Magnetic Fields in the Atmospheres of the Sun and Stars

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Before starting...

Concentrate on observations: only few equations
Will use cgs units

Many people have contributed tremendously with material, advice etc. Without their help this lecture would never have been possible. Only some are named here:

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Thank you!
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- Activity in stellar envelopes caused by the magnetic field
Introduction
The Sun in White Light

Gas at 5800 K
The Dynamic Sun

Prominence

Sunspot

9-Nov-2008
19:33:59 UT
The Violent Sun

Flare

Solar wind and coronal mass ejections
In order to understand the dynamics and activity of the Sun, we need to know and understand the magnetic field.

The source of the Sun’s activity is the magnetic field.

Wiegelmann 2004
Stellar magnetic fields

Magnetic fields are found on stars throughout the HR-diagram. Often they produce activity on the star or influence its evolution (e.g. of stellar rotation).

Berdyugina 2008
Basics of polarimetry and the measurement of solar magnetic fields
Methods of solar magnetic field measurement

- **Direct methods:**
  - Zeeman effect \(\rightarrow\) polarized radiation
  - Hanle effect \(\rightarrow\) polarized radiation
  - Gyroresonance and Bremsstrahlung \(\rightarrow\) polarized radiation (in radio range)

- **Indirect methods: Proxies**
  - Bright or dark features in photosphere (sunspots, G-band bright points)
  - Ca II H and K plage
  - Fibrils seen in chromospheric lines, e.g. H\(\alpha\)
  - Coronal loops seen in EUV or X-radiation
Atom in magnetic field

Consider the Hamiltonian of an atom in a magnetic field (Gaussian cgs units; atom in L-S coupling)

\[
H = -\frac{\hbar}{2m} \nabla^2 + V(r) + \xi(r) \mathbf{L} \cdot \mathbf{S} + \left( -\frac{e}{2mc} \mathbf{B} \cdot (\mathbf{L} + 2\mathbf{S}) + \frac{e^2}{8mc^2} (Br \sin \theta)^2 \right)
\]

First 3 terms are kinetic energy, electronic potential, spin-orbit coupling with \( \xi(r) = 1/(2m^2c^2r)(dV/\,dr) \)

Last two terms are magnetic energy terms derived from magnetic vector potential

For fields up to B~10 MG (1 kT), magnetic terms are small compared to Coulomb potential. Fine structure and field treated by perturbation theory

Following J. Landstreet
Magnetic field regimes

\[
H = -\frac{\hbar}{2m} \nabla^2 + V(r) + \xi(r) \mathbf{L} \cdot \mathbf{S} + \left( -\frac{e}{2mc} \mathbf{B} \cdot (\mathbf{L} + 2\mathbf{S}) + \frac{e^2}{8mc^2} (Br \sin \theta)^2 \right)
\]

- Perturbation theory regimes:
  - Quadratic magnetic term << linear term << spin-orbit term: (linear) Zeeman effect
  - Quadratic magnetic term << spin-orbit term << linear term: Paschen-Back effect
  - Spin-orbit term << linear term << quadratic magnetic term: quadratic Zeeman effect

- Schiff 1955, Quantum Mechanics, Chapt. 23 & 39

Following J. Landstreet
(Linear) Zeeman effect

- In weak-field (Zeeman) limit, atomic energy level is only slightly perturbed by \((e/2mc)\mathbf{B} \cdot (\mathbf{L}+2 \mathbf{S})\).

- In L-S coupling (light atoms), \(J\) and \(M_J\) are good quantum numbers. Magnetic moment of atom is aligned with \(J\). Energy shift of level is proportional to \(\mathbf{B} \cdot \mathbf{J}\), so there are \(2J+1\) different magnetic sublevels.

\[ E_i = E_{i0} + g_i (e\hbar/2mc) \mathbf{B} \cdot \mathbf{M}_J = E_{i0} + \mu_0 g_i M_J \mathbf{B} \]

where

\[ g_i = 1 + \left[ J(J+1) + S(S+1) - L(L+1) \right] / \left[ 2 J(J+1) \right] \]

is the (dimensionless) Landé factor (L-S coupling).
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).
Splitting patterns of lines

- Depending on $g$ of the upper and lower levels, the spectral line shows different splitting patterns

- **Positive:** $\pi$ components: $\Delta M_J = 0$

- **Negative:** $\sigma$ components: $\Delta M_J = \pm 1$

- **Top left:** normal Zeeman effect (rare)

