Simulations of solar magneto-convection

Alexander Vögler

Max-Planck-Institut für Aeronomie
Katlenburg-Lindau, Germany

IMPRS Seminar Lindau, Dezember 17, 2003

Outline

- What is magneto-convection?
- The simulation code
- Simulations of photospheric magneto-convection
- Outlook

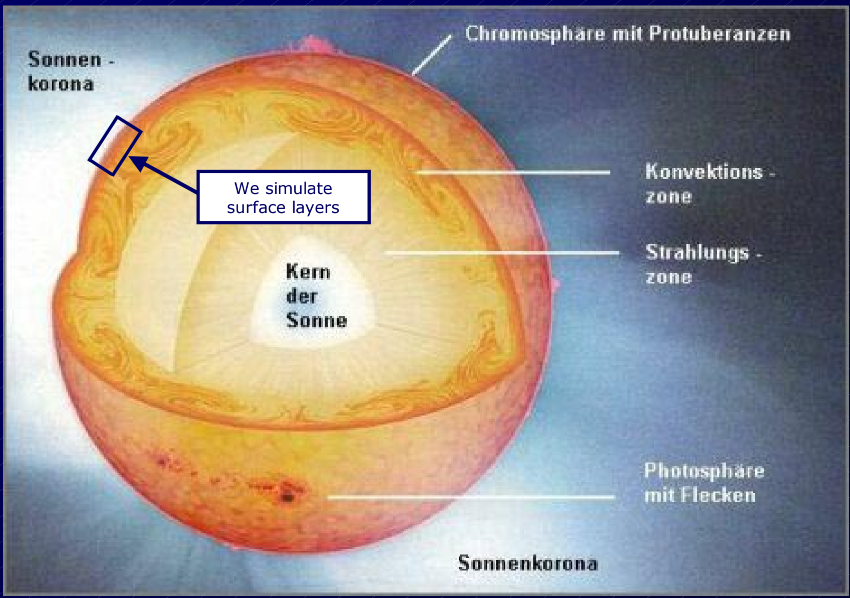
Outline

- What is magneto-convection?
- The simulation code
- Simulations of photospheric magneto-convection
- Outlook

What is magneto-convection?

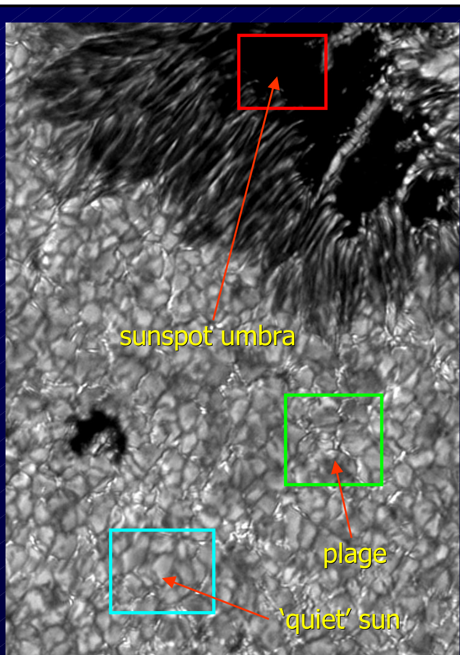
- Interaction between convective flows and magnetic field in an electrically well-conducting fluid
- High Reynolds numbers: nonlinear dynamics, structure and pattern formation
- Key processes
  - Generation of magnetic fields: self-excited dynamo
  - (Re)distribution of magnetic flux
  - Dynamics: waves, instabilities
  - Energetics: interference with convective energy transport, non-thermal heating

Magneto-convection in the photosphere



Regimes of magneto-convection in the photosphere

- <B> increases: quiet Sun → plage → umbra
- horizontal scale of convection decreases
- convective energy transport decreases



G-band image: KIS/VTT, Obs. del Teide, Tenerife & M. Sailer, Univ. Obs. Göttingen

Thermal convection

- Schwarzschild/Ledoux criterion for onset of convection:

$$\nabla > \nabla_{ad} + \frac{\varphi}{\delta}\nabla\mu \qquad \text{with} \qquad \nabla = \frac{d\ln T}{d\ln p}$$

$$\varphi = \partial\ln\rho / \partial\ln\mu$$

$$\delta = -\partial\ln\rho / \partial\ln T$$

μ : mean molecular weight

- In diffusive systems, the Rayleigh number must exceed a critical value

$$Ra > Ra_{crit} \qquad \text{with} \qquad Ra \propto \frac{\nabla - \nabla_{ad}}{\kappa\nu}$$

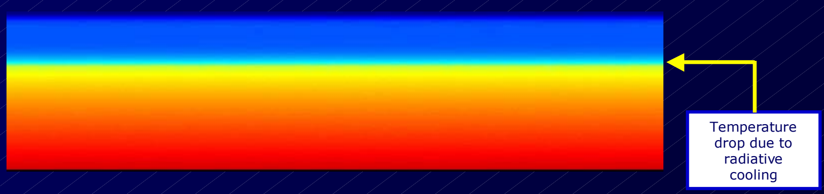
κ: thermal diffusivity

ν: kinematic viscosity

Thermal convection in the photosphere

- cooling layer around visible surface

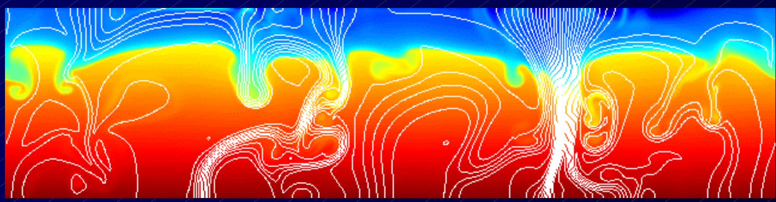
➔ superadiabatic T-gradient at τ=1



- radiative cooling drives strong downflows

Effects of magnetic fields

Convection → Magneto-Convection



- flux expulsion: Lorentz force suppresses motions in strong fields
- convective field amplification: radiative cooling
  → partial evacuation
  → superequipartition fields

Outline

- What is magneto-convection?
- The simulation code
- Simulation of photospheric magneto-convection
- Outlook

Realistic solar simulations: what is required ?

- 3D
- full compressibility
- partial ionization
- non-local, non-grey radiative transfer
- open boundaries
- sufficiently big box (covering the relevant spatial scales)

- *and:* extensive diagnostic tools to compare with observations (continuum & spectral line & polarization diagnostics, tracer particles, etc.)

