Introduction to Daytime Astronomical Polarimetry

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Introduction to Solar Polarimetry

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Overview

- Solar polarimetry covers a very broad range of wavelengths, from X-rays (e.g. in flares) to radio waves (coming from corona), including UV, visible and IR.

- Most polarimetric observations have been made in the visible, followed by the IR and radio waves.

- A range of processes have been proposed as sources of the polarization:
  - Zeeman effect
  - Scattering polarization
  - Bremsstrahlung
  - Gyroresonance radiation

I won’t talk much about processes
The Sun, a Boring Star?

Never look directly into the Sun with unprotected eyes!

Never ever with a Telescope that doesn’t have a blocking filter!
The Dynamic Sun

Prominence (gas at 10000 C)

Active region loops (1 million degrees)
The Violent Sun

Flare

Coronal mass ejection
The dynamics and activity of the Sun are driven by its Magnetic Field.
Zeeman diagnostics

- Direct detection of magnetic field by observation of magnetically induced splitting and polarisation of spectral lines.

- Clear Zeeman splitting seen in sunspots. Outside spots often subtle effect in intensity ➔ Use unique polarisation signature.

- Measurement of polarization is central to measuring solar magnetic fields.

- Zeeman effect: by far most common way of measuring solar B field.
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Zeeman splitting of atomic levels & lines

- Transitions between Zeeman split upper and lower atomic levels lead to spectral lines that are split in wavelength.

- Transitions are allowed between levels with \( \Delta J = 0, \pm 1 \) & \( \Delta M_J = 0 (\pi), \pm 1 (\sigma_b, \sigma_r) \) (for the most common types of transitions: electric dipole radiation).
Stokes profiles produced by the Zeeman effect

- **Stokes** \( I \) = intensity; complex dependence on \( B \)
- **Stokes** \( Q \) = net linear polarisation; samples transverse component of \( B \)
- **Stokes** \( U \) = net linear polarisation, rotated by 45° relative to \( Q \); also samples transverse component of \( B \). \( Q \) & \( U \) give azimuth of \( B \)
- **Stokes** \( V \) = net circular polarisation; samples longitudinal component of \( B \)
Effect of changing field strength: typical solar absorption line

Formula for Zeeman splitting (for $B$ in G, $\lambda$ in Å):

$$\Delta \lambda_H = 4.67 \times 10^{-13} g_{\text{eff}} B \lambda^2 \text{ [Å]}$$

Splitting between observed $\sigma$-peaks = $\Delta \lambda_H$ only if

Zeeman splitting $\Delta \lambda_H > \Delta \lambda_D$ = Doppler width of line

Stokes $V$ shows splitting = $\Delta \lambda_H$ only for $B > 1000$ G
Stokes profiles: dependence on $B$, $\gamma$, and $\phi$ for Zeeman split line

Juanma Borrero
Zeeman splitting $\sim \lambda^2$

$I$ and $V$ images showing magnetic features and no magnetic features for Fe I 1564.8 nm and Fe I 630.2 nm.

$B$ in a snapshot of 3D MHD simulation of a piece of Sun.
- **Magnetogram:** Roughly speaking, a map of the (LOS) magnetic field

- Useful when star can be resolved, e.g. Sun

- **Magnetograph:** Instrument to make maps of Stokes $V$ in wing of Zeeman sensitive line

- Conversion of polarization into magnetic field requires a careful calibration

Magnetogram obtained by MDI on SOHO
What does a magnetogram show?

- Plotted at left:
  - Top: Stokes $V$ along a spectrograph slit
  - Bottom: Sample Stokes $V$ profile
  - Red bars: example of a spectral range used to make a magnetogram, which shows longitudinal component of $B$
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- In practice a combination of multiple $\lambda$ ranges is used to counter effects of Doppler shifts and large Zeeman splitting

- Nowadays also vector magnetograms, providing maps of full magnetic vector
The Sun’s Measured Magnetic Field

Sequence of Magneto-grammes over a Solar rotation

MDI/SOHO
Spectrograph-polarimeters vs. Filter-polarimeters

- Sun is an extended object in the sky → make images → 2D
- Zeeman effect needs spectral information → 3D
- Sun changes rapidly → make movies → 4D
  ➔ 4-D data hyper-cube needed, but current instruments only allow 2-D recordings at any one time
  ➔ Give priority to either instantaneous spatial or $\lambda$ coverage

**Spectrograph:** 1 spatial + spectral dimension simultaneously → scan to get 2$^{nd}$ spatial dimension → 3D data cube

**Filtergraph:** record 2 spatial dimensions simultaneously → scan to get spectral dimension → 3D data cube

Repeat with time to get information on evolution → 4D
Spectropolarimeter data

Time needed to scan this region: roughly 20 min
Filtergraph data
The Sun’s Measured Magnetic Field

Sequence of Magneto-grammes over a Solar rotation

MDI/SOHO
The Sun’s Measured Magnetic Field

Sequence of Magneto-grammes over a Solar rotation

MDI/SOHO

Spatial resolution approx. 3000 km
Higher Resolution Shows More Details

Sunspot: Magnetogram & Ca II K image by Hinode
Higher Resolution Shows More Details