- **Rest:** anomalous Zeeman effect (usual)
Zeeman effect observed

- First measurement of a cosmic magnetic field, in a sunspot, was carried out 1908 by G.E. Hale

- On Sun: Zeeman effect changes spectral shape of a spectral line (subtle in most lines outside sunspots)

- Zeeman effect also introduces a unique polarization signature

- Measurement of polarization is central to measuring solar magnetic fields
Polarized radiation

- Polarized radiation is described by the 4 Stokes parameters: $I, Q, U$ and $V$

- $I =$ total intensity $= \left[ I_{\text{lin}}(0^\circ) + I_{\text{lin}}(90^\circ) = I_{\text{lin}}(45^\circ) + I_{\text{lin}}(135^\circ) = I_{\text{circ}}(\text{right}) + I_{\text{circ}}(\text{left}) \right]$

- $Q = I_{\text{lin}}(0^\circ) - I_{\text{lin}}(90^\circ)$

- $U = I_{\text{lin}}(45^\circ) - I_{\text{lin}}(135^\circ)$

- $V = I_{\text{circ}}(\text{right}) - I_{\text{circ}}(\text{left})$

- Note: Stokes parameters are sums and differences of intensities, i.e. they are directly measurable
Polarization and Zeeman effect

Longitudinal Zeeman Effect

Transverse Zeeman Effect
Zeeman effect: information content

- **Line splitting**
  - Stokes $I \Rightarrow B$

- **Line broadening**
  - Stokes $I$ : no info on $B$

- **Polarization**
  - Stokes $V \Rightarrow \langle B_{\text{long}} \rangle$
  - Stokes $Q, U, V \Rightarrow B$

- **Atomic diagnostics (hot gas)**
  - Zeeman effect (except some Ap stars & WDs)

- **Molecular diagnostics (cool)**
  - Zeeman & Paschen Back

(ZIMPOL, J. Stenflo)
Effect of changing field strength

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

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

$$g_{\text{eff}} = \frac{1}{2}(g_l + g_u) + \frac{1}{4}(g_l + g_u)(J_l(J_l + 1) - J_u(J_u + 1))$$

$g_{\text{eff}}$ is the effective Landé factor of line

For large $g_{\text{eff}} B \lambda^2$: $\Delta \lambda_H = \Delta \lambda$ betw. σ-component peaks
Zeeman splitting $\sim \lambda^2$

Fe I 630.2 nm

Fe II 656428 nm
Dependence on $B$, $\gamma$, and $\phi$

- $I \sim \kappa_\sigma (1+\cos^2 \gamma)/4 + \kappa_{TT} \sin^2 \gamma/2$
- $Q \sim B^2 \sin^2 \gamma \cos 2\phi$
- $U \sim B^2 \sin^2 \gamma \sin 2\phi$
- $V \sim B \cos \gamma$

- $V$: longitudinal component of $B$
- $Q$, $U$: transverse component of $B$
- Above formulae for $Q, U, V$ refer to relatively weak fields (e.g. $B$ and $B^2$ dependence of field)
- Zeeman splitting etc. is hidden in $\kappa_\sigma$ and $\kappa_{TT}$. For $Q$, $U$, $V$ these dependences have not been given for simplicity.
Dependence on $B$, $\gamma$, and $\phi$

- $I \sim \kappa_\sigma(1 + \cos^2 \gamma)/4 + \kappa_\pi \sin^2 \gamma/2$
- $Q \sim B^2 \sin^2 \gamma \cos 2\phi$
- $U \sim B^2 \sin^2 \gamma \sin 2\phi$
- $V \sim B \cos \gamma$

- $Q$, $U$: transverse component of $B$
- $V$: longitudinal component of $B$

Formulae for $Q,U,V$ refer to weak fields.

$\kappa_\sigma$ and $\kappa_\pi$ (splitting etc.) not given for $Q,U,V$ for simplicity.
- **Magnetograph:**
  Instrument to make maps of (net circular) polarization in wing of Zeeman sensitive line

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

- **Image:** Example of magnetogram obtained by MDI

- Conversion of polarization into magnetic field requires a careful calibration.
What does a magnetogram show?