The MPAe/UofC Radiation MHD (MURAM) Code

Basis Code (Univ. of Chicago)

- 3D compressible MHD
- cartesian grid
- 4th order centered spatial difference scheme
- explicit time stepping: 4th order Runge-Kutta
- MPI parallelized (domain decomposition)

Extensions for solar applications (MPAe)

- radiative transfer: short characteristics
  non-grey (opacity binning), LTE
- partial ionisation (11 species)
- Hyperdiffusivities for stabilization
- open lower boundary condition

The MHD Equations

Continuity equation

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0$$

Momentum equation

$$\frac{\partial \rho \mathbf{u}}{\partial t} + \nabla \cdot \left(\rho \mathbf{u}\mathbf{u} + \left(p + \frac{|\mathbf{B}|^2}{8\pi} \right) \underline{1} - \frac{\mathbf{B}\mathbf{B}}{4\pi} \right) = \rho \mathbf{g} + \nabla \cdot \underline{\tau}$$

Energy equation

$$\frac{\partial e}{\partial t} + \nabla \cdot \left(\mathbf{u} \left(e + p + \frac{|\mathbf{B}|^2}{8\pi} \right) - \frac{1}{4\pi} \mathbf{B} (\mathbf{u} \cdot \mathbf{B}) \right) = \frac{1}{4\pi} \nabla \cdot (\mathbf{B} \times \eta \nabla \times \mathbf{B}) + \nabla \cdot (\mathbf{u} \cdot \underline{\tau}) + \nabla \cdot (\chi \rho \nabla \frac{e}{\rho}) + \rho (\mathbf{g} \cdot \mathbf{u}) + Q_{rad} \, ,$$

$$Q_{rad} = -\nabla \cdot \mathbf{F} = 4\pi\rho \int \kappa_\nu (J_\nu - S_\nu) d\nu$$

$$\frac{dI_\nu}{ds} = -\kappa_\nu \rho (I_\nu - S_\nu)$$

Radiative Transfer Equation

Induction equation

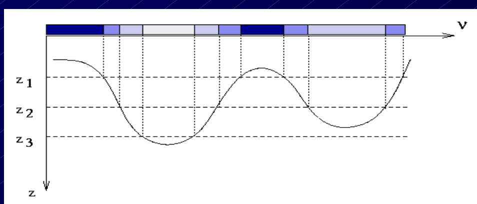
$$\frac{\partial \mathbf{B}}{\partial t} + \nabla \cdot (\mathbf{u}\mathbf{B} - \mathbf{B}\mathbf{u}) = -\nabla \times (\eta \nabla \times \mathbf{B}) \, .$$

Non-grey treatment of radiative transfer

Multigroup method:

(Nordlund 1982, Ludwig 1992, Vögler et al. 2003)

- frequencies are grouped into frequency bins according to the height in the atmosphere where $\tau_\nu = 1$ is reached



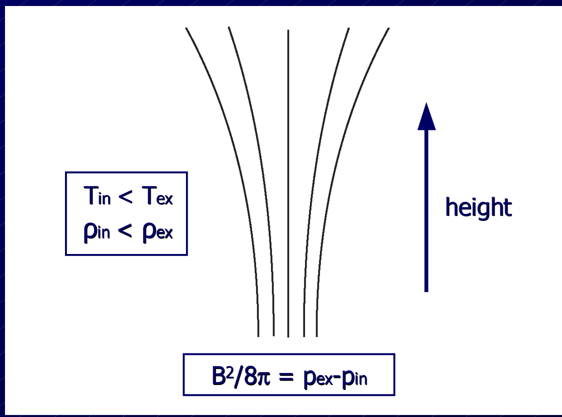
-> calculation of
- bin-averaged opacities
- bin-integrated source function

- transfer equation is solved for each bin ν separately:

$$\frac{dI_\nu}{ds} = -\kappa_\nu \rho (I_\nu - S_\nu)$$

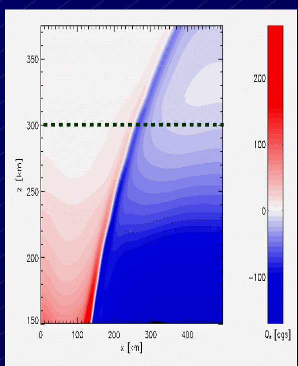
- Non-grey treatment necessary for accurate radiative heating rates:

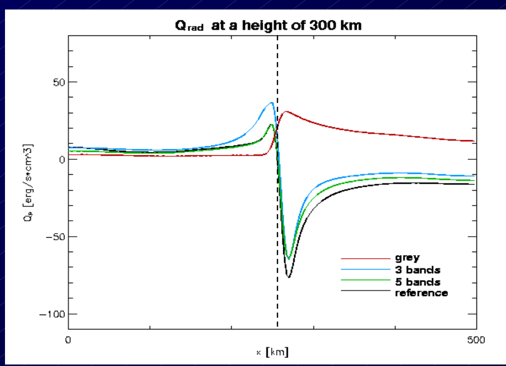
2D magnetic flux-sheet model



- Non-grey treatment necessary for accurate radiative heating rates:

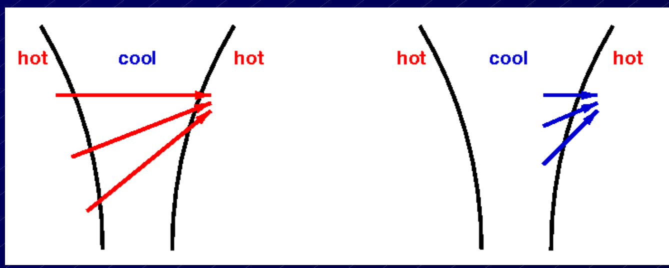
2D magnetic flux-sheet model





➔ Grey RT can lead to qualitatively incorrect heating rates

- Effect of line-opacities on directional heating/cooling:



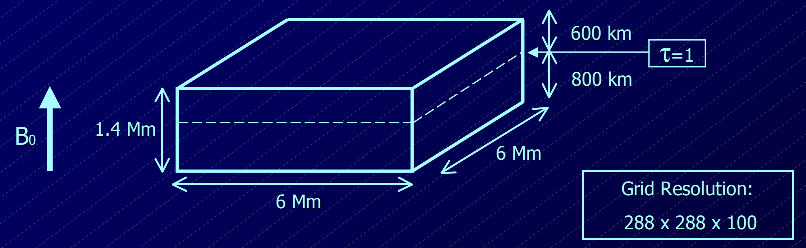
grey case

non-grey case

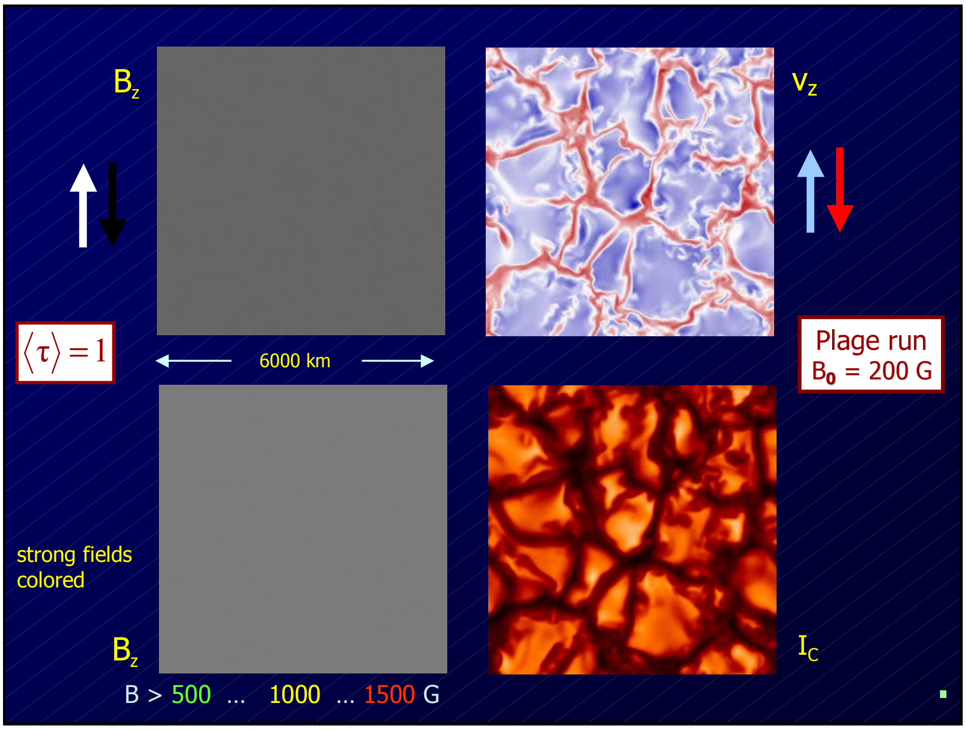
Outline

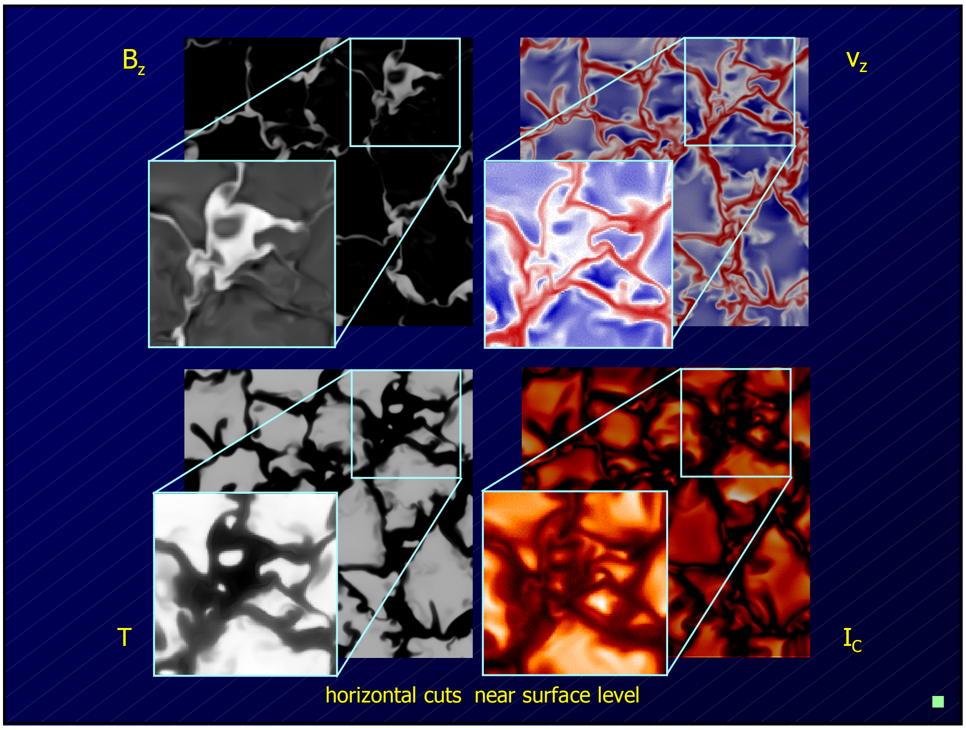
- What is magneto-convection?
- The simulation code
- Simulations of photospheric magneto-convection
- Outlook

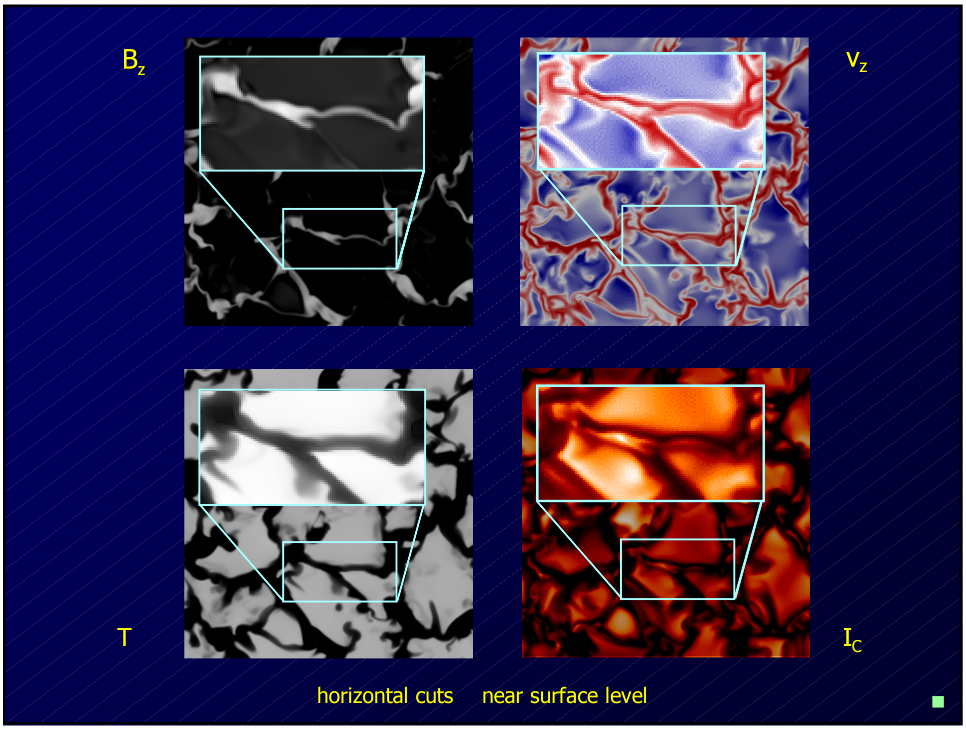
Simulation of a solar plage region



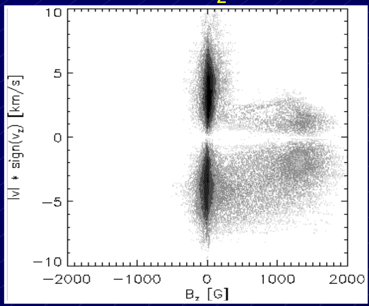
- start convection without magnetic field
- initially vertical magnetic field introduced after convection has become quasi-stationary
- initial field strength: B_0= 200 G




