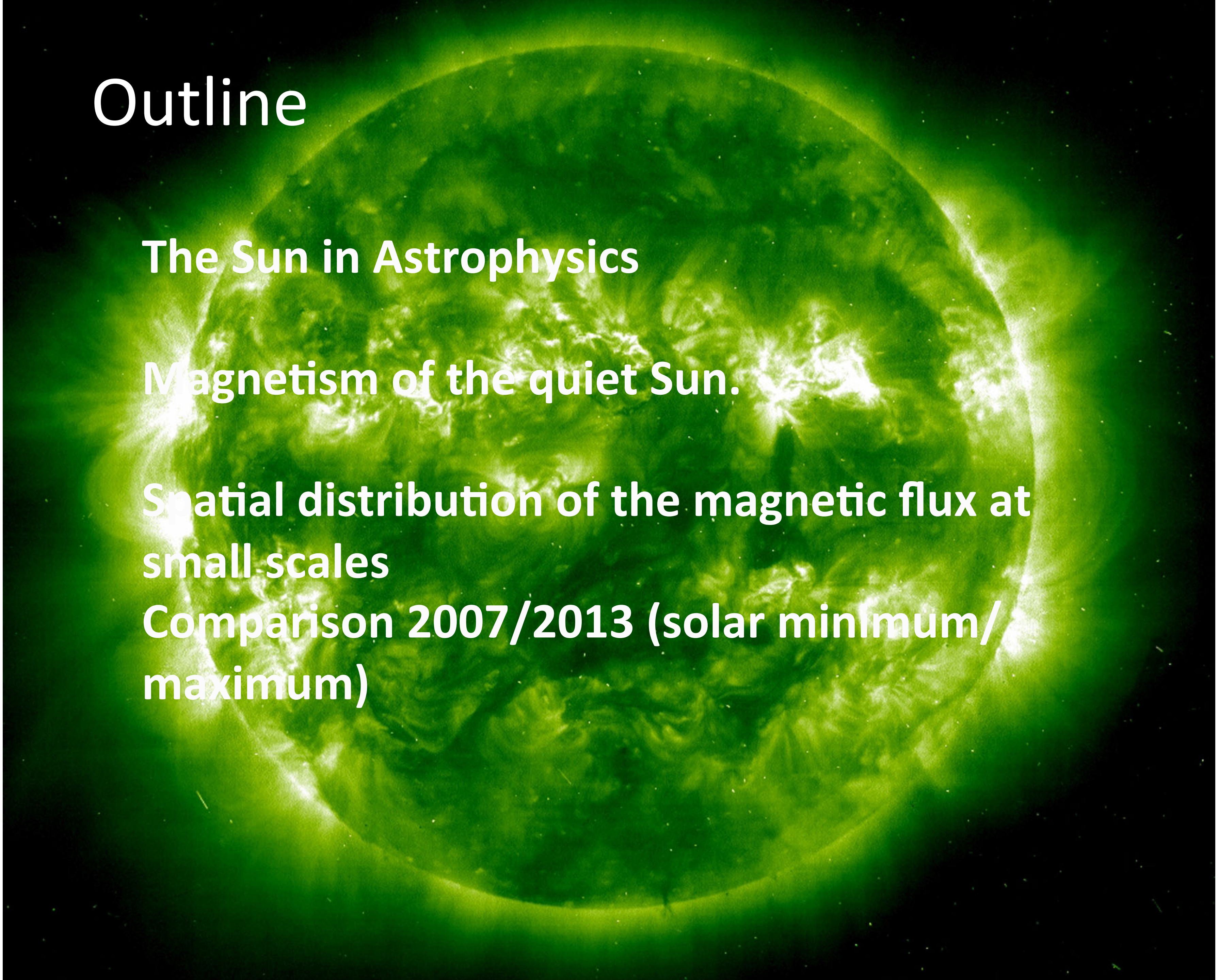
Quiet-Sun magnetic fields

Marianne Faurobert & Gilbert Ricort
Lagrange Laboratory

Outline



The Sun in Astrophysics

Magnetism of the quiet Sun.

Spatial distribution of the magnetic flux at small scales

Comparison 2007/2013 (solar minimum/ maximum)

The Sun in Astrophysics

- ***The Sun as a star***
- Best observed star : a test bed for stellar physics

- ***The Sun as a laboratory for plasma physics:***
- Dynamo mechanisms
- Plasma turbulence
- Magnetic reconnection and particule acceleration

- ***The Sun as our star***
- Solar-terrestrial relations: space weather, climate change

