Solar magnetic fields & plasma physics (from measurements)

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Observations → polarimetric analysis $I,Q,U,V$ → inversion $aB,\theta,\psi$ 2-component atmosphere (UNNOFIT code) → ambiguity resolution (divB?)

3 steps

the THEMIS tower
(European site of Izaña, Tenerife island)
According to the field strength (\& \( \lambda \))

- **Zeeman effect** (strong field, typically \( > 100 \) G)
  - Active regions (about sunspots)
  - Quiet regions (far from sunspots)

- **Hanle effect** (weak field, typically \( < 100 \) G)
  - "Second Solar Spectrum" (solar limb)
  - Prominences
  - Corona
Solar Zeeman effect

• Active regions (spatially resolved field)
  – Magnetic field vector map-making
  – Electric field vector map-making (rotB)
  – Magnetic helicity map-making (+ velocity data)

• Quiet regions (spatially unresolved field)
  – Unresolved Fluxtubes ?
UNNOFIT inversion code


• Article Bommier, 2016, JGR Space Physics, 121, 5025 (MTSSP Conference 2015)
  – Quiet region magnetic fluxtubes:
    – Diameter 30 km
    – Distance 230 km
    – Field strength 1.3 kG

• Project for UNNOFIT implementation in the SDO/HMI data treatment pipeline (Stanford)
Second Solar Spectrum

• Linear polarization formed by scattering and observed close to the solar limb. Hanle effect (weak field).
  – Weak polarization \( \Rightarrow \) weak spatial resolution

• Theoretical challenge
  – Multilevel/multiline, line profiles (PRD), NLTE polarized radiative transfer, Hanle effect

• Non-perturbative theory in the density matrix formalism: Bommier (1997a, 1997b, 2016a)

• Numerical application to the Na I D line polarization modeling (Bommier, 2016b, preliminary)
  – @ IDRIS, 20 Mh in 2017-2018 for 400 iteration steps
Fig. 1. Intensity (top panel) and degree of linear polarization (bottom panel) for the spectral region around the Na\textsuperscript{i} \text{D}_2 5889.97 and \text{D}_1 5895.94 \text{Å} lines, obtained near the north polar limb on April 3, 1995. The level of the continuum polarization, obtained from Fluri & Stenflo (1999), is given by the horizontal dashed line. The polarization peaks in the line cores, in particular that of the \text{D}_1 line, remain enigmatic.

Since there is abundant evidence from Hanle-effect observations ruling out the possibility that a sufficiently large fraction of the solar atmosphere could be occupied by that weak magnetic fields (e.g. Bianda et al. 1998a,b, 1999), we seem to be led to the conclusion that the explanation by Landi Degl’Innocenti of the \text{D}_1 polarization peak in terms of lower-state polarization must also be ruled out (cf. Stenflo 1999). The Hanle-effect observations refered to include lines like Ca\textsuperscript{i} 4227 \text{Å}, which has \textit{J}=0 for the lower level and no nuclear spin, and therefore cannot be subject to optical depopulation pumping effects. For these reasons the observed \text{D}_1 and \text{D}_2 polarization peaks still remain an enigma, a challenge for the theorists. It is hard to see how lower-state atomic polarization can really play a significant role at all in the magnetized and highly conductive solar atmosphere. A variation of the optical pumping scheme could be that other, more short-lived atomic states than the initial one can couple and transfer atomic polarization to the intermediate state of the scattering transition. This possibility needs to be looked into, but until then, the \text{D}_1 polarization will remain a mystery.

3. Comparison between the \text{D}_1 polarizations of Na\textsuperscript{i} and Ba\textsuperscript{ii}

The polarization peak in the Doppler core of the Na\textsuperscript{i} \text{D}_1 line is prominent in our various recordings at different disk positions and in different observing runs, but the polarization amplitude varies, while the amount of wing polarization remains more constant (but of course varies with limb distance). Fluctuations in the Doppler core with invariant wing polarization is a characteristic signature of the Hanle effect (cf. Stenflo 1994, 1998), as was demonstrated for the Na\textsuperscript{i} \text{D}_2 line in Stenflo et al. (1998), for the Ca\textsuperscript{i} 4227 \text{Å} line in Bianda et al. (1998a, 1999), and for the Sr\textsuperscript{ii} 4078 \text{Å} line in Bianda et al. (1998b).

Fig. 2 illustrates how the wing polarization of the Na\textsuperscript{i} \text{D}_1 line can stay the same, while the core polarization varies. The thicker curve is the same as that of Fig. 1, obtained in April 1995 near the solar north pole, while the two thinner curves were obtained in September 1996 at two different locations near the solar south pole. The September 1996 recordings have a polarization amplitude that is almost twice that of the April 1995 recording. We also have recordings with smaller or almost vanishing core peaks, but we have here chosen to illustrate the higher peaks, because they accentuate the mystery and constrain the possible theoretical models more. Such high peaks do not allow much room for depolarizing effects (e.g. due to weak magnetic fields).

