Magnetic structuring at spatially unresolved scales

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Magnetograms of the active and quiet Sun

Question: What would the field look like with infinite resolution

To answer this question the line-ratio technique was introduced in 1971
5250 / 5247 line ratio technique

Slope gives intrinsic field strength

Line ratio vs. Δλ (verifies physical validity of the model)

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For the interpretation of the line-ratio data a 2-component model was introduced

\[ \langle B \rangle = aB \]

Since with the two-component model \( B \) is found to be 1 - 2 kG, while \( a \) is typically about 1\%, the concept of intermittent magnetic flux tubes was introduced.

The flux tubes became the theoretical counterpart of the 2-component model.
Extension of the 2-component model through use of the Hanle effect

Spatial resolution element

Magnetic component, filling factor $a$, field strength $B$

Not a “non-magnetic” atmosphere but a mixed-polarity, tangled or turbulent field
Resulting “standard model”

- **Flux tubes** expanding with height, forming canopies above the photosphere. Contribute to the Zeeman effect.
- **Weaker tangled or turbulent field** in between. No information from the Zeeman effect, but accessible with the Hanle effect.

This **dualistic scenario** is however an artefact of applying two diagnostic tools, which are highly complementary: the Zeeman and Hanle effects. The real world is not dualistic.
The area of the left magnetogram is only 0.35 % of the area covered by the right one (scale in arcsec).

Fractal patterns of observed flux densities.

Scale invariance

Empirical PDFs:
La Palma (thick), MDI (thin), Voigt profile (dashed)

Comparison between theory (Stein & Nordlund 2002; solid line for $B_z$, dashed line for $|B|$) and the empirical Voigt function (dotted)

Probability distribution functions PDF

From Stenflo & Holzreuter 2002
PDF of the 2-component model

δ function peak for “non-magnetic” component

δ function peak for magnetic component

“Turbulent” field

“Desert” to be bridged

Field strength

$B_{\text{turb}}$

$B_{\text{flux tube}} \sim 1 \text{ kG}$

Peak ratio $\sim 100$, since the magnetic filling factor is $\sim 1\%$ for the quiet Sun

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Hinode, quiet Sun, spatial resolution ~ 200 km.

The magnetic field is however structured on much smaller scales.
Average Stokes V and Q profiles (Hinode quiet Sun)

Dashed curves: $\partial I / \partial \lambda$

The asymmetry is due to subresolution correlations between spatial gradients of the magnetic and velocity fields.

There is an enormous spread in the $V$ asymmetry for weak flux densities.

This is evidence for ubiquitous magnetic structuring at scales very much smaller than the Hinode 200 km resolution scale.

Evidence from the Stokes $V$ asymmetry $a$ of subresolution structuring

$$a = \frac{V_{\text{blue}} + V_{\text{red}}}{V_{\text{blue}} - V_{\text{red}}}$$
Flux densities in the 6302 \( \text{Å} \) vs. the 6301 \( \text{Å} \) line assuming spatially resolved fields

If the fields were spatially resolved they would fall along the dashed line

Evidence from Stokes \( V \) line ratio

Line ratio vs. flux density for the two populations

Evidence for magnetic structuring on subresolution scales

Relative strength of weak population

Gaussian decomposition of cross section at 50 G

Two distinct populations

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Evidence from Stokes $I$ – magnetic field correlations

Tight correlation between Stokes $I$ (the intensity profile) and the magnetic flux density

$6302 / 6301$ line ratio in $d / w$

$d = $ Stokes $I$ line depth

$w = $ Stokes $I$ line width

Evidence for the entangled effect of Zeeman saturation (due to the effect of large Zeeman splitting on Stokes $I$) and correlation between magnetic fields and the thermodynamic structure on subresolution scales

Since $\partial I / \partial \lambda \sim d / w$, Stokes $V$ scales with $d / w$.
Distributions of the inclination angle $\gamma$ of the magnetic field

Horizontal PDF means isotropic distribution.
Negative slope means predominance of horizontal fields.
Positive slope means predominance of vertical fields.

Histogram for flux densities
(a) 0 - 15 G
(b) all flux values

Histogram exclusively due to the actual noise in the data, derived via Monte-Carlo simulation

Fit parameter $\alpha$ vs. flux density

The solid curve is a fit $\alpha \sim B^2$

Predominance of vertical flux

Isotropic case
Probability density function for the vertical flux density

Dashed curve: observations

Solid curve: representation of the noise-deconvolved observed histogram with a function that is the sum of a symmetric Lorentz profile and an anti-symmetric line dispersion profile.

\[
\frac{[ ( \gamma / 2 )^2 + 0.038 B ]}{[ B^2 + ( \gamma / 2 )^2 ]}
\]

\( \gamma = 8 \text{ G} \)

Dotted curve: the symmetric part (Lorentz function part) of this expression.
Estimate of the lower end of the scale spectrum

**Magnetic Reynolds number**

\[ R_m = \mu_0 \sigma \ell_c v_c \]

**Spitzer conductivity**

\[ \sigma = 10^{-3} T^{3/2} \text{ (SI units)} \]

**Kolmogorov turbulence (inertial range)**

\[ v_c = k \ell_c^{1/3} \text{ (where } k \text{ is a constant)} \]

With \( R_m = 1 \) at the diffusion limit, and \( k = 25 \)
(corresponding to 2.5 km/s for \( \ell_c = 1000 \text{ km} \)), we get

\[ \ell_{\text{diff}} = 1 / (\mu_0 \sigma k)^{3/4} , \text{ or} \]

\[ \ell_{\text{diff}} = 5 \times 10^5 / T^{9/8} \]

For \( T = 10,000 \text{ K} \) we get

\[ \ell_{\text{diff}} = 15 \text{ m} \]
Future steps

The magnetic structuring continues four orders of magnitude below the current spatial resolution limit.

For the spatially unresolved domain we need to transcend the 2-component approach to distribution functions (PDFs).

From the excellent Hinode data set for the quiet Sun we have inferred magnetic distribution functions for the strength and orientation of the field vector, valid for flux densities at the 200 km scale.

To infer the magnetic PDFs in the unresolved domain we first need to explore the scaling laws in the resolved domain and compare them with numerical simulations of magneto-convection.

The PDFs in the resolved domain appear to have a high degree of scale invariance, but this needs to be quantified in detail.
Thank you!