B_z
v_z
T
I_C
horizontal cuts near surface level


B_z
v_z
T
I_C
horizontal cuts near surface level

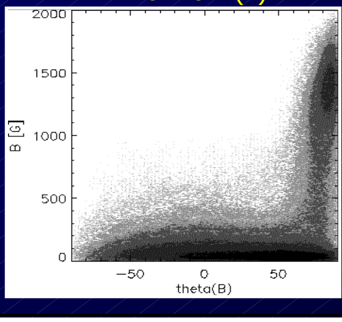
v vs. B_Z



Statistical properties in a layer around $\langle \tau \rangle = 1$

- strong fields inhibit motions
- downflows preferred in regions of strong field

B vs. inclin.(B)

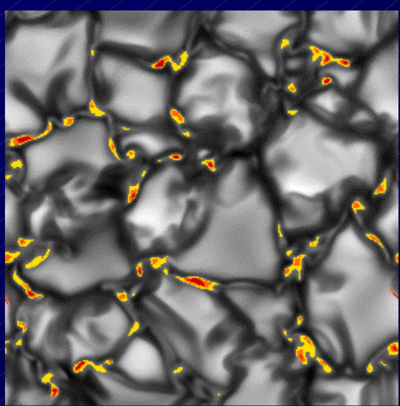


- strong fields are vertical
- weak fields: orientation more evenly distributed

Plage run

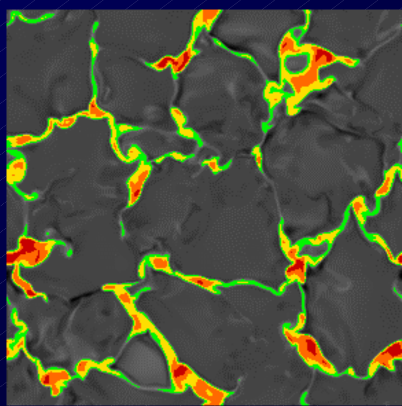
Relation between flux concentrations and continuum intensity

Plage run



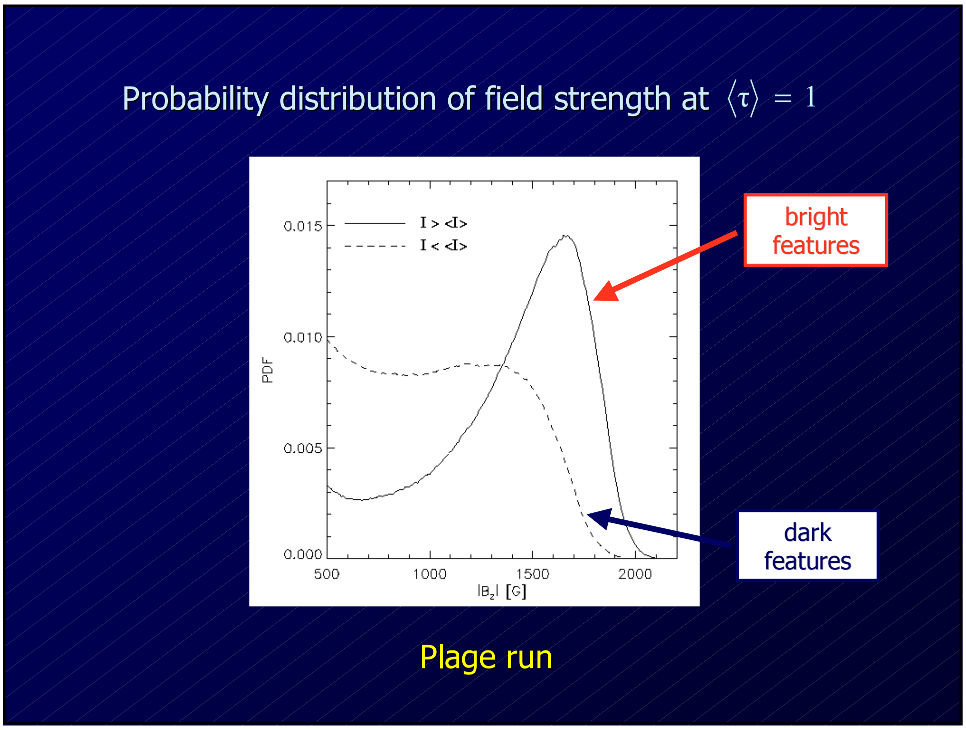
Continuum intensity:

I > 1.0 ... 1.2 <I>

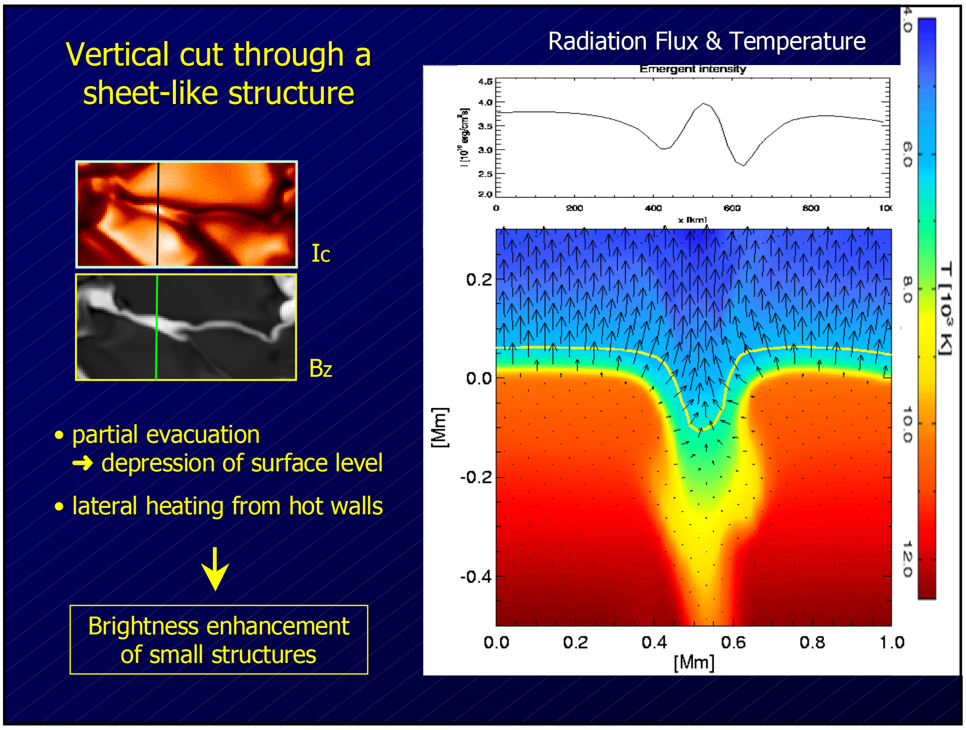


Field strength:

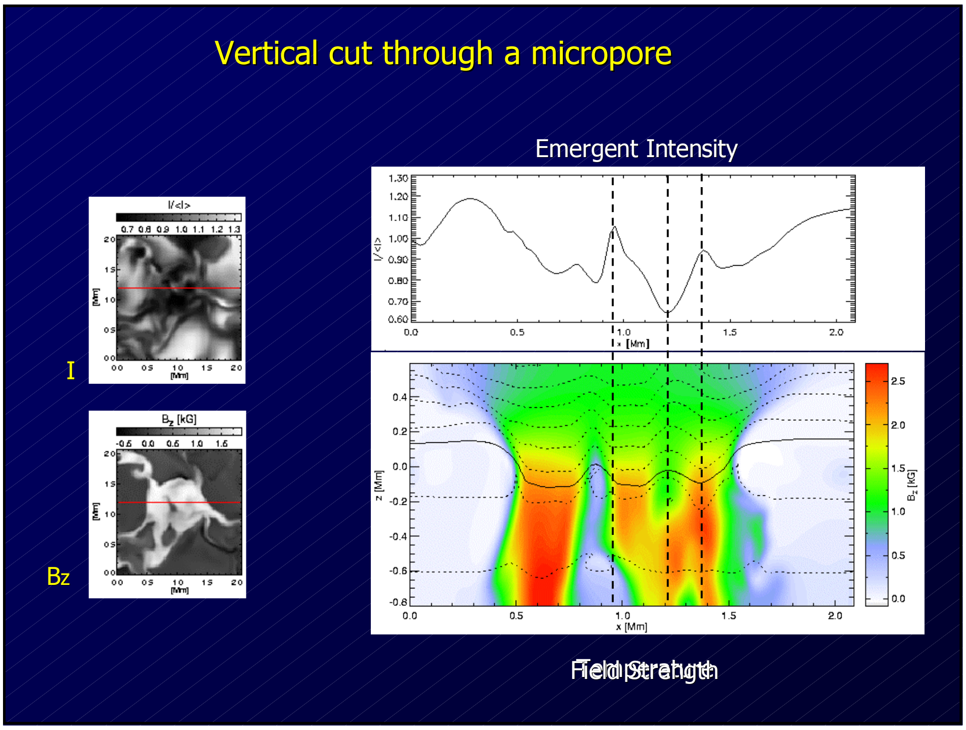
B > 500 ... 1000 ... 1500 ... 1700 G

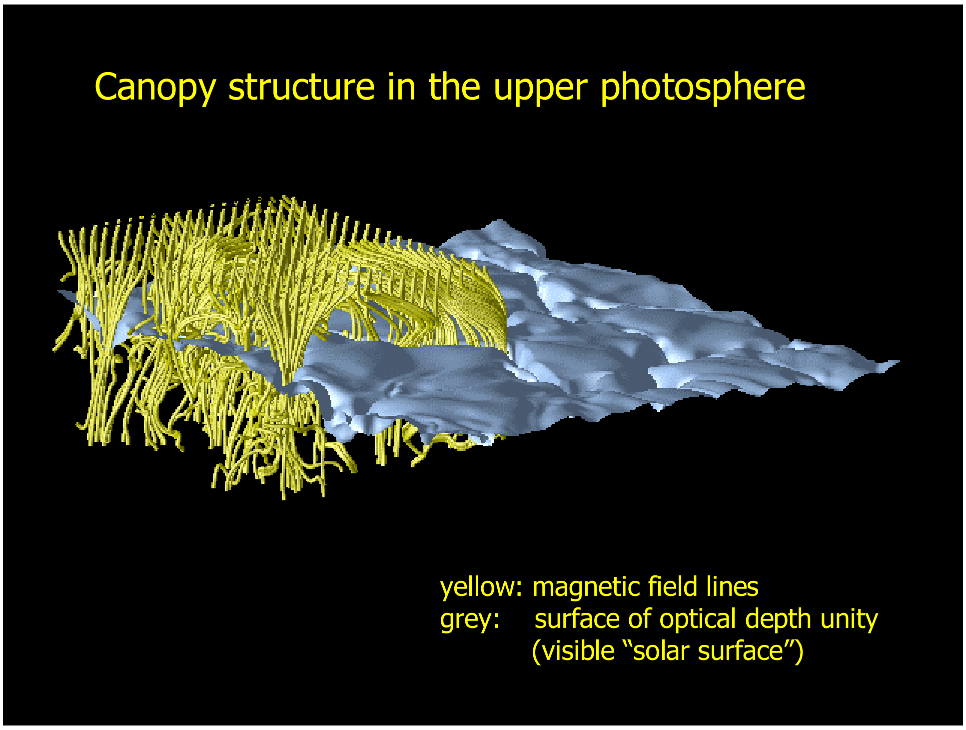


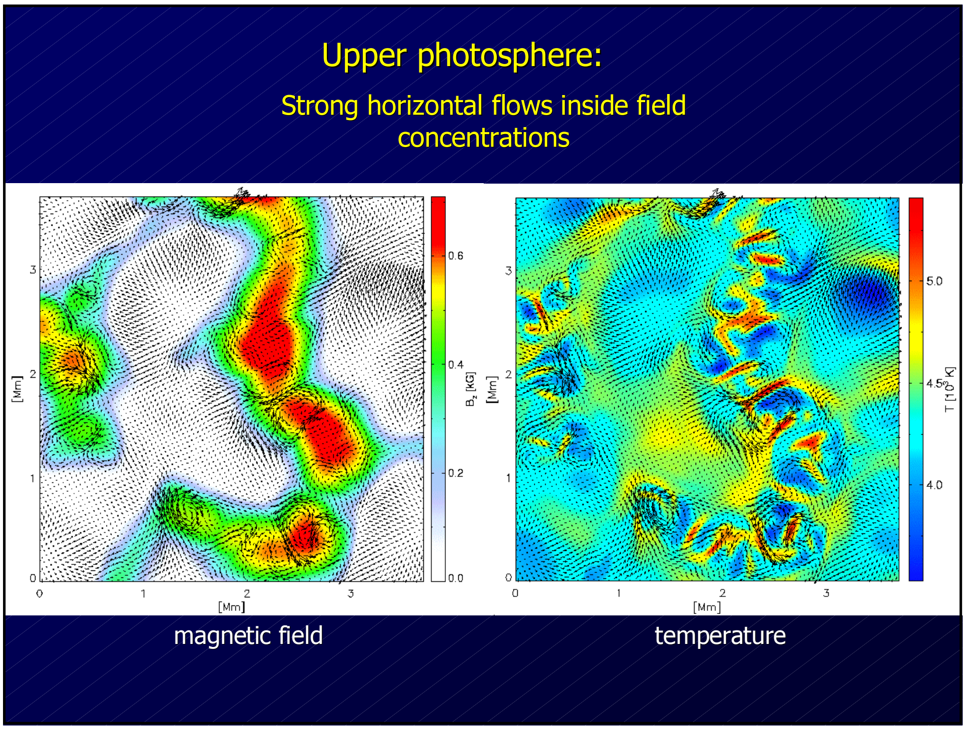
Probability distribution of field strength at ⟨τ⟩ = 1
0.015
0.010
0.005
0.000
PDF
I > <I>
I < <I>
500
1000
1500
2000
|B_z| [G]
bright features
dark features
Plage run