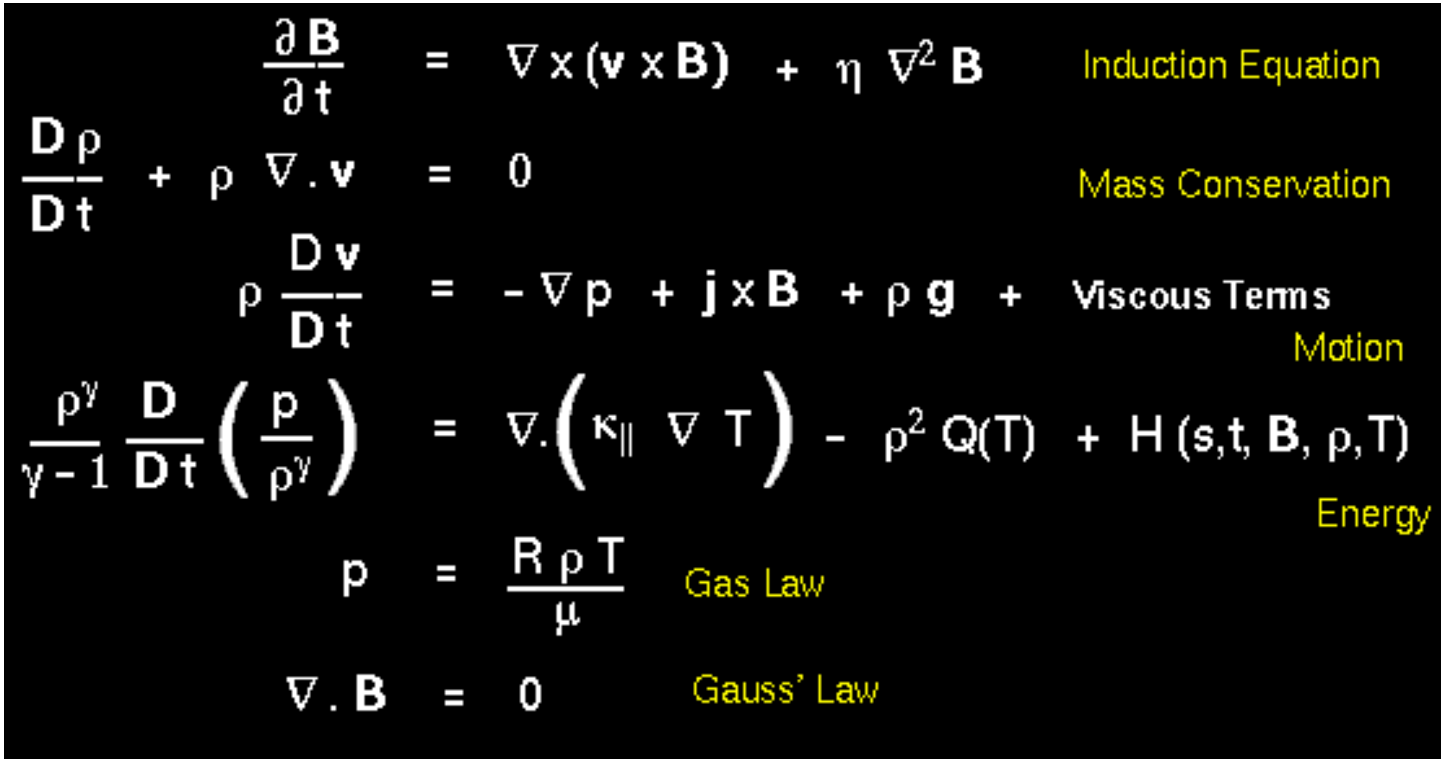
Some key questions in solar physics

- How is the solar corona heated?
- How is the solar wind accelerated?
- How is the solar magnetic field generated inside the Sun (solar activity cycle)?
- How are solar flares and coronal mass ejections triggered?
- Variations of the solar irradiance?

The magnetic field plays a crucial role in all these phenomena

Magneto-Hydrodynamics of the Sun

- Coupling between the plasma motions and the evolution of the magnetic field



$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}) + \eta \nabla^2 \mathbf{B}$$

Induction Equation

$$\frac{D\rho}{Dt} + \rho \nabla . \mathbf{v} = 0$$

Mass Conservation

$$\rho \frac{D\mathbf{v}}{Dt} = -\nabla p + \mathbf{j} \times \mathbf{B} + \rho \mathbf{g} + \text{Viscous Terms}$$

Motion

$$\frac{\rho^\gamma}{\gamma - 1} \frac{D}{Dt} \left(\frac{p}{\rho^\gamma} \right) = \nabla . \left(\kappa_{\parallel} \nabla T \right) - \rho^2 Q(T) + H(s, t, \mathbf{B}, \rho, T)$$

Energy

$$p = \frac{R \rho T}{\mu}$$

Gas Law

$$\nabla . \mathbf{B} = 0$$

Gauss' Law

Induction equation

- Two terms: advection (I) + diffusion (II)

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{v} \times \mathbf{B}) + \eta \nabla^2 \mathbf{B}$$

$$\boxed{\frac{I}{II} = \frac{L_0 \ v_0}{\eta} = R_m}$$

Magnetic Reynolds number

Typical value in the photosphere

$\eta = 1 \ \mathrm{m}^2 / s,$ $L_0 = 10^5$ m, $v_0 = 10^3$ m/s --> $\mathbf{R_m = 10^8}$

