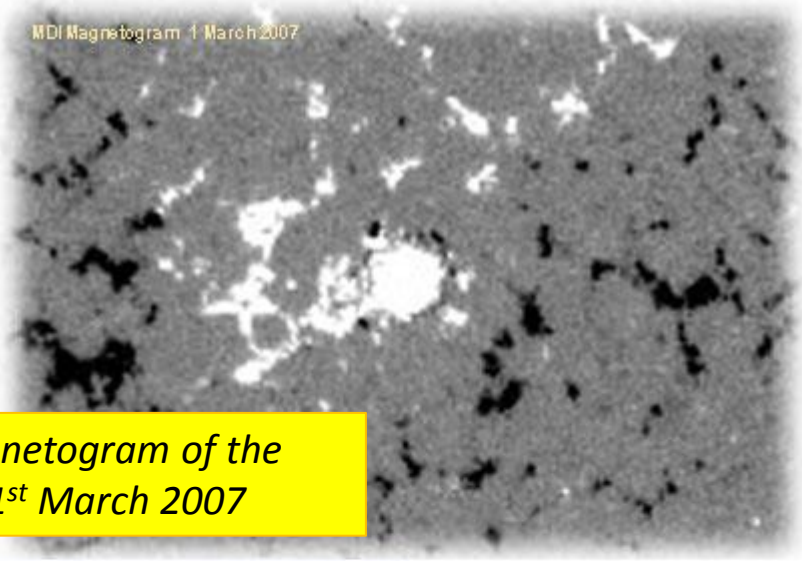
Fluxules are "flying" around with dominant outward "motions" (moving magnetic features) with fragments of opposite polarity moving inward…



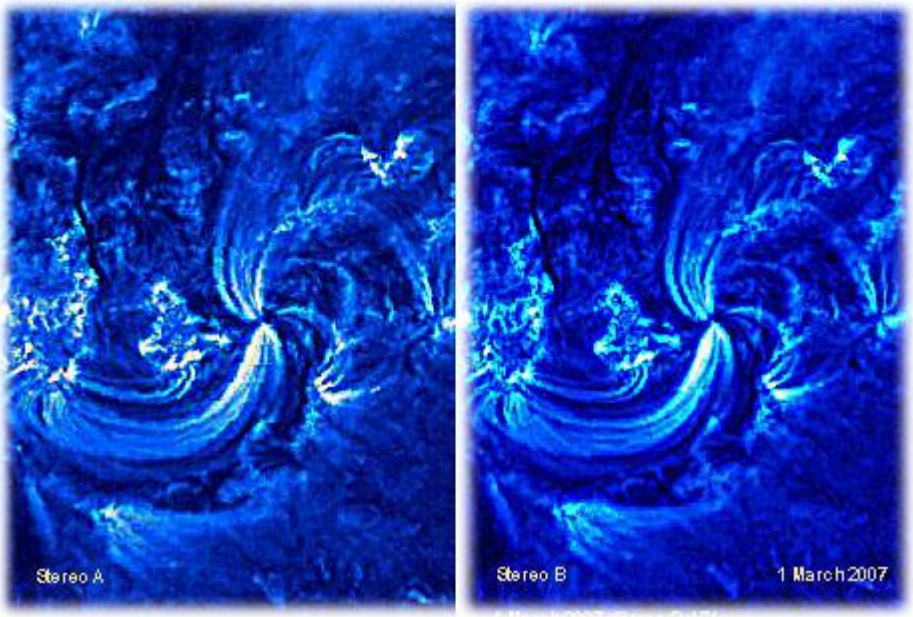
At very high resolution in the Hα blue wing NST BBSO observations of July 1st, 2010: curved threads and filament observed suggesting magnetic connections at coronal level, or is it a “neutral” sheet?
Also: cool jets and spikes (Yurchyshyn et al 2014)

We now look at the “flows” using **proper motion** analysis
of both **bright** (high T°) and **dark** (high B)
features of a sunspot at **HR**:

i/ dynamical behavior of penumbral structures;
ii/ analysis of the core of the sunspot



