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## 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)

⇒ divergence  $\neq 0$

much larger than the measurement inaccuracies

for 1.5e-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 x 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  $\sim 0$ )

**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  $\beta$  (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
    - ⇒ the derivative of  $\vec{M}$  along its direction is known
  - allocate an appropriate limit condition