- **I** >> **II** --> the magnetic field is advected by the plasma motions: it is “frozen-in”

Diffusion time

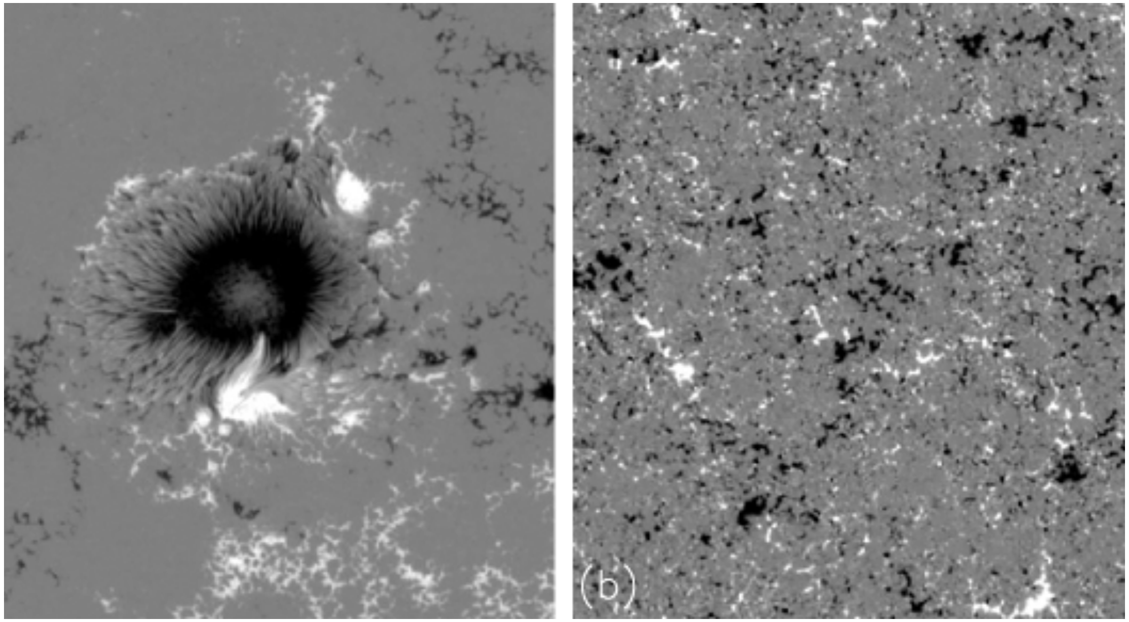
$$t_d = L_0^2 / \eta$$

For a typical sunspot : $(\ \eta = 1\ \mathrm{m^2/s},\ L_0 = 10^6\ \mathrm{m}),\ \mathbf{t_d = 10^{12}\ sec}$

In the solar photosphere *advection time= diffusion time* for $l \approx 15\ m$

This means that the magnetic field can form coherent structures on very small spatial scales that we are far from resolving with our instruments.

How is the magnetic field structured?

