

Physics 681: Solar Physics and Instrumentation – Lecture 9

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Polarimetry

- Zeeman splitting
- Assume weak magnetic field (LS or Russel-Saunders coupling)
- Quantum numbers: L orbital angular momentum of the electrons, S spin angular momentum, J total angular momentum, and M_j magnetic quantum number
- Landé factor

$$g = 1 + \frac{J(J+1) + S(S+1) - L(L+1)}{2J(J+1)}$$

- Displacement of the line in the presence of a magnetic field

$$\Delta\lambda_B = \lambda - \lambda_0 = \frac{e}{4\pi cm_e} g^* \lambda^2 B \quad \text{with } g^* = gM - g'M'$$

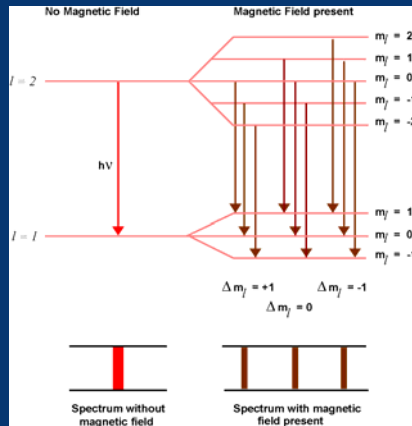
- Normal Zeeman effect or Lorentz triplet: $S = S' = 0$
 $\Delta M_j = -1, 0, +1 \Rightarrow g^* = -1, 0, +1$



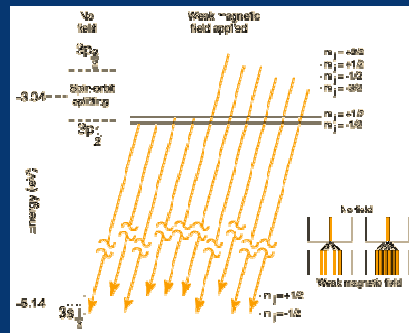
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Normal and Anomalous Zeeman Effect



<http://w.home.cern.ch/w/wadhwa/www/zeeman.html>



<http://hyperphysics.phy-astr.gsu.edu/hbase/quantum/sodzee.html>

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- Solar spectral lines are broadened by micro- and macro-turbulence and by pressure \Rightarrow the components of a Zeeman multiplet are normally not resolved
- The triplet consists of two shifted σ -components and an unshifted π -component
- Longitudinal Zeeman effect: line-of-sight (LOS) $\parallel B$
 $\Rightarrow \sigma$ -components with circular polarization of opposite sense
- Transverse Zeeman effect: LOS $\perp B \Rightarrow \pi$ -component (linearly polarized $\perp B$) and σ -components (linearly polarized $\parallel B$)
- $\Delta\lambda_B \approx \lambda^2 \Leftrightarrow \Delta\lambda_D \approx \lambda$
- Polarized light (propagating in the z -direction)

$$E_x = \xi_x \cos \phi \quad \text{and} \quad E_y = \xi_y \cos(\phi + \varepsilon)$$

- Stokes vector $I^2 = Q^2 + U^2 + V^2$