- **Plotted at left:**
  - **Top:** Stokes \( I, Q \) and \( V \) along a spectrograph slit
  - **Middle:** Sample Stokes \( Q \) profile
  - **Bottom:** Sample Stokes \( V \) profile
  - **Red bars:** example of a spectral range used to make a magnetogram. Often only Stokes \( V \) is used (simplest to measure), gives longitudinal component of \( B \).
Synoptic maps approximate the radial magnetic flux observed near the central meridian over a period of 27.27 days (= 1 Carrington rotation).
Dependence on $B$, $\gamma$, and $\phi$

- $I \sim \kappa_\sigma (1+\cos^2 \gamma)/4 + \kappa_{\Pi} \sin^2 \gamma/2$
- $Q \sim B^2 \sin^2 \gamma \cos 2\phi$
- $U \sim B^2 \sin^2 \gamma \sin 2\phi$
- $V \sim B \cos \gamma$

- $Q$, $U$: transverse component of $B$
- $V$: longitudinal component of $B$

- Formulae for $Q, U, V$ refer to weak fields
- $\kappa_\sigma$ and $\kappa_{\Pi}$ (splitting etc.) not given for $Q, U, V$ for simplicity
Measured Magnetic Field at Sun’s Surface

Month long sequence of magnetograms (approx. one solar rotation)

MDI/SOHO
May 1998
Cancellation of magnetic polarity

Spatial resolution element

Unresolved magnetic features with field strength $B$ and filling factor

$$f = \sum_i \frac{A_i}{A_{\text{tot}}}$$

= positive polarity magnetic field

= negative polarity magnetic field

Stokes $V$
Stokes V signal cancellation

Stokes V signal only samples the net magnetic flux.

Extreme case:

- negative polarity magnetic flux
  - \[
  \begin{array}{c}
  \text{negative polarity} \\
  \text{magnetic flux}
  \end{array}
  \]
  =

- positive polarity magnetic flux
  - \[
  \begin{array}{c}
  \text{positive polarity} \\
  \text{magnetic flux}
  \end{array}
  \]

\[
\begin{align*}
\text{negative polarity magnetic flux} & + \\
\text{positive polarity magnetic flux} & = \\
\text{net magnetic flux}
\end{align*}
\]
Scattering polarisation at Sun’s limb

- If collisions are rare, light is scattered.
- Illumination of atoms is anisotropic due to:
  - Limb darkening ($dT/dz < 0$, where $T = \text{temp.}$)
  - Atom high in atmosphere.
- Scattering + anisotropy $\Rightarrow$ linear polarisation parallel to limb.
- **Hanle effect**: Modification of scattering polarisation by magnetic field. 2 effects:

  - **Depolarisation**
    - depends on field orientation
    - depends on $B$ (it is complete if $\Delta \lambda_H \gg$ natural line width, i.e. for $B > 0.1$-100 G)
    - also present for unresolved mixed polarity fields

  - **Rotation of polarisation plane**
    - depends on $B$, $\gamma$, $\chi$
    - only if field is spatially resolved
Hanle diagnostics: simple examples

- **Depolarisation**
  - No rotation

- **No depolarisation**
  - No rotation

- **Depolarisation + Rotation**
Example of Hanle rotation & depolarisation

- More complex to describe Hanle than Zeeman effect

- Hanle parameters:
  - **Depolarization factor** $p/p_{\text{max}}$ where $p$ is polarization degree for $B\neq 0$, $p_{\text{max}}$ is $p$ for $B=0$
  - **Angle of rotation** $\beta$, with $\tan 2\beta = U/Q$ ($\beta=0$ for $B=0$)

- Atmospheric parameters
  - **Field strength parameter** $\Omega$, with $\Omega=2g_u\omega_L/\gamma_N \sim B$, where $\gamma_N$ is natural damping constant, $\omega_L$ is Larmor frequency, $g_u$ is Landé factor of upper level,
  
  \[ \gamma_N = \frac{\mu_0 e^2 \omega^2}{6\pi m_e c} \quad \omega_L = \frac{e}{2m_e} B \]

  - **Field azimuth** $\chi$, with $\chi=0$ for $B \parallel \text{LOS}$
Hanle effect example (contd.)

- Hanle depolarisation in general changes between $0.2B_0$ and $5B_0$

\[ B_0 = \frac{2m\gamma_N}{eg_u} \]

- Expression for $B_0$ is equivalent to saying that for $B=B_0$ we have $\omega_L = \gamma_N$

Stenflo 1994

Illustration for horizontal field seen exactly at limb, scattering radiation coming exactly from below.