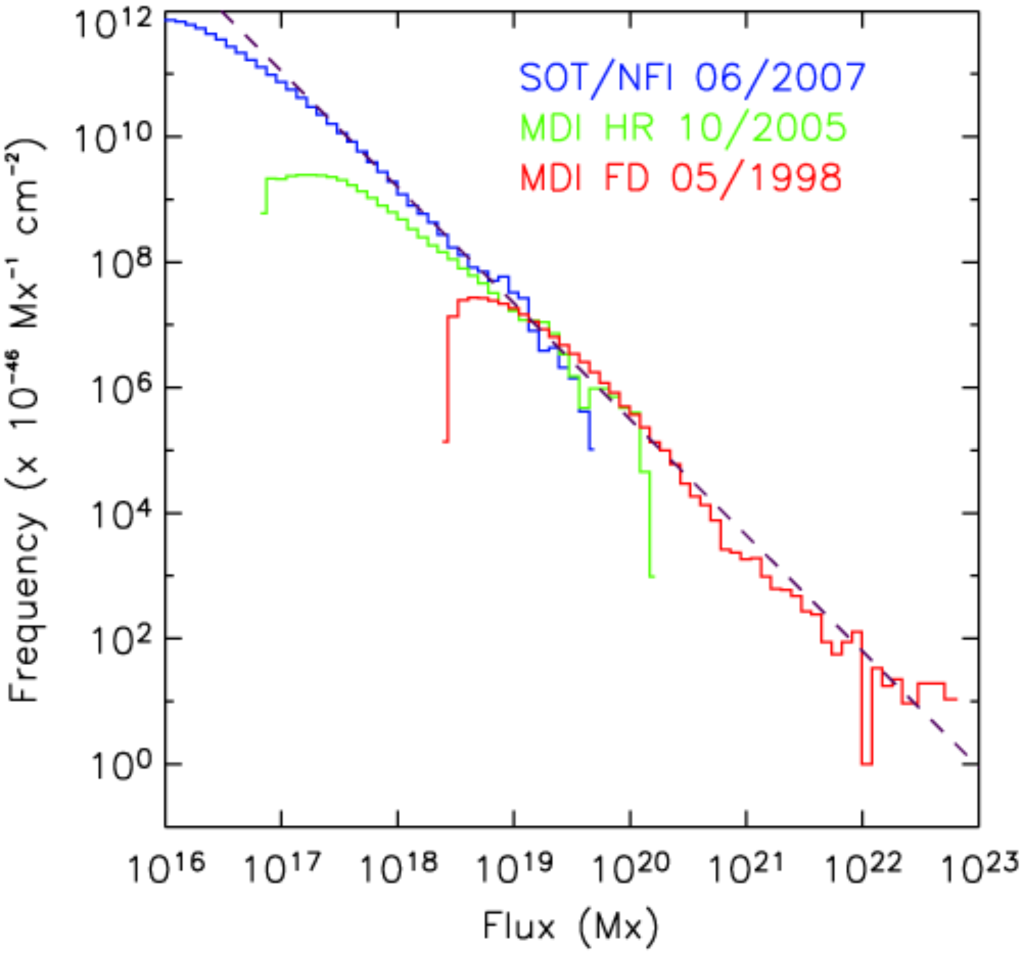


Sunspot

quiet Sun

Circular polarization (Zeeman effect) in FeI 630.2 nm line
gives the longitudinal **magnetic flux density** over the pixel in the photosphere
The dimensions of both figures are 110 Mm and the pixel size is 110 km.
(Hinode satellite)

Histogram of feature frequency vs. magnetic flux.

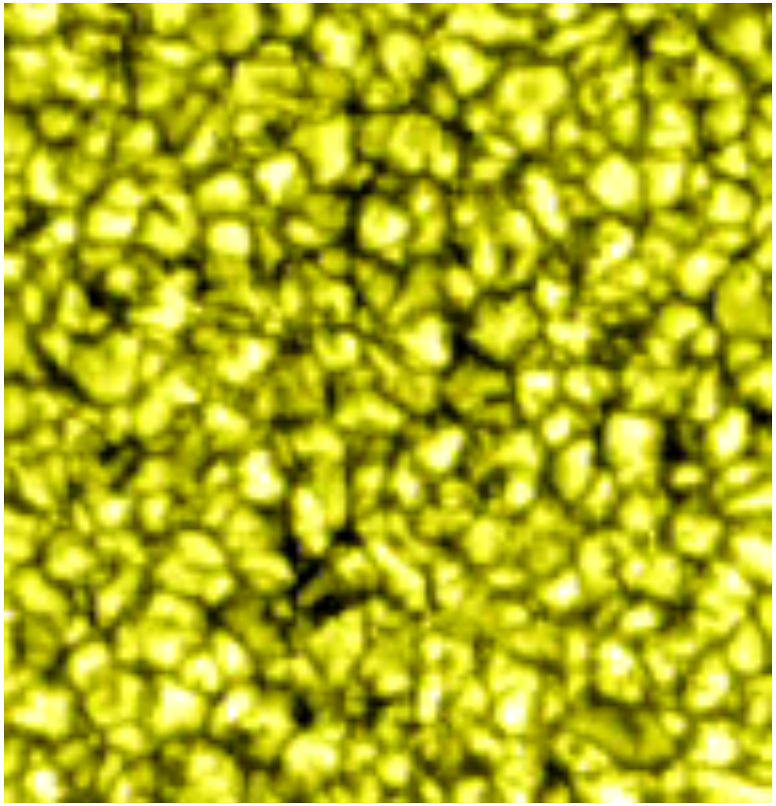


- No characteristic scale: power-law distribution over more than 5 decades in flux