Fortunately there exists a strongly polarizing multiplet with the the same \textit{J} quantum numbers as that of multiplet no. 1 of neutral sodium, namely multiplet no. 1 of ionized barium.
magnetic field vector at the Sun's surface sunspot group

15 February 2011 from 00:00 to 04:00 TU
X2.2 flare at 01:45

vertical component of the electric current vector obtained from the Maxwell equation \( \text{rot } \vec{B} = \mu_0 \vec{J} \)

LESIA, Observatoire de Paris, & "Solar Dynamics Observatory" satellite
courtesy G. Aulanier
OHM code
Observed non-zero divB

• Magnetic flux decreases with increasing height (always same sign)
  – \(|\frac{dBz}{dz}| \approx 3 \text{ G/km}\) (in and about sunspots)
  – 10 references
• Now we measure also the transverse field
  – \(|\frac{dBx}{dx} + \frac{dBy}{dy}| \approx 0.3 \text{ G/km}\)
  – 7 references
• \(\Rightarrow\) apparently \(\text{div}B \neq 0\)
• Average div is the div of average B
• Intuition: horizontal and vertical are not equivalent in the Sun’s surface layer: anisotropy
• Physics of stratified media: a factor of 20 (Froude number)
Ambiguity resolution (divB)

Sunspot of negative polarity observed close to disk center
2 spectral lines: HINODE/SOT/SP Fe I 6301.5 Å et 6302.5 Å

resolution "as is"
Minimizing |divB|
→ failure

resolution "with scaling"
Minimizing |divB|
with Δx and Δy divided by 10
→ success
The outcome belongs to plasma physics
My proposed explanation

- **Anisotropic** Debye shielding
- The flow velocity is the same for the particle of interest and its "cloud" ⇒ it can be factorized
- ⇒ the Debye formalism, developed for the electric potential, can be also applied to the magnetic potential

\[ V = \frac{1}{4\pi\varepsilon_0} \frac{q}{r} \quad \vec{A} = \frac{\mu_0}{4\pi} \frac{q\vec{v}}{r} \]

1 particle of charge \( q \) and velocity \( \vec{v} \)
Discussion

• non-zero divB is usually ascribed to monopole
• A monopole causes flux creation
• Shielding causes flux fading
  – another way to modify the flux  
  – due to a plasma physics effect 
  – The shielding has to be anisotropic
• In solid **anisotropic** media, the divergence of the magnetic **field** (H) may be $\neq 0$
Experiment?

- Walter Gekelman and collaborators
- Large Plasma Device (LAPD) @ UCLA
- about 50,000 measurement points
- accuracy 50 μG on B
- External applied field Bz = 330 G
- internal created field up to 10 G
- Anisotropic flows
- Reports observed non-zero divB (in 2012 and 2016 papers)
  - assigned to detector misalignment
- need of "divergence-cleaning" the data
The influence of boundary conditions on the development of tearing modes has also been explored. In particular, the influence of line-tied boundary conditions has been considered within both the MHD\cite{12,16} and kinetic\cite{17} descriptions of tearing. To extend the theory to nonperiodic systems, the basic approach involves superimposing multiple eigenmodes from the periodic theory in order to satisfy the line-tied boundary condition in the nonperiodic case. In sufficiently large systems, one can often superimpose just two tearing eigenmodes from the periodic theory, which is sufficient to approximately satisfy the boundary conditions. The results from these papers suggest that in large space and astrophysical plasmas, the stability constraints arising from boundary conditions are not overly restrictive, and thus the basic scaling predictions for the tearing mode growth rate will survive in non-periodic systems.

3. Experimental setup

The experiment was done in the upgraded Large Plasma Device (LaPD) at UCLA\cite{18}. The machine is pictured in figure 1.

Figure 1. Photograph of the LAPD device. The solenoidal coils, which produce the axial magnetic field, are yellow and purple. The machine is over 24 meters long and the plasma column is 18 meters long. The 60 cm-diameter barium oxide cathode, which produces the DC discharge for the background plasma, is in the larger chamber on the left. The LaB$_6$ cathode used to produce the neutral sheet is in a second vacuum chamber barely visible on the extreme right. There are over 450 diagnostic ports.

Figure 2. Experimental setup (not to scale) for making the background plasma and the current sheet. The cathode and anode used to make the background plasma are shown at the right. The background magnetic field points in the $z$ direction. The slot location ($z=0$) is taken to be $z=0$. The switches shown are high-current transistor switches, and the two cathode-anode systems are electrically independent of one another. The start of the coordinate system is at the slot and center of the device ($x=y=0$).

Making a current sheet

He, $5.4\times10^{-5}$ Torr

LaB$_6$

$B_0=200$ G

C mask

$1$ Hz, $15$ ms pulses

$70$ V, $4$ kA

$LaB_6: V_d=260$ V, $I_d=390$ A, $T_{pulse}=3.5$ ms