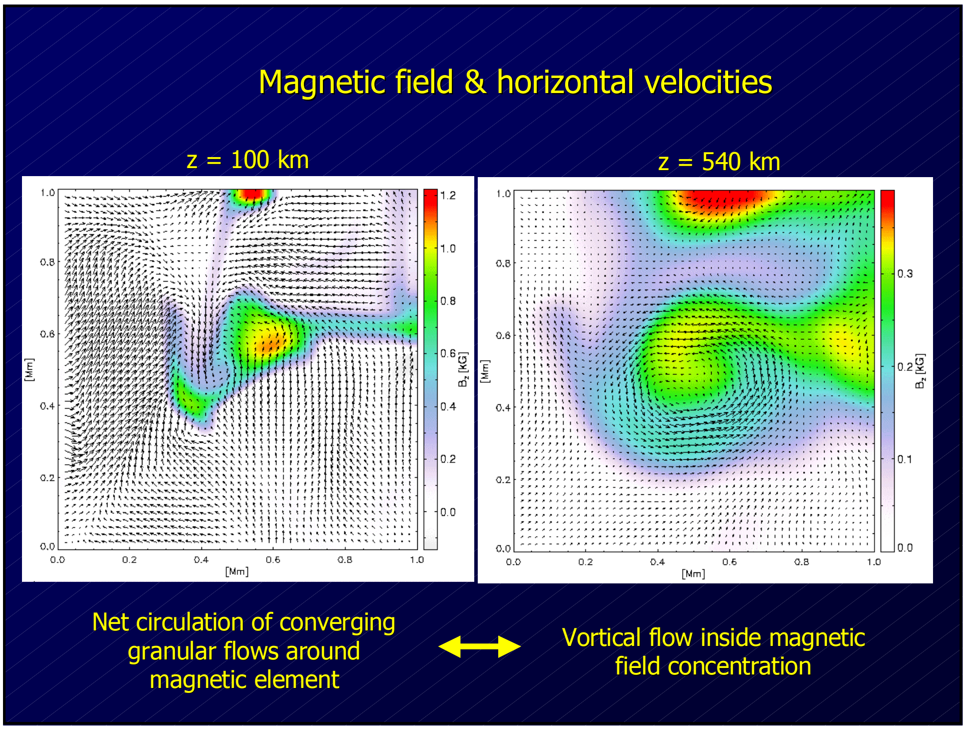


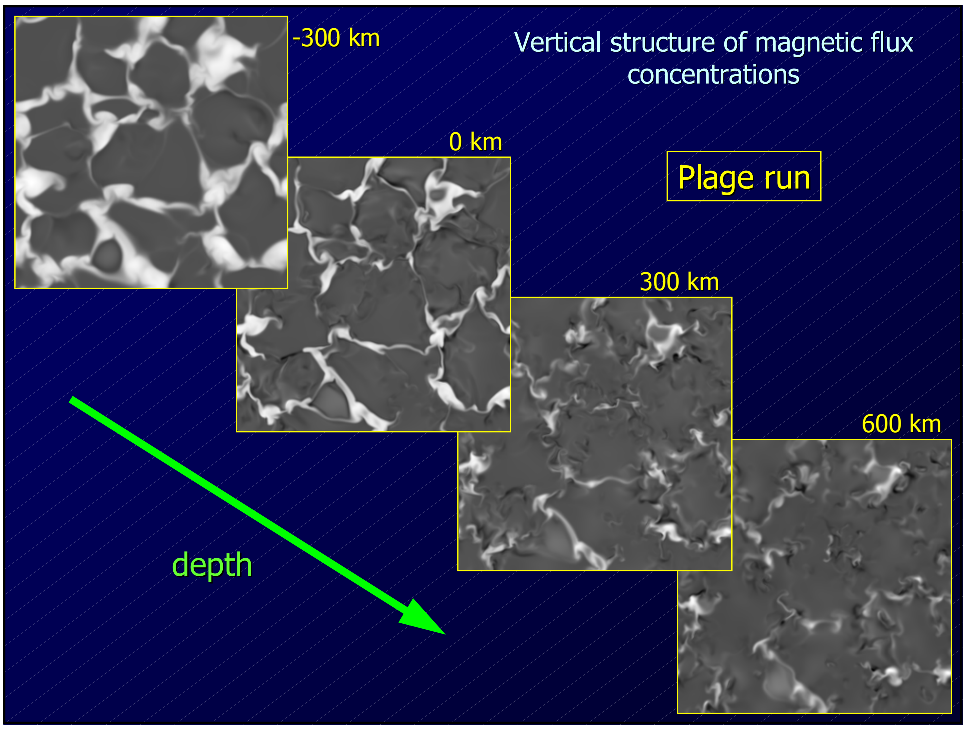
Vertical cut through a sheet-like structure
Ic
Bz
• partial evacuation
➜ depression of surface level
• lateral heating from hot walls
Brightness enhancement of small structures
Radiation Flux & Temperature
Emergent intensity
x [km]
[Mm]
T [10³ K]
4.0
6.0
8.0
10.0
12.0
0.2
0.0
-0.2
-0.4
0.0
0.2
0.4
0.6
0.8
1.0

