Radiative MHD simulation of sunspot structure

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The problem

• No fundamental progress in our understanding of sunspots for decades

• Why?
  - insufficient resolution of fine structure
  - no information about subsurface properties
  - insufficient computational power for ab-initio simulations

• Recently, the situation has changed!
  - AO, image selection & reconstruction, spectro-polarimetry from space (Hinode)
  - local helioseismology
  - massively parallel computers
Basic questions

Are sunspots monolithic („deep“) or clusters („shallow“)?
Basic questions

What causes the small-scale structuring in the umbra and penumbra?

How is the energy transported in the umbra (20%) and in the penumbra (75%)?
Umbral dots: magneto-convection

Local-box simulation of a small volume ($6 \text{ Mm} \times 6 \text{ Mm} \times 1.6 \text{ Mm}$) in a sunspot umbra (Schüssler & Vögler, 2006)

$\langle B \rangle = 2500 \text{ G}$

(Schüssler & Vögler, 2006)
Umbral dots: magneto-convection

- **Brightness**

- **Vertical velocity** (blue: up, red: down)

- **Magnetic field** (bright: high, dark: low)

- **Density fluctuation** (blue: deficit, red: excess)

- **Temperature fluctuation** (blue: cooler, red: hotter)
The new observational picture of penumbral structure

- Dark cores of bright filaments
- Evershed flow along dark cores
- „Uncombed” magnetic structure

Scharmer et al. (2002)

- $B_{\text{hor}} \approx \text{const.}, B_{\text{vert}}$ varies strongly
- „twisting filaments”, roll motion

Zakharov et al. (2008)
MHD simulation sunspots
First attempt: Heinemann et al. (2007)

Field inclination

12 Mm $\times$ 6 Mm $\times$ 3 Mm

Field strength
Large-scale structure

$\tau$ @ 630 nm = 0.1
Large-scale structure

\[ \tau_{630 \text{ nm}} = 0.1 \]

incl(B)

vx

\[ \text{Horizontal distance [Mm]} \]

\[ \text{Field inclination} \]

\[ \text{Velocity [km/s]} \]
Penumbral filaments: vertical cuts
Detailed structure of a penumbral filament

$\tau_{@630 \text{ nm}} = 0.1$

$v_x = -1.4 \text{ km/s} \ldots 3.3 \text{ km/s}$

$v_y = -2.1 \text{ km/s} \ldots 1.5 \text{ km/s}$

$I_c = -0.13 \langle I \rangle \ldots 1. \langle I \rangle$

$v_z = -0.9 \text{ km/s} \ldots 0.7 \text{ km/s}$
Detailed structure of a penumbral filament

\[ \tau_{630 \text{ nm}} = 0.1 \]

- 670 G ... 1970 G
- 17 deg ... 61 deg

\[ |B_x| \]

- 940 G ... 640 G
- 980 G ... 3050 G

\[ \text{inc}(B) \]

\[ \tau_{630 \text{ nm}} = 0.1 \]
Profiles perpendicular to the filament
Profiles perpendicular to the filament

![Graph showing Bz, Bx, and By field strengths vs. arcsec](image.png)
Cuts perpendicular to the filament

\[ I_c \]

\[ \text{inc}(B) \]
Cuts perpendicular to the filament
Cuts along to the filament