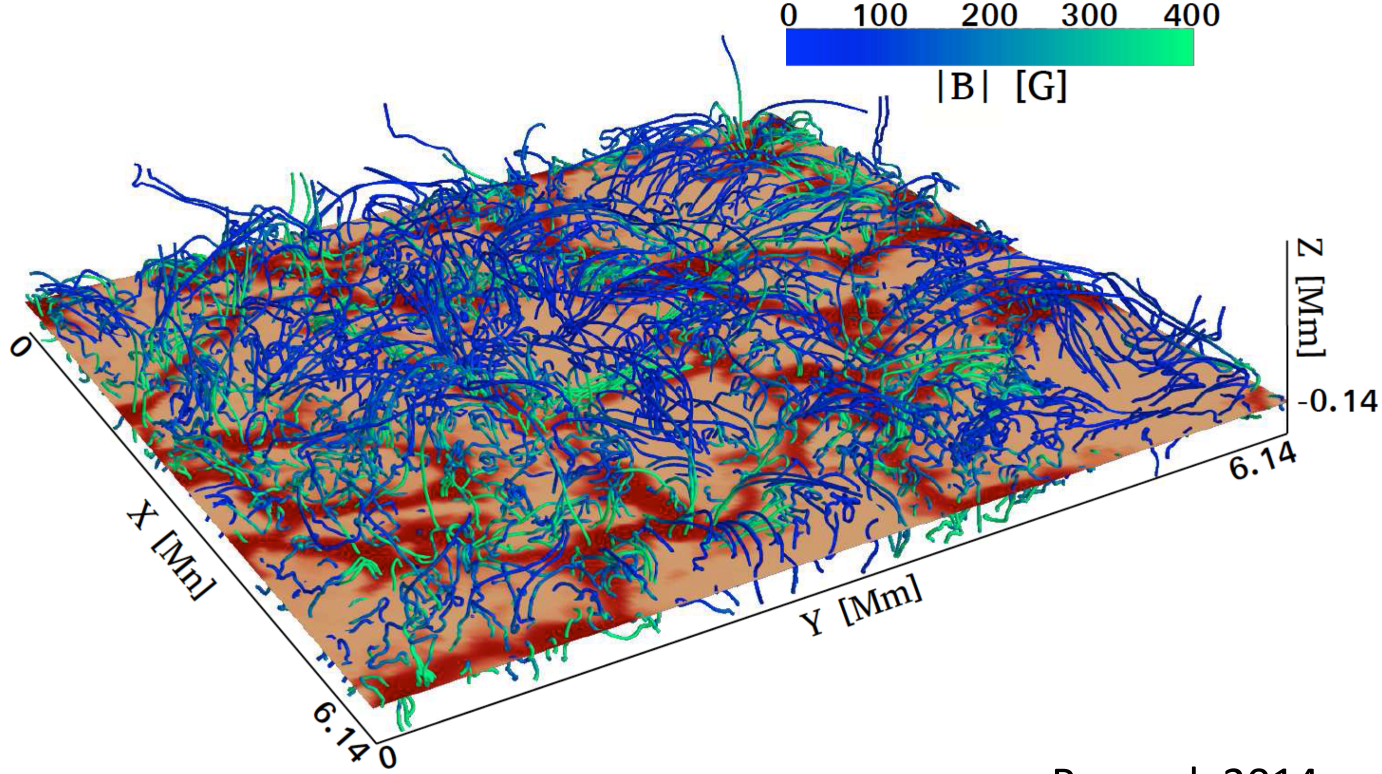
- **3 orders of magnitude more magnetic flux in the quiet sun than in active regions ….**

Parnell et al., 2009, ApJ

Quiet Sun dynamics
Photospheric granulation



3D MHD simulations showing small-scale dynamo in the quiet sun



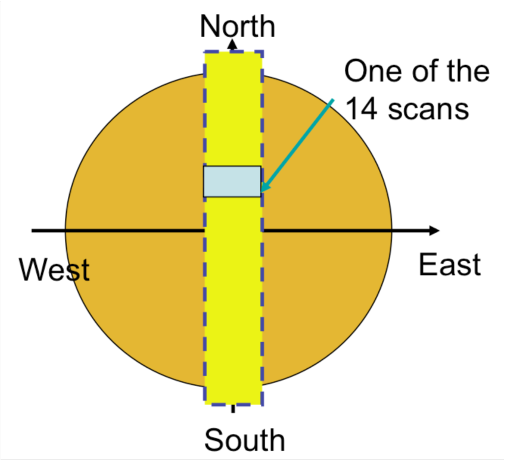
Rempel, 2014

Magnetism of the quiet sun (Small-scale/global dynamo)

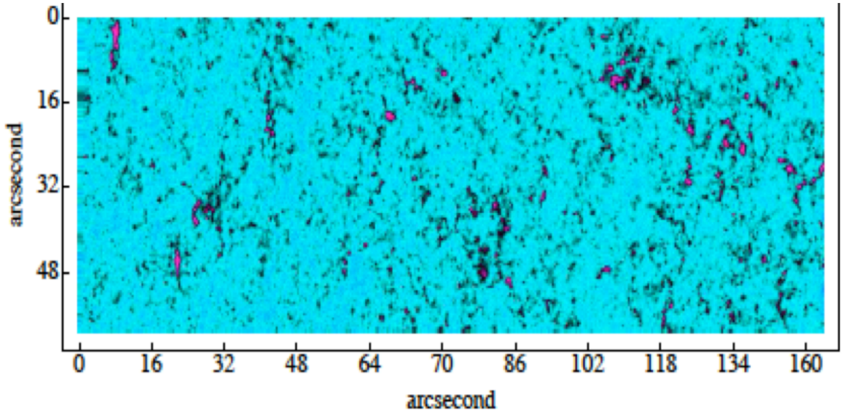
- Very difficult to observe because:
- The magnetic structures are not resolved (mixed polarities at small scales)
- The polarization signals are weak (typically 1% of the continuum intensity or less)
- → Instrumental requirements: High angular resolution + High polarimetric sensitivity
- →New solar telescope: DKIST, 4m-miror with adaptive optics (under construction in Hawaï). In Europe: EST (in project for the Canary Islands)
- Space: Hinode (resolution 0.3’’- 0.05 ’’), Sunrise (0.15’’)

Small-scale distribution of the magnetic flux in the internetwork.