Spatial resolution approx. 200 km

Sunspot: Magnetogram & Ca II K image by Hinode
Structure and dynamics at small spatial scales

Radiation-MHD Simulations of small-scale magnetic fields

Magnetic field  Vögler et al.  Intensity

Spatial resolution 10 km
Cancellation of Stokes $V$ signals

Spatial resolution element

Unresolved magnetic features with magnetic flux

$$\Phi_i = B_i A_i$$, where

- $B_i = B$ in element $i$
- $A_i = \text{area of elem. } i$

Field pointing towards observer

= positive polarity magnetic field

Field pointing away from observer

= negative polarity magnetic field
Stokes $V$ signal cancellation

Stokes $V$ signal only samples the **net magnetic flux**

**Extreme case:**

- Negative polarity magnetic flux
- Positive polarity magnetic flux (within spatial resolution element)

\[ \text{negative polarity} \quad \text{positive polarity} \quad = \quad (\text{within spatial resolution element}) \]
Scattering polarization

- Atoms scatter light resonantly, if collisions are rare
- Atoms sitting in the atmosphere, scatter radiation from solar surface
- If incoming light is anisotropic (i.e. mainly from one direction) \(\Rightarrow\) scattered light is **linearly polarized parallel to limb**
Scattering polarisation at Sun’s limb

- Atoms high in atmosphere:
  - Scatter radiation since collisions are rare (low density)
  - Produce linearly polarized radiation because of anisotropic illumination
    - Limb darkening ($dT/dz < 0$, where $T = \text{temp.}$)
    - High location of atom
- Scattering + anisotropy $\Rightarrow$ linear polarisation $\parallel$ limb
Hanle effect: Modification of scattering polarisation by magnetic field. 2 effects:

- **Depolarisation**
  - depends on field orientation
  - depends on $B$ (complete depolarisation if $\Delta \lambda_H \gg$ natural line width; i.e. radiative width)
  - also present for unresolved mixed polarity fields!

- **Rotation of polarisation plane**
  - depends on $B, \gamma, \chi$
  - only if field is spatially resolved
  - Works for weak fields, where Zeeman is ineffective (corona)
When does the Hanle effect work?

- Needs scattering polarisation. Scattering of radiation takes place when collisions between the scattering atom and electrons are weak, i.e. where the density is low.

- Best in upper photosphere and chromosphere (on disk), in corona (off limb).

- Works if Zeeman splitting is comparable to natural line width: 0.1 ... 100 G.

- Important: Hanle effect samples a regime in which Zeeman effect is insensitive, e.g. in corona (most Zeeman measurements are restricted to the lower-middle photosphere).
Now you have the data, then what?

If you torture the data long enough, they will confess!

Gerard Piel

Which method of torture is the most effective for analysing solar Sokes data?

For simplicity, I’ll only consider Zeeman-effect
Zeeman effect: information content

- **Intensity line profile**
  - Stokes $I$ has information on $B(z)$, but this info is hidden if splitting incomplete. Stokes $I$ is also affected by elemental abundances, $T(z)$, $P(z)$, $v_{\text{turb}}(z)$, $v_{\text{LOS}}(z)$, etc.

- **Polarization line profiles**
  - Stokes $V \Rightarrow \langle B_{\text{long}} \rangle(z)$
  - Stokes $Q, U \Rightarrow \langle B_{\text{trans}} \rangle(z)$
  - Stokes $Q, U, V \Rightarrow B(z)$ (full vector)
  - $Q, U, V$ also react to $T, P, v_{\text{turb}}, v_{\text{LOS}}$...

- **Physical quantities often effect Stokes profiles non-linearly & non-uniquely**

Hinode/SP Lites et al.
Inversions: automated extraction of physical parameters

Slide by M. van Noort

Technique pioneered by Bruce Lites
Inversions: automated extraction of physical parameters

More or less simple model: stratification of various physical quantities at one position on Sun.
\( \alpha \) = Set of free parameters

Solution of polarized radiative transfer equations

Observations at a telescope with a spectro-polarimeter

The Sun

Slide by M. van Noort
Inversions: automated extraction of physical parameters

Solution of polarized radiative transfer equations

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The Sun

Observations at a telescope with a spectro-polarimeter

Determine differences $\Delta S$ between computed and observed Stokes spectra

Slide by M. van Noort
Inversions: automated extraction of physical parameters

Solution of polarized radiative transfer equations

Use $\Delta S$ to find a better set of free params $\alpha$

Observations at a telescope with a spectro-polarimeter

The Sun

Slide by M. van Noort
Temperature

Inversion of a 3D data set:
Sunspot fine structure

Magnetic field strength
Sunspot fine structure

Inclination of magnetic field
Sunspot fine structure

Azimuth of magnetic field
Modern inversions allow such maps to be determined over a range of heights (the heights sampled by the inverted spectral lines).