MDI magnetogram of the sunspot 1st March 2007



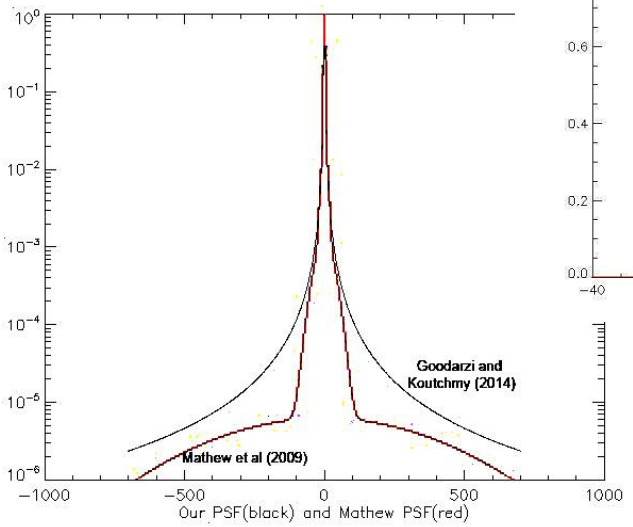
Stereo view of the region from Secchi A & B (STEREO)

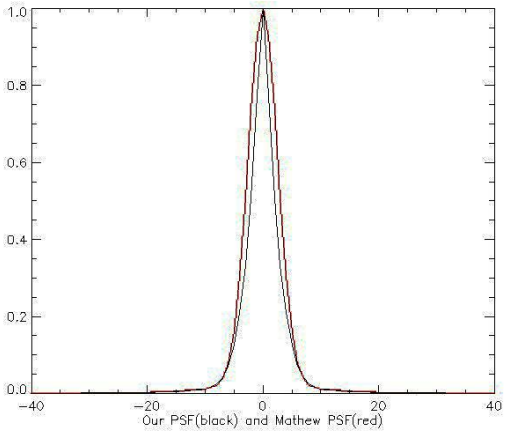
We now select a single sunspot well observed with the SOT of Hinode on **March 1st 2007; seeing free** observations using a narrow **blue filter** at 450 nm
Excellent resolution (0”0545/ px)
43 min time sequence

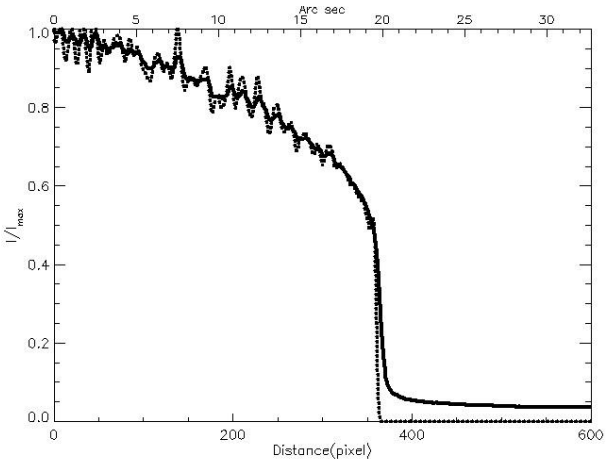
Stray light should be removed taking into account a deduced **PSF** to process **(deconvolve)** images.

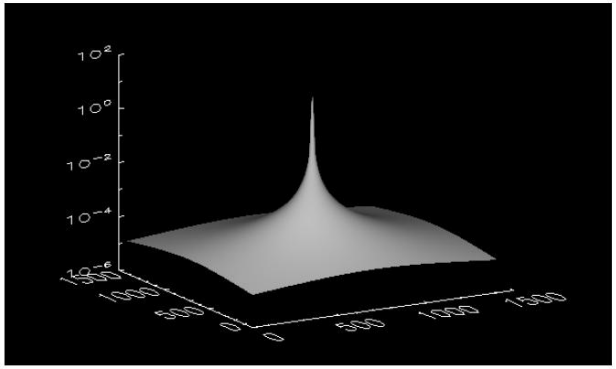
Several papers were published using SOT (Hinode) observations, especially for analyzing the penumbra and umbral dots. (Norwegian/Spanish teams)

See also the poster of Goodarzi et al.