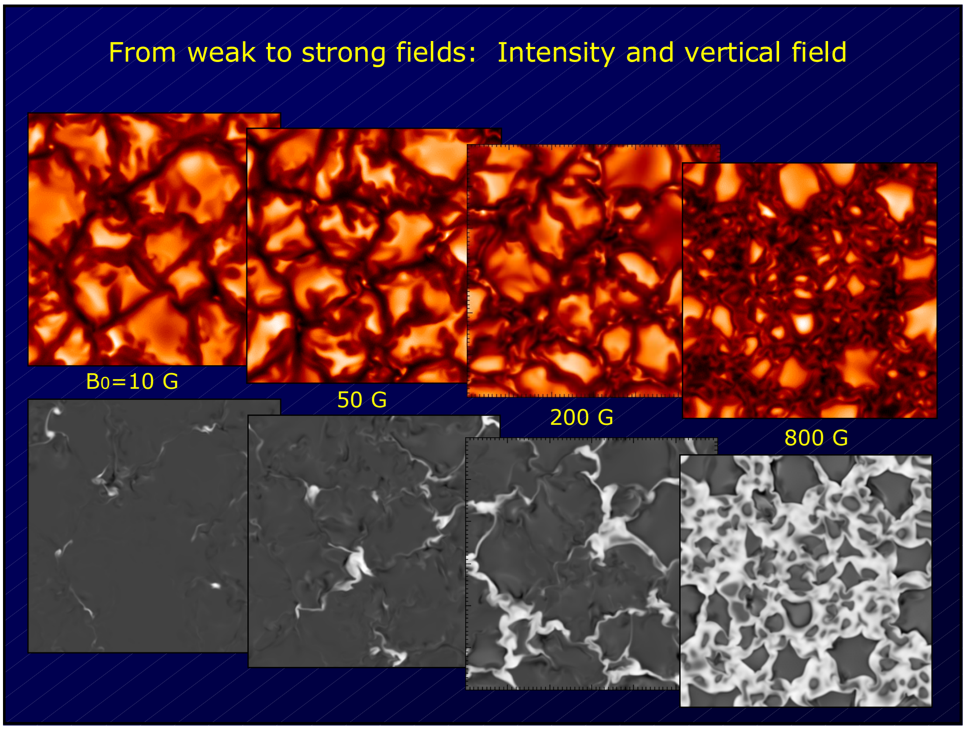

Vertical cut through a micropore
Emergent Intensity
I
Bz
Field Strength


Canopy structure in the upper photosphere
yellow: magnetic field lines
grey: surface of optical depth unity
(visible “solar surface”)

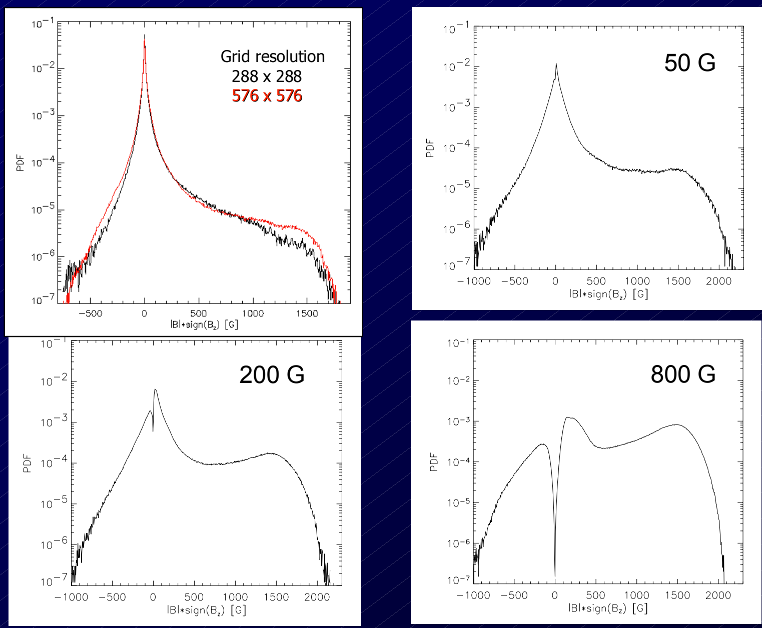

Upper photosphere:
Strong horizontal flows inside field concentrations
[Mm]
B_z [KG]
T [10^3 K]
magnetic field
temperature


Magnetic field & horizontal velocities
z = 100 km
z = 540 km
[Mm]
B_z [KG]
Net circulation of converging granular flows around magnetic element
Vortical flow inside magnetic field concentration

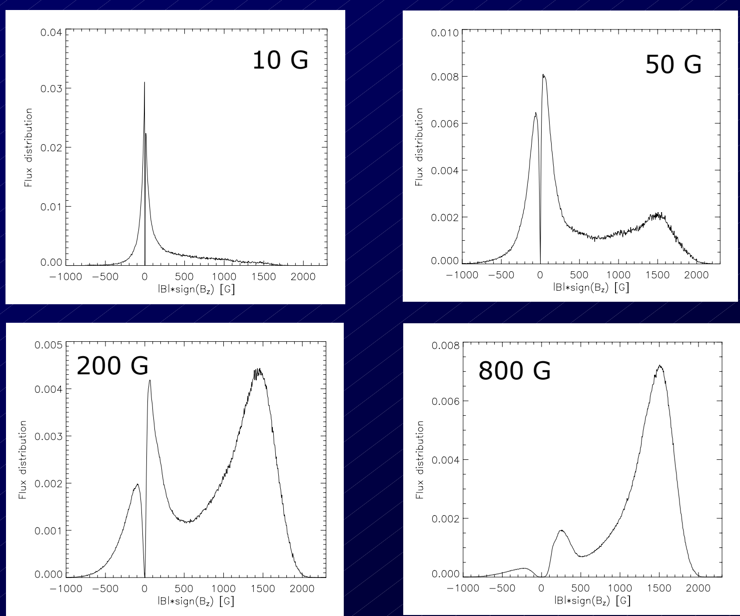

Vertical structure of magnetic flux concentrations
Plage run
-300 km
0 km
300 km
600 km
depth


From weak to strong fields: Intensity and vertical field
B0=10 G
50 G
200 G
800 G

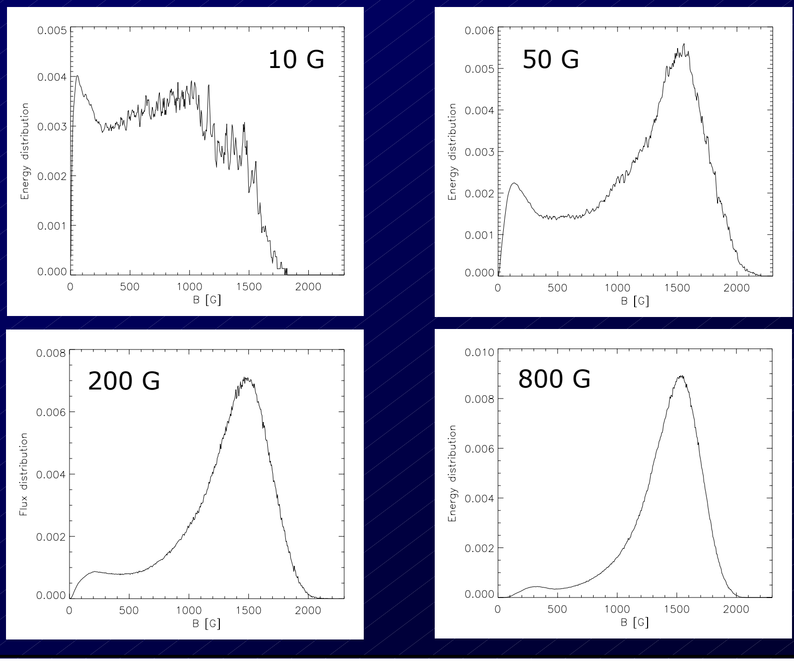
Probability distribution of field strength