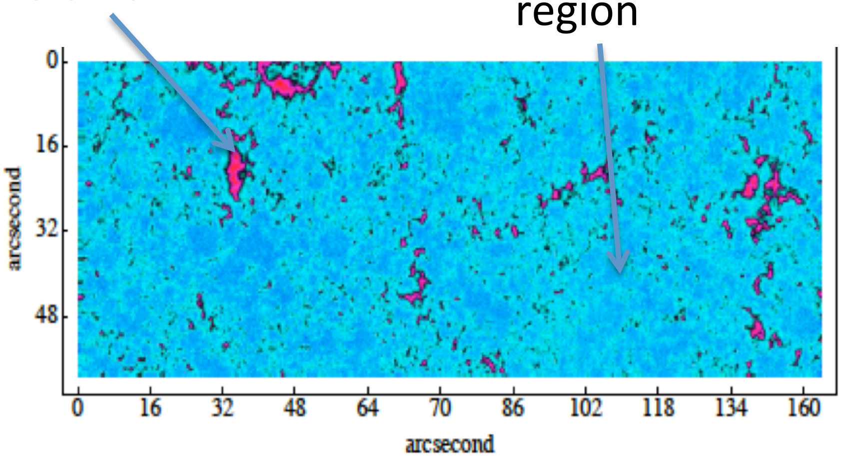
- Observational study with Hinode/SOT spectro-polarimeter



Scans with the spectrograph slit give maps of the intensity and polarization in the FeI 630 nm lines at various disk positions.
We select very quiet 10’’ x 10’’ regions.
Resolution: 0.3’’ (220 km)



South limbe



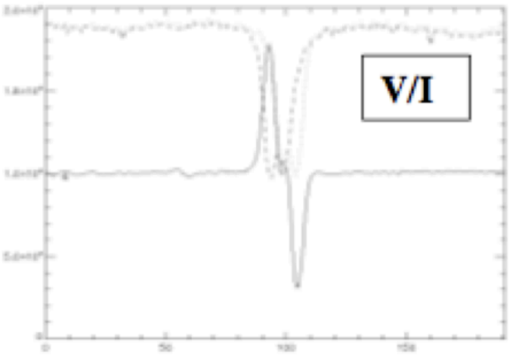
Magnetic network element

Internetwork region

Disk center

Unsigned magnetic flux measurement

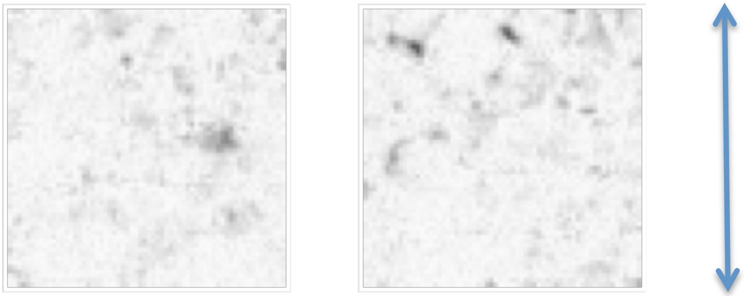
Weak field limit: $V(\lambda) = -4.39 * 10^{-13} \lambda^2 g B_{//} \frac{dI}{d\lambda}$



Line integration $\left| \int_{-\Delta\lambda}^{0} V(\lambda) d\lambda - \int_{0}^{\Delta\lambda} V(\lambda) d\lambda \right| = 2 * 4.39 * 10^{-13} \lambda^2 g B_{//} (I_c - I_0)$

Gives the unsigned magnetic flux density in the pixel

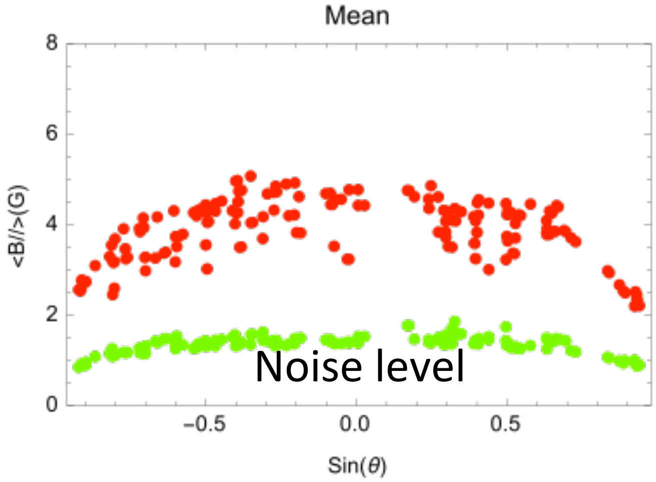
Internetwork magnetic flux
Comparison 2007/2013