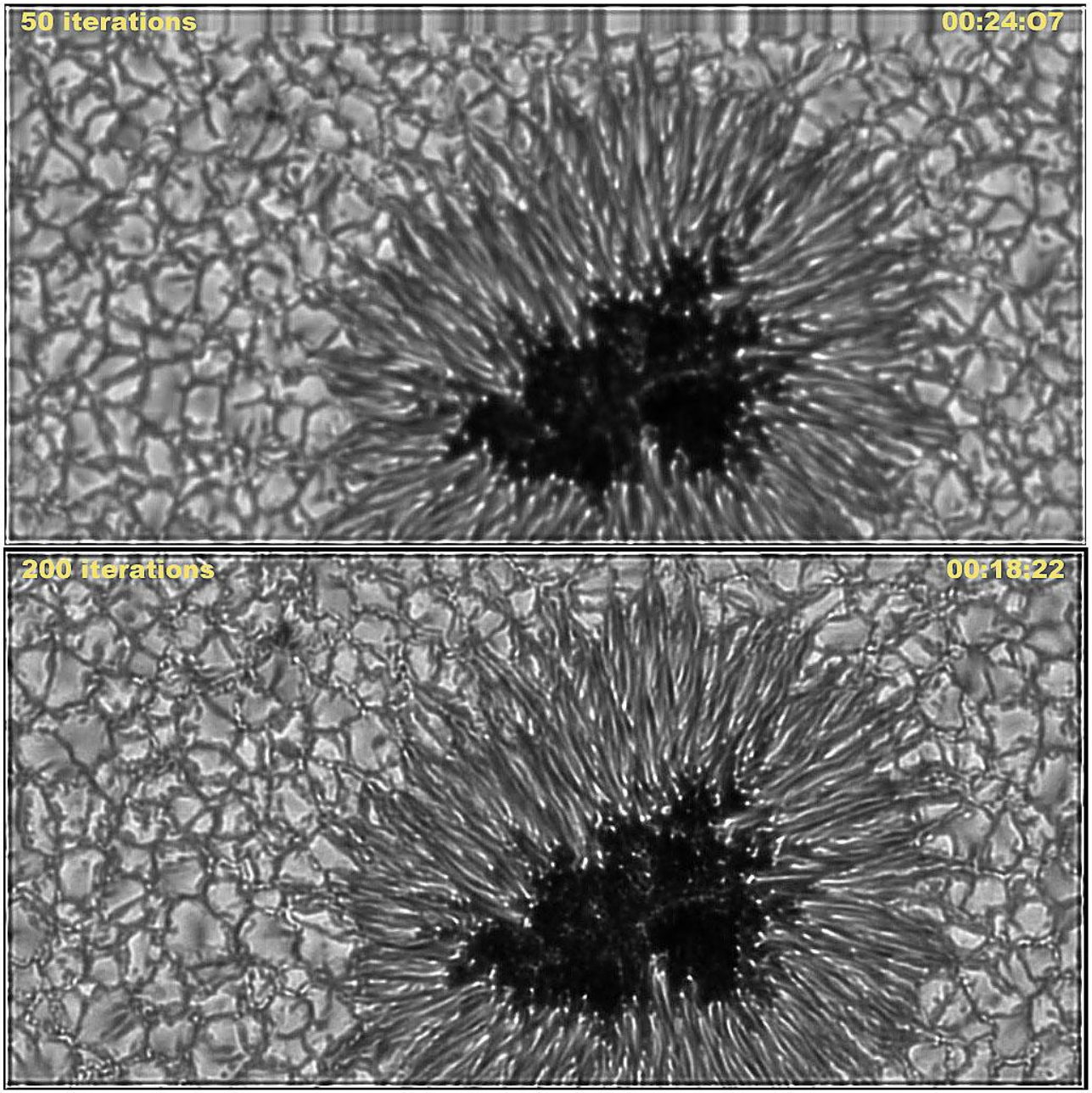




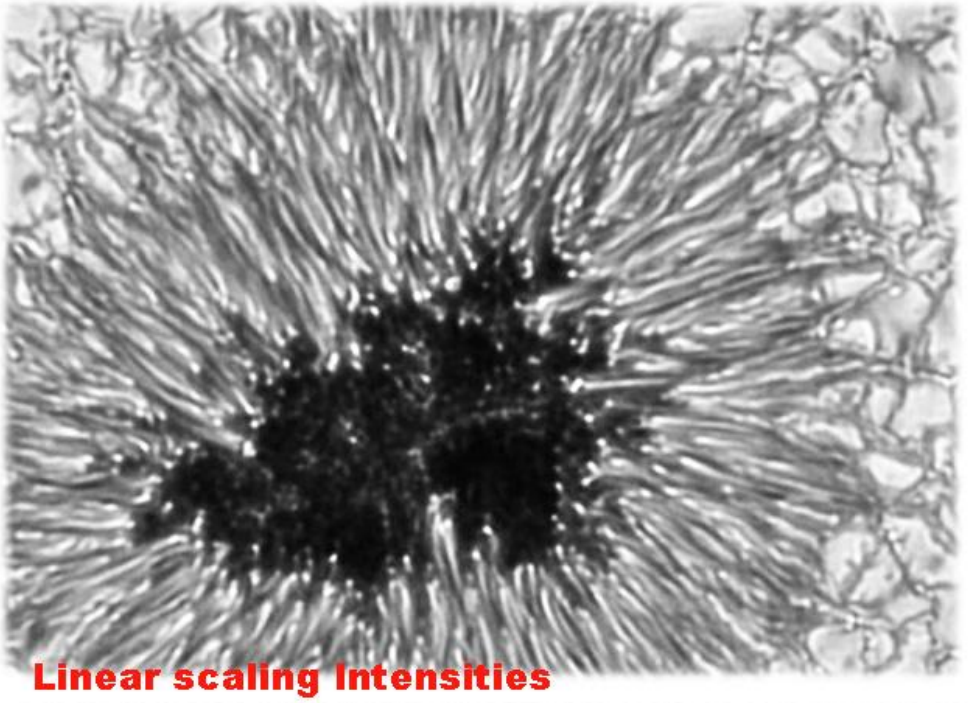
A new PSF was deduced using images from:

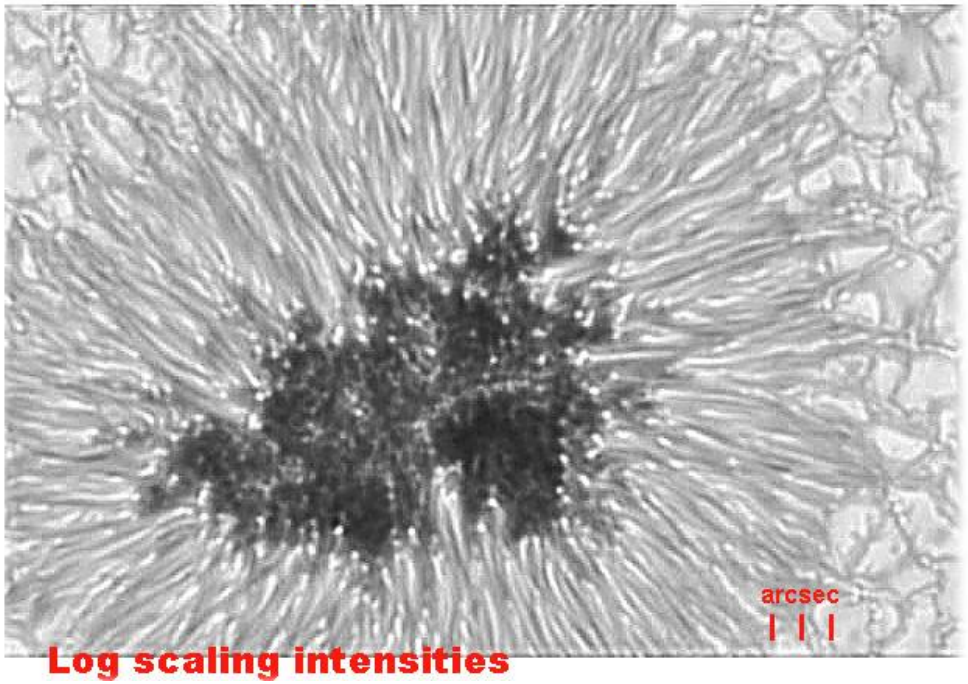
i) the transit of planet Venus (59” diameter) with both on disk and off disk images;

ii) the limb of the Sun, including both extreme- limb intensities and the stray light outside the disk, up to 1’5



Deconvolution using the IDL Max-likelihood routine
(Richardson 1972; Lucy 1974)
after the PSF was obtained:
importance of the number of iterations



