Measurement Methods of Chromospheric and Coronal Magnetic Fields

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Solar Magnetism

George Hale (1908)
Observation of spectral line splitting in sunspots

Zeeman Effect

Start of the solar magnetism era
Effects of Magnetic Field in the Solar Atmosphere

- Source of the solar activity
- Coupling
- Heating of the upper atmosphere
- Sun-interplanetary medium connection
- Solar wind acceleration
- Structuring of the atmosphere

“If it were not for its magnetic field, the Sun would be as dull a star as most astronomers think it is” [R. Leighton 1965]
Solar magnetic field: Gross view

* **Closed component:**
  - Most of the solar magnetic flux (> 90%);
  - Closely correlated with sunspot activity;
  - Strong fields (KG) occupy on average < 1% of the solar surface;
  - Responsible for the total irradiance variations; …

* **Open component:**
  - Small contribution to the solar magnetic flux;
  - Poorly correlated with sunspot activity;
  - Form the interplanetary field & solar wind; …

* The photosphere (chromosphere) is approximately a 2-D layer
  The magnetic field is 2-D vector field

* Any coronal remote measurement is affected by the line of sight
  The coronal field is 3-D and weak; More difficult to measure

[Stenflo 1982; Wang et al. 2005; …]
Qualitative measurements of the magnetic field
Field topology

Based on the emission properties of the plasma

- Contrast effect
- Temperature sensitivity of species emission
- Plasma trapping in the field lines
  \[ \beta \ll 1 \text{ in the solar atmosphere} \]

No information on the field strength nor “orientation”

Observing different lines formed at different layers:
*Topological evolution of the magnetic field through the solar atmosphere*
**Photosphere**

**Brightness contrast** *(Continuum 4320 Å)*

- **Sunspots Umbrae** *(KG vertical fields)*; **Penumbrae** *(Flux tube threads at different inclinations)*;
- **Pores** *(Emerging strong flux)*; **Light bridges**; **Granulations**; **Dark network lanes**; ...

**G-band: Better contrast**

**Bright points** *(Concentration of tiny flux tubes; Resolution <100 Km)*

[Muller & Roudier 1984; Rutten et al. 2001; Steiner et al. 2001; Berdyugina et al. 2003; Zakharov et al. 2005]
Lower Chromosphere Ca II H & K
Umbrae; penumbrae; light Bridges; Granulation in negative; Bright plages

Upper Chromosphere H-α
Dark filaments; Homogeneous distribution of the field; Canopy

Cool material with coronal extension: Prominences; Spicules: Mass flow & shocks driving; Heating of the chromosphere; Relation to flux tubes

[De Pontieu et al. 2004]
Corona UV & X-ray emissions
Good tracers of the magnetic field

Corona Density distribution
Streamers (closed field: Slow Wind);
Coronal holes (open field: Fast Wind);
Polar plumes & interplumes;
Superradial expansion; ...

SOHO/EIT & LASCO/C1
[Banaszkiewicz et al. 1998]
Quantitative measurements of the magnetic field

Direct measurements: in situ

Available measurements are recorded faraway from the Sun $0.3 \leq r \leq 1$ AU (Pioneer, Mariner: Behannon 1978; …; HELIOS: Musmann et al. 1977; Mariani et al. 1978 & 1979; …)

Average of the radial and azimuth components with high accuracy

Remote sensing measurements

Based on the polarization properties of the radiation emitted by magnetized plasma

Zeeman effect
Hanle effect
Radio emission

Polarization

Daily averages of $|B_r|$  Daily averages of $|B_\phi|$
Zeeman Effect

Magnetic field induces

_splitting of atomic levels

_change in spectral line profiles (measurable if splitting ≥ Doppler width)

Polarization signature

Zeeman $\lambda$-splitting: $\Delta \lambda \propto g_{\text{eff}} B \lambda^2$

Chromosphere: Works better in the visible & infra-red
Corona: Works better in the infra-red (weakness of the field)

Fe 6302 Å
Fe 15648 Å

[Schüssler et al. 2003]
Zeeman effect works for:
Strong fields (100 < B < KG) with homogeneous polarities (sunspot, plages, pores, ...) 
Small area of the solar surface

No Zeeman effect in mixed polarities regions: cancellation effect
Need high spatial resolution

Corona: Not many applications due to field & emission weakness
Need active regions at the limb with strong coronal emission
[Solanki et al. 2003; Lagg et al. 2004]

Measurement of the 3-D magnetic vector (He I 10830 Å): identification of emerging loops & current sheet (signature of heating) high in the chromosphere