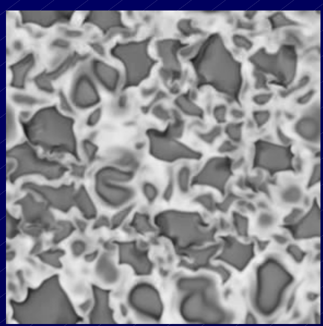
Distribution of magnetic flux



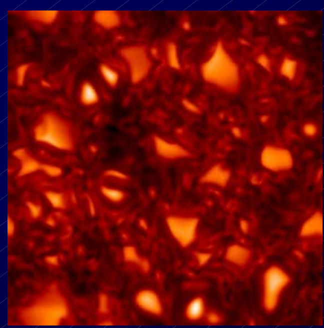
Distribution of magnetic energy



Convection in a strong field: B_0 = 800 G



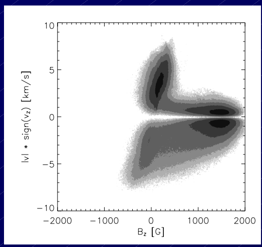
vertical magnetic field



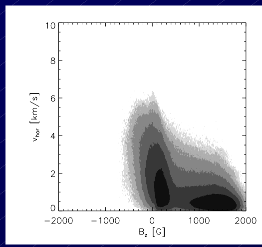
intensity

- reduction of horizontal length scales
- isolated bright upflows (→ umbral dots ??)

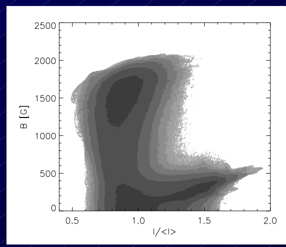
Convection in a strong field: B_0 = 800 G



Bz vs |v|*sgn(vz)



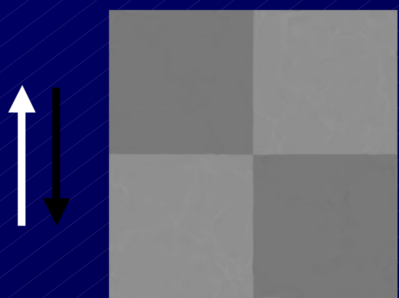
Bz vs v_{hor}



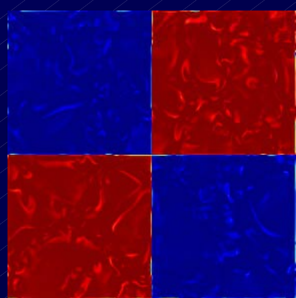
Intensity vs |B|

- strong upflows in weak field regions
- horizontal motions strongly suppressed
- high intensity contrast (22-25 %) due to bright upflows

Convection in a bipolar region:
decay of magnetic flux



vertical magnetic field



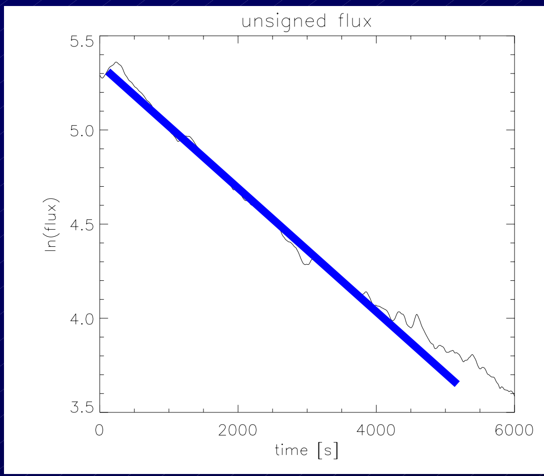
weak fields

+200 G

0 G

-200 G

Convection in a bipolar region:
decay of surface flux



Exponential decay:

$$\frac{\partial B}{\partial t} = \eta_t \cdot \left(\frac{\partial^2 B}{\partial x^2} + \frac{\partial^2 B}{\partial y^2} \right)$$

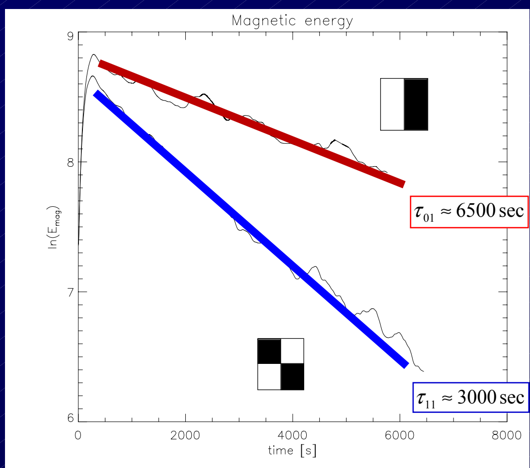
$$B \propto \exp(-t/\tau)$$

$$\eta_t = (\tau \; (k_x^2 + k_y^2))^{-1}$$

$$\tau \approx 3000 \sec$$

$$\eta_t \approx 1.5 \cdot 10^{12} cm^2 / s$$

Convection in a bipolar region:
decay of magnetic energy



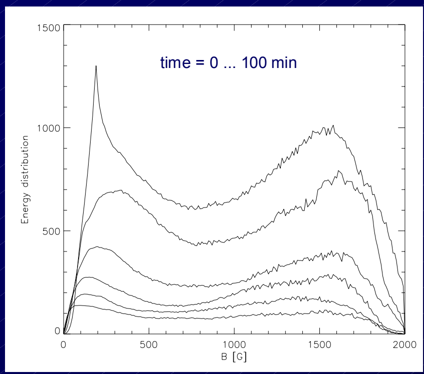
- The energy decays at the same rate as the flux:

$$E_{MAG} \propto \exp(-t/\tau)$$

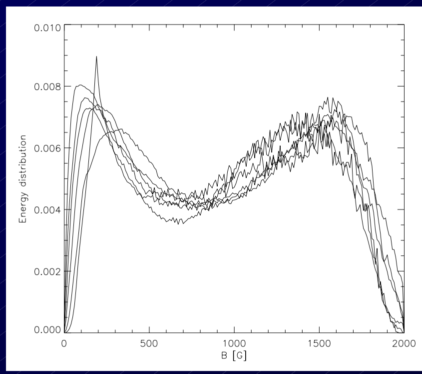
- The decay rates are consistent with an effective „turbulent" diffusivity:

$$\tau_{01} / \tau_{11} \approx 2.2 \approx (k^2{}_x + k^2{}_y) / k^2{}_x$$

Convection in a bipolar region:
Distribution of magnetic energy



energy distribution
for successive times



normalized distributions

- Distribution of magnetic energy is time-independent
- About 30% of the energy stored in weak fields

What else, what next ... ?

- Larger domains ➔ meso/supergranulation
  (→ S. Shelyag)
- Larger magnetic structures: large pores, sunspots
  (→ R. Cameron)
- Formation of bipolar regions by flux emergence
  (→ M. Cheung)
- Extended height range:
  convection zone ➔ chromosphere

Thank you for your att...