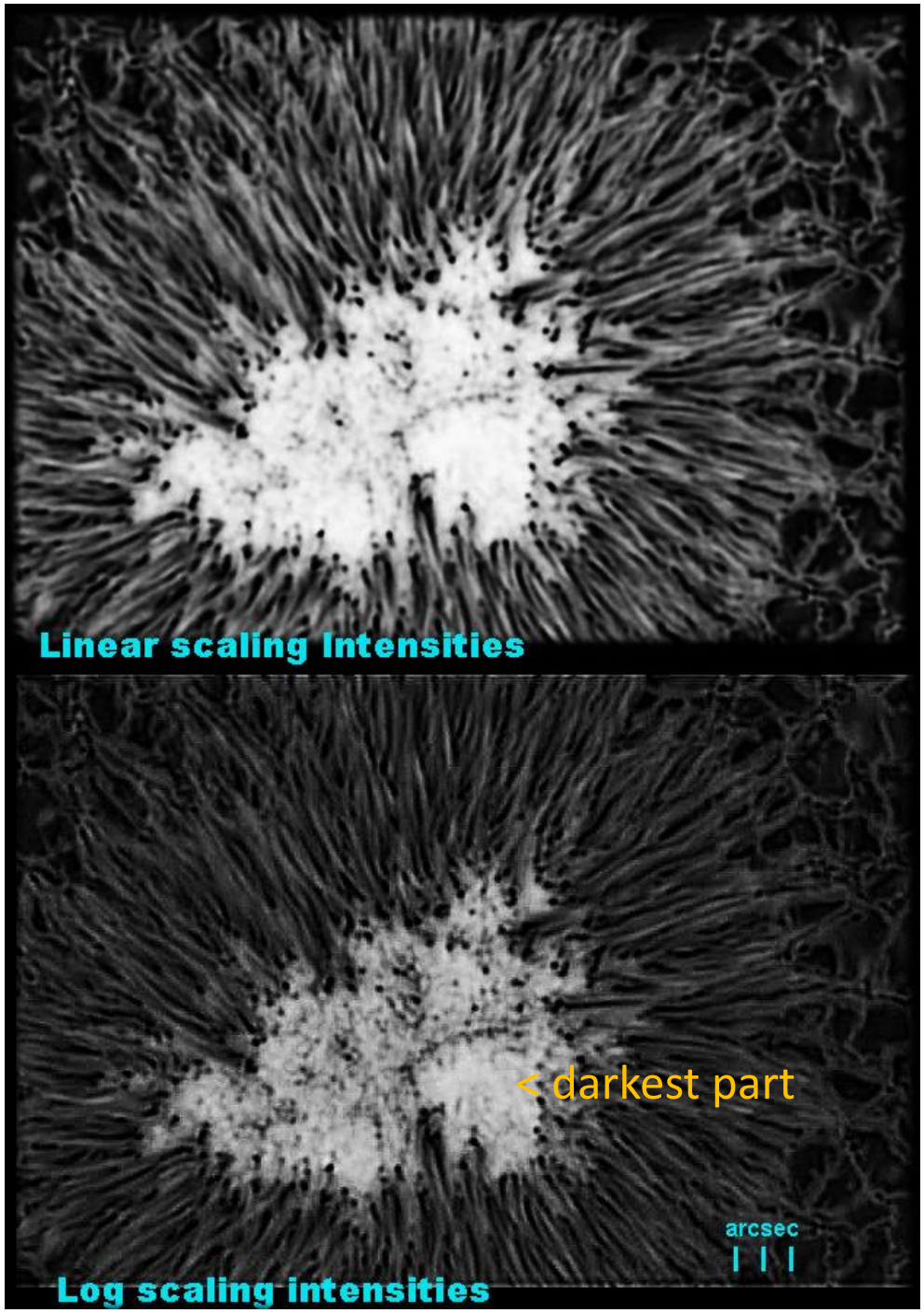


Importance of the visualization process: log scaling better to look at the core

Note:

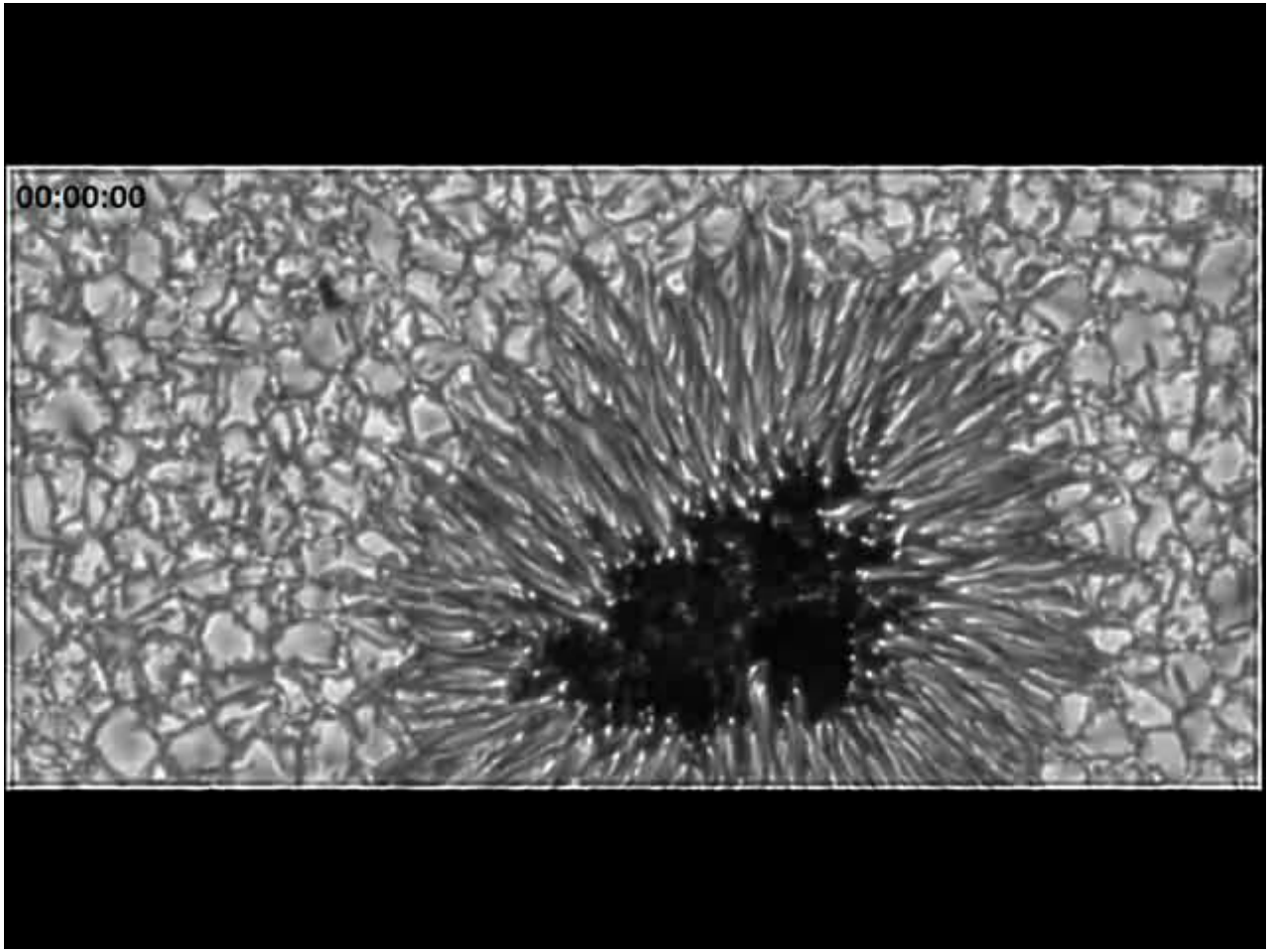
i) dark filaments and dark lanes;

ii) twisted penumbral bright filaments



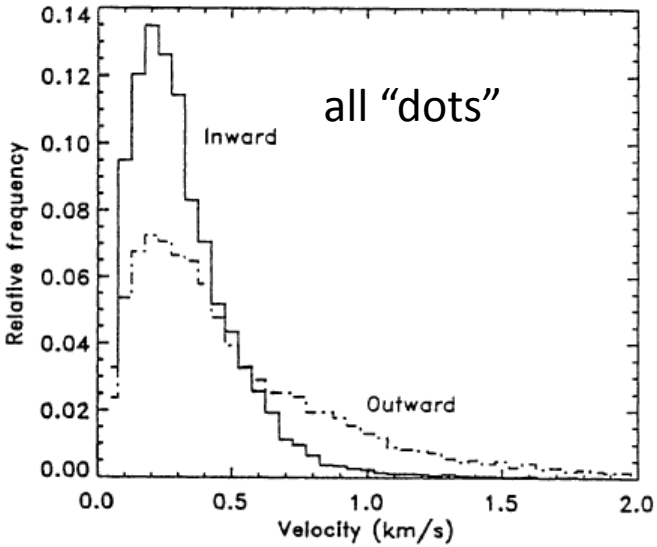
Negative display to better show **the core**.