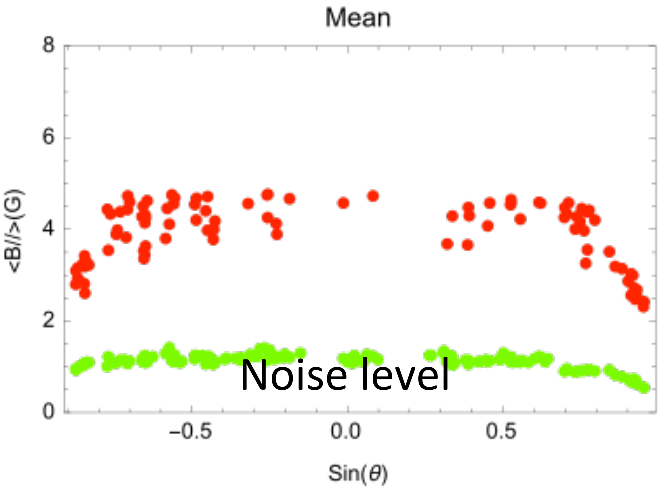
10.2’’

98 selected regions
between -70° and +70°

2007 solar minimum



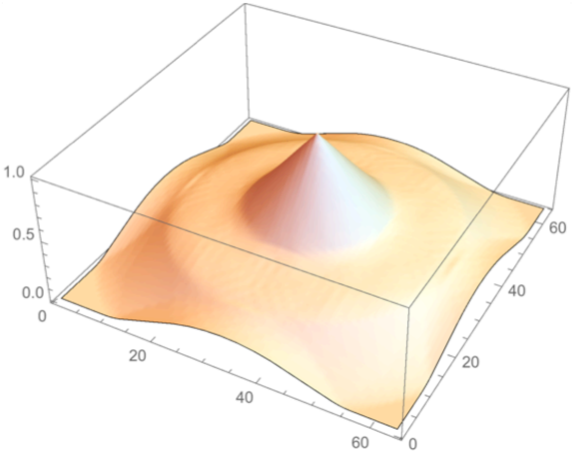
2013 solar maximum



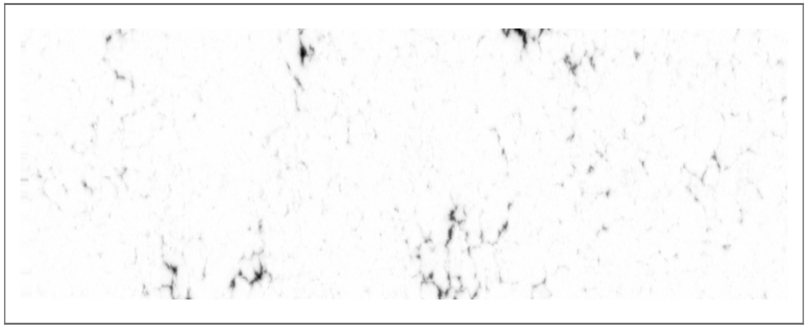
Deconvolution of the maps

The maps are affected by the convolution with the instrument PSF:
- Diffraction by the pupil of the telescope (50 cm- miror and its central obscuration) + aliasing due to undersampling + defocus

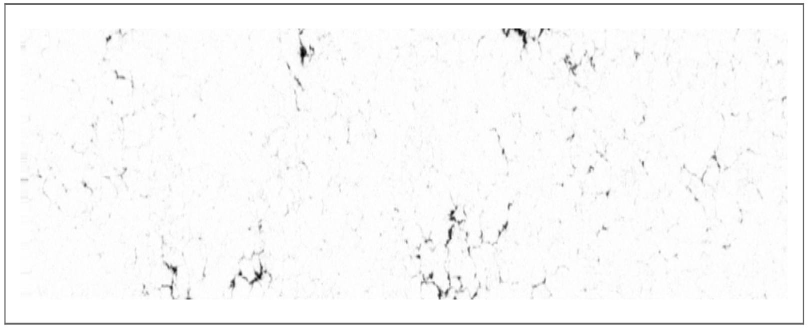
MTF with undersampling by the camera: the MTF does not reach 0 at the cut-off frequency of the telescope



