



Solar photosphere magnetization

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THEMIS

via the **law in magnetized media** $\vec{B} = \mu_0 (\vec{H} + \vec{M})$

Observations: a recent review by Horst Balthasar (2018, Solar Phys. 293, 120)

« The Problem of the Height Dependence of Solar Magnetic Fields in Sunspots »

- any method, from the simplest (model integration like Pahlke & Wiehr, 1990, 6 spectral lines) to the most sophisticated (several node SIR code inversion)
- any line
- any telescope (ground-based, spatial like HINODE/SOT/SP)

all agree into

$|dB_z/dz| \approx 3 \text{ G/km}$ (vertical gradient) **whereas** $|dB_x/dx + dB_y/dy| \approx 0.3 \text{ G/km}$ (horizontal gradient)

\Rightarrow **divergence $\neq 0$**

much larger than the measurement inaccuracies

for $1.5\text{e-}3$ polarimetric accuracy, typically 10 G inaccuracy on the longitudinal field and 20 G inaccuracy on the transverse field (Bommier, V., 2007, A&A, 464, 323 and further results.)

Sami Solanki (2003, Astron. Astrophys. Rev., 11, 153) wrote on p. 184

« No satisfactory solution has been found as yet for the unexpectedly small vertical gradients obtained by applying the $\text{div } \vec{B} = 0$ condition. »

What is measured is \vec{H}

Zeeman hamiltonian of an atom embedded in magnetised matter $-\mu_0 \vec{m} \cdot \vec{H}$ (\vec{m} : atomic magnetic moment)

First demonstration in Langevin (1905, Annales de Chimie et de Physique, 5, 70)

Our demonstration:

After a macroscopic average:

$$\vec{B} = \mu_0 (\vec{H} + \vec{M})$$

\vec{B} : the magnetic *induction*

\vec{H} : the magnetic *field*

\vec{M} : the density of magnetic moments or *magnetization*, including

- the atomic magnetic moments \vec{m}
- the magnetic moment of the free charges spiralling about the field

Magnetic energy in a magnetized medium

$$\frac{1}{2} \int \vec{H} \cdot \vec{B} d^3\vec{r} = \frac{\mu_0}{2} \int \vec{H} \cdot (\vec{H} + \vec{M}) d^3\vec{r} = \underbrace{\frac{\mu_0}{2} \int H^2 d^3\vec{r}}_{\text{field energy}} + \underbrace{\frac{\mu_0}{2} \int \vec{M} \cdot \vec{H} d^3\vec{r}}_{\text{matter energy in the field}}$$

– taking into account the external field source contribution (Jackson, 1975), the Zeeman hamiltonian results into $-\mu_0 \vec{m} \cdot \vec{H}$

– the surrounding magnetic moments originate the *depolarizing field* $\vec{H}_d \subset \vec{H}$ (Weiss, 1907, Journal de Physique Théorique et Appliquée, 6, 661)

div \vec{H} may be non-zero, but div \vec{H} has to be fed via div \vec{M}

$$\text{in a plasma } \mu_0 \vec{M} = -\frac{\beta}{2} \vec{B}$$

in the solar photosphere the neutral H density is $n_H \sim 10^{16} \text{ cm}^{-3} \Rightarrow$ neutral $\beta \sim 1$

but the electron density is $n_e \sim 10^{12} \text{ cm}^{-3} \Rightarrow$ charged $\beta \sim 10^{-4} \Rightarrow \mu_0 \vec{M} \ll \mu_0 \vec{H}, \vec{B}$

Our proposal for feeding div \vec{H} : the **electron thermal escape inside the Sun**

- at $0.5 R_\odot$, the e^- thermal velocity is $14 \times$ the escape velocity (protons 0.34)
- initially, e^- and protons are in same number
 - their electric field roughly cancel by pair
 - therefore, an escaping e^- is submitted to the electric field of a single proton
- at $0.5 R_\odot$, the e^- thermal velocity is $6 \times$ the escape velocity from the corresponding proton
- but when the electron density decreases, the electron becomes submitted to several protons
 - the density ratio for the e^- thermal velocity 3 x smaller than the escape velocity from protons is $\sim 6 \times 10^3 \approx 18^3$
- each layer expands towards exterior up to $9 = 18/2 \times$ its width. The spreading velocity is extremely slow (1.7 m/year)
- the summation over 9 layers densities leads to e^- photosphere density similar to the H density
- at the H density, $|dH_z/dz| \approx 3 \text{ G/km}$ is recovered
- the corresponding protons remain inside the star (total charge ~ 0)

Rebuild \vec{B} (for MHD modeling) from the \vec{H} measurements

\vec{B} is responsible for the Lorentz forces induced on the charged matter by the magnetic field

For rebuilding \vec{B} , 2 possibilities:

$$\left. \begin{array}{l} \vec{B} = \mu_0 (\vec{H} + \vec{M}) \\ \mu_0 \vec{M} = -\frac{\beta}{2} \vec{B} \end{array} \right\} \Rightarrow \mu_0 \vec{H} = \left(1 + \frac{\beta}{2}\right) \vec{B}$$

– if the charge density n_{ep} is known for computing β (of charges) :

- else, numerically rebuild \vec{M} from its measured divergence $\text{div } \vec{M} = -\text{div } \vec{H}$
 - $\text{div } \vec{M}$ is known because $\text{div } \vec{H}$ is measured (from 2-line measurements)
 - the direction of \vec{M} is known because $\vec{B}, \vec{H}, \vec{M}$ are all parallel
 - \Rightarrow the derivative of \vec{M} along its direction is known
 - allocate an appropriate limit condition