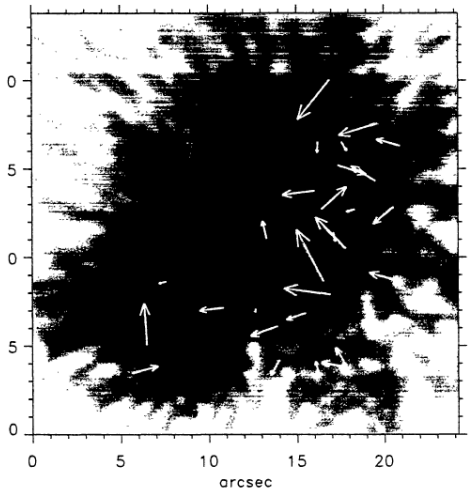
Note:
i) The “flat” bottom of the darkest part of the core;
ii) Alignments of u.d.
iii) Very bright features penetrating into the umbra

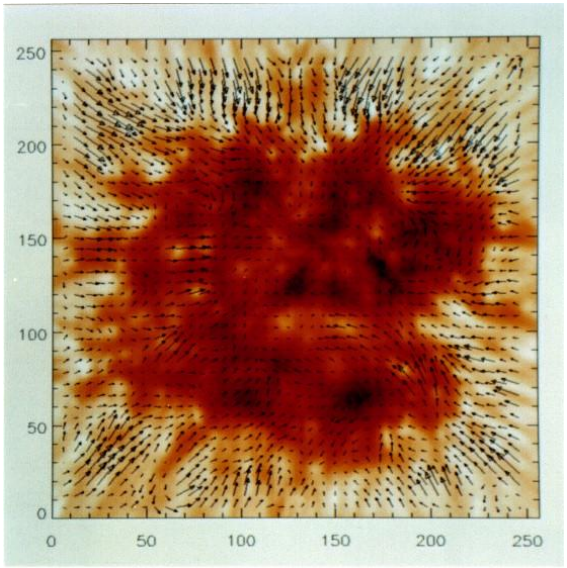


43 min long movie from deconvolved SOT (Hinode) 450 nm images

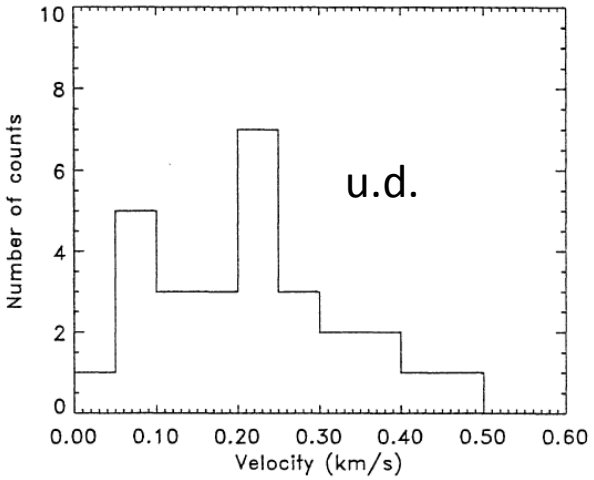
Inward motion of "peripheral" bright dots (PdM; SVST)