Before deconvolution

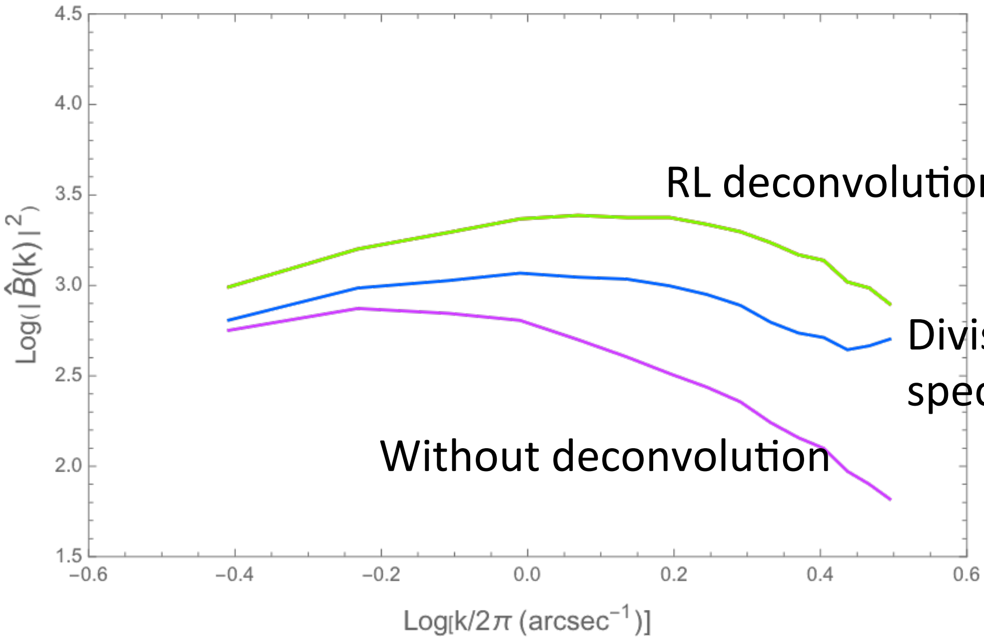


After deconvolution



Fourier power spectra

Effect of the deconvolution on the power spectrum of the magnetic flux fluctuations



RL deconvolution

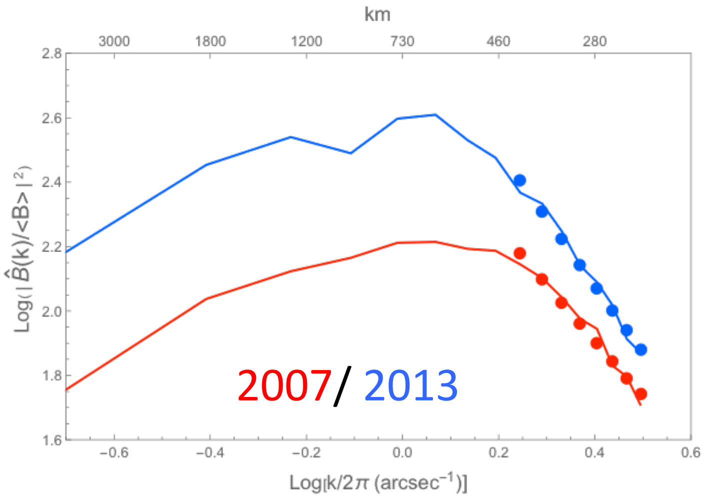
Division of the Fourier spectrum by the MTF

Without deconvolution

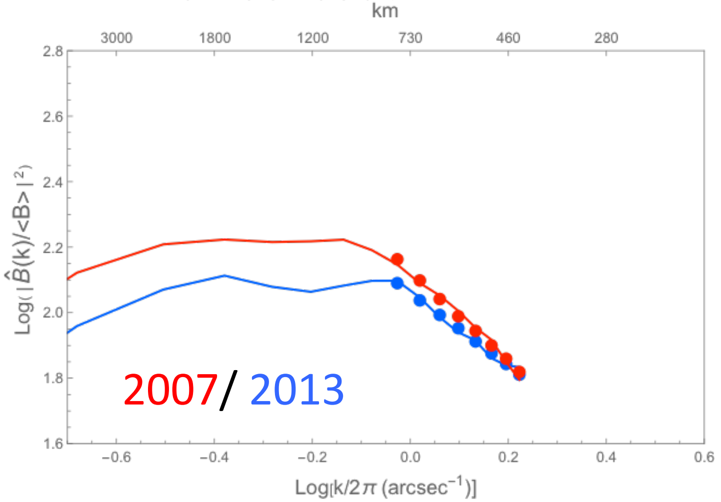
Comparison 2007/2013

minimum/maximum

Disk center



ϑ= 60° south



Change of both the shape and amplitude of the power spectrum between solar minimum and maximum.

- Two broad peaks at maximum, only one at minimum
- At disk center: more power at solar maximum but close to the pole: more power at solar minimum.

Conclusion

- The spatial distibution of the magnetic flux in the internetwork of the quiet Sun varies with the solar cycle.

  At solar maximum: two maxima in the Fourier power spectrum:

  at characteristic scales of 1300 km (granulation) and 700 km.

  At solar minimum: the scale at 1300 km is not detected.

  The magnetic structures at 700 km could be due to a small-scale dynamo in the quiet Sun, operating independently of the global dynamo.

- The power of the fluctuations seen at the equator increases at solar maximum but close to the pole it decreases: could be due to the decay of large-scale structures of the global dynamo advected on granular scales and transported toward the poles by the meridian ciculation.

Going Further

- The small scale dynamo is probably operating through the whole convection zone and interacting with the cyclic dynamo (not considered in the models)
- To understand the physical mechanisms of the coupling we need to determine the 3 components of the magnetic field at small scales (not only the flux density): DKIST (2020), EST???.

Thank you!