The Second Solar Spectrum
Volume I, II & III
Visible – UV Zeeman effect

[Achim Gandorfer]
Coronal Zeeman effect

[Harvey 1969]  Fe XIV 5303 Å green line above active regions and in prominences  
\[ B = 13 \pm 20 \text{ G} \]

[Kuhn 1995]  Fe XIII 10747 Å above active regions using Evans coronagraph: Upper limit on \( B \) of 40 G

[Lin et al. 2000]  Fe XIII 10747 Å above active region  
\[ B(1.12 - 1.15 R_\odot) = 10 - 33 \text{ G} \]

These measurements suffer poor spatial & temporal resolution
**Hanle Effect:** Modification of the linear polarization of resonant scattered radiation by a local magnetic field

**Classical interpretation:**

Excited atom ≡ damped ($\propto A_{ul}^{-1}$) oscillators precessing around $B$ at

- $\omega \tau \approx 1$
- $P \neq P_0$ ; $\varphi \neq 0$

> $P$ & $\varphi$ are function of the three components of $B$

> Ideally Hanle effect provides non-ambiguous vector field
The Hanle effect

* Works for typical fields < 100 G (depends on the spectral line);

* Needs high polarimetric sensitivity & moderate spatial resolution (weakness of the Hanle signal)

* Needs resonance scattering:
  Solar limb (Stenflo & Keller 1997; etc.; Talk by J. Trujillo);
  Prominences (Sahal-Bréchot et al. (1977); etc.; Talk by A. Lopez Ariste)

* Unlike Zeeman effect: Field strength from depolarization by turbulent fields [Stenflo 1982]

* Hanle strong-field regime \((\omega_L >> A_{ul})\)
  Direction of the field [Charvin 1965]

[Querfeld 1974, 1977; Arnaud & Newkirk 1987; …]
Mainly radial field \((Fe \, green \, & \, IR \, lines)\)
[Stenflo & Keller 1997] Polarization picks in the corps of Na I D-lines

Enigma!!!

[Landi Degl’Innocenti 1998] Polarization in the ground level: “Evidence against turbulent and canopy-like magnetic fields in the solar chromosphere” or milligauss field

[Bianda, Stenflo & Solanki 1999] Hanle depolarization of lines with unpolarized lower level: evidence for turbulent and/or canopy-like fields

[Schrijver & Zwaan 2000] Na I D-lines are formed below the canopy & above the turbulent photospheric fields of few Gauss strength that drop off very fast

Hanle effect works better in the UV

Observation of O vi 1032 Å in the polar coronal hole at ~1.3 R⊙ under different angles with respect to the polar axis [Raouafi et al. 1999 & 2002a,b]

First measurement of the polarization of a UV line in the corona

\[ p = 9 \pm 2\% ; \quad \varphi = 9 \pm 6° ; \quad r = 2.88 \pm 0.05 \]

Constraints on the magnetic field in the polar coronal holes: \( B \sim 3 \, G \) [Hassler et al. 1997]

\( \varphi \neq 0 \): Evidence of Hanle effect signature in the polar coronal holes

Possibility of measuring the magnetic field in the corona using UV lines
**Gyroresonance emission**

Interaction of the circular polarized electromagnetic modes\((x \, \& \, o)\) with the electrons yield a strong circular polarization signal

Powerful diagnostic of \(100 \leq B \leq 2000\) Gauss

Opacity is significant only at the first discrete harmonics of \(\omega_B\):

\[
B_{\text{max}} = \frac{V_{\tau=1}}{2.8 \times 10^6} s \quad (s = 2 \, \text{or} \, 3)
\]

Observing at the different harmonic frequencies yield isogauss surfaces of the magnetic field at different coronal heights

**Limitation:** No information on the Gyroresonance emission height

**Compensation:**

Stereoscopic observations [Aschwanden & Bastian 1994]

Extrapolations [Lee et al. 1998]

...
Faraday rotation: Rotation of the plane of linear polarization of radio radiation propagating through a magnetized plasma with density $n_e$

Radio refractive index

$$n^2 \approx 1 - \frac{\omega_p^2}{\omega^2} \left( 1 \mp \frac{\Omega_e}{\omega} \right)$$

- $\omega$: wave frequency
- $\omega_p$: plasma frequency
- $\Omega_e$: $e^-$ gyrofrequency

$$v_p = c \mp \frac{c \omega_p^3}{2 \omega^3} \Omega_e$$

- RH circular polarization
- + LH circular polarization

Rotation of the plane of linear polarization by

$$\Delta \chi \propto \int_{\text{LOS}} n_e \vec{B} \cdot d\vec{s}$$ [Nicholson 1983]