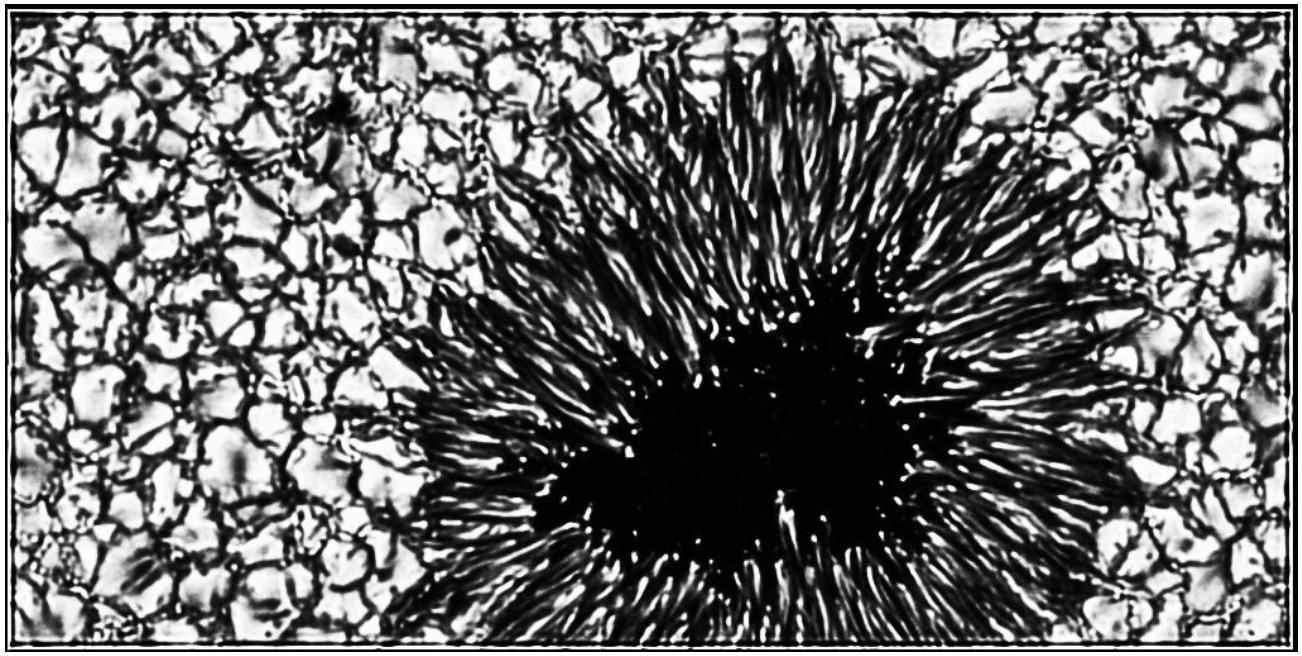


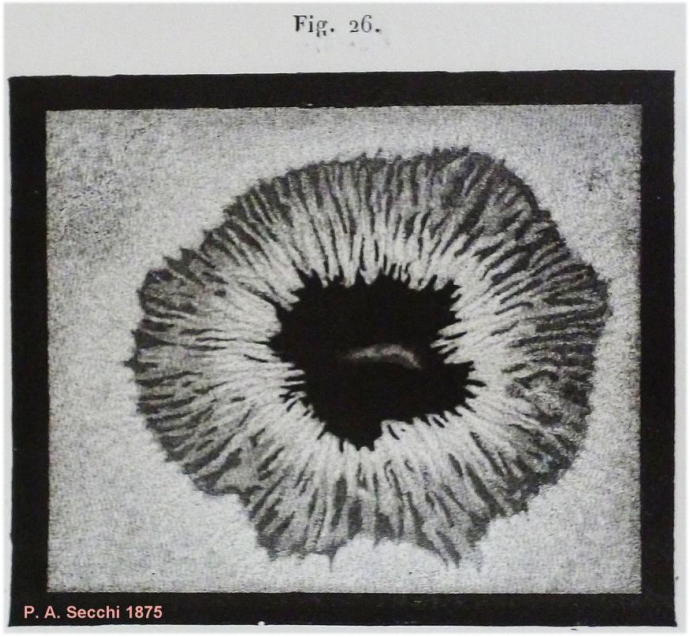
Sobotka et al 1995 (video obs. SVST- peripheral dots/ Inward)



Roberto Molowny- Horas PhD (1994) (video obs. 0"2/px 468 nm SVST)

Highly contrasted inner penumbra structures with intensities similar to photosphere intensities





Drawing by the father A. Secchi (1875), from visual observations with a 25 cm aperture refractor.

Conclusions

- Single sunspot: excellent prototype of a sunspot to understand the physics and evolution;
- Large scale magnetic connections with both the chromosphere and the corona with spiral « arms » possibly matching the motion of the super- penumbra magnetic elements of the moat;
- Deconvolved and stray light subtracted images showing large contrasts and new features;
- Evidence of penumbral dynamic dark up-flowing radial magnetic strands « pushing » outward elongated bright quasi- radial filaments with evidence of twisting and dark lanes;
- Inward motion of bright elements toward the periphery of the umbra with an excess of brightening suggesting non linear processes occuring at the umbral boundary;
- Umbra filled with 0 ’’2 bright elements moving horizontally with different « life-times » (sometimes repetition);
- The core shows a flat bottom;
- Dynamo model of Larmor/Alfven/Solov’ev seems compatible with the observed properties near the surface, with additional dynamical connections further out toward the chromosphere and corona.