Coronal Faraday effect is effective from $\sim 4$ to $\sim 15$ R$_\odot$ & during occultation of

* Natural sources (Galactic or extragalactic: Sofue et al. 1976; Bird et al. 1980; Mancuso & Spangler 1999; ...): Advantage is the existence of these sources around the Sun & their spatial extend

* Interplanetary space probes (PIONEER: Stelzried et al. 1970; HELIOS: Bird 1982, Pätzold et al. 1987; ...): Observations are only possible close to the ecliptic & rare
Study of the fluctuating and turbulent component of the coronal plasma \((B, n_e, \text{waves})\) through time variations of rotation measures (RM) [Hollweg et al. 1982; HELIOS]

Magnetic field in CMEs \(B(7.5 \ R_\odot) = 10 - 20 \ \text{mG}\) [Bird et al. 1985; HELIOS]

Limitations of the method: Occultation occurs infrequently; 2-D mapping is not possible; Model dependence of Faraday rotation (Needs density model \(n_e\) to diagnose \(B\) and visa versa)
Extrapolation of the magnetic field

Potential fields ($J=0$: simple topologies); Linear & Non-linear force-free field ($J//B$: complex topologies)

Powerful tools for evaluating

- The energetics and activity of coronal magnetic structures (active regions, filaments, loops, etc.)
  [Heyvaerts & Hagyard 1991; Amari et al. 1999; ...]
- Coronal flows [Marsch et al. 2004]
- Large scale coronal field [Wiegelmann et al.]
- ...

Need accurate photospheric fields: errors may affect the reconstruction of the coronal field [Klimchuk & Canfield 1994]

Force-freeness of photospheric fields? Values of $\alpha$ may not be appropriate in the corona since the photosphere is not force-free [Metcalf et al. 1995]

Need chromospheric & coronal measurements to constraint extrapolation models + Proxies (loops, ...) for comparison
Other methods

**Bremsstrahlung emission**
LOS averaged field strengths from circular polarization signal from active regions (accuracy as low as 1-6 Gauss with RATAN-600 & VLA radio telescopes)

[Brosius et al. 1997; Bogod & Gelfreikh 1980; Gelfreikh 1994; …]

*Talk By S. White*

**Coronal loop oscillations**
Flare-generated oscillations of coronal loops:
Absolute value of the magnetic field strength [Nakariakov & Ofman 2001]

**Simulations**

G-Band

20 km resolution
[Schüssler et al. 2003]

**Observations**

SST ~100 km resolution
[Scharmer et al. 2002]
**Magnetometry** *(future projects)*

**Coronal field:**
**Advanced Technology Solar Telescope** *(4 m; 2012; Polarization in the infra-red);*
**Solar Probe** *(2013)* **Two solar polar passes at ~4 R⊙:** **Golden opportunity for in-situ measurements of the coronal field close to the Sun**

**Chromospheric field:**
**GREGOR** Tenerife 1.5 m; wind flushing; $\lambda = 0.39 \text{ nm} - 2.5 \mu\text{m}$; FOV 300"; Spatial resolution 70 km; Adaptive optics.
**DOT++** La Palma 1.4 m; wind flushing; Adaptive optics (speckle reconstruction); Spatial resolution 0.07".
**New Solar Telescope** *(2016)* *(1.6 m)* *(1005) high order adaptive optics + speckle + real-time speckle image reconstruction; Visible & infrared (IR) polarimetry; $\lambda = 0.39 - 1.6 \mu\text{m}$; Spatial Resolution: 0.07" at 300 nm & 0.1" at 1.565 μm.
**Advanced Technology Solar Telescope** *(Haleakala, Hawaii)* 4 m
Polarization sensitivity $10^{-4}$; $\lambda = 0.3 - 35 \text{ mm (UV – IR)}$; Spatial resolution < 0.1"; High-order adaptive optics.
Conclusions

What is needed is complete picture for the solar atmosphere

- Combine the different techniques: Proxies; Zeeman & Hanle effects; radio observations; Simulations, ...
- Simultaneous multi-line observations: field at different layers
- Combine ground and space observations
- Improve measurements of the other plasma parameters (densities, temperatures, flows, …)
- ...

Future of the solar magnetic field

- Promising future for strong fields
- More work has to be done for weak fields
- Much more work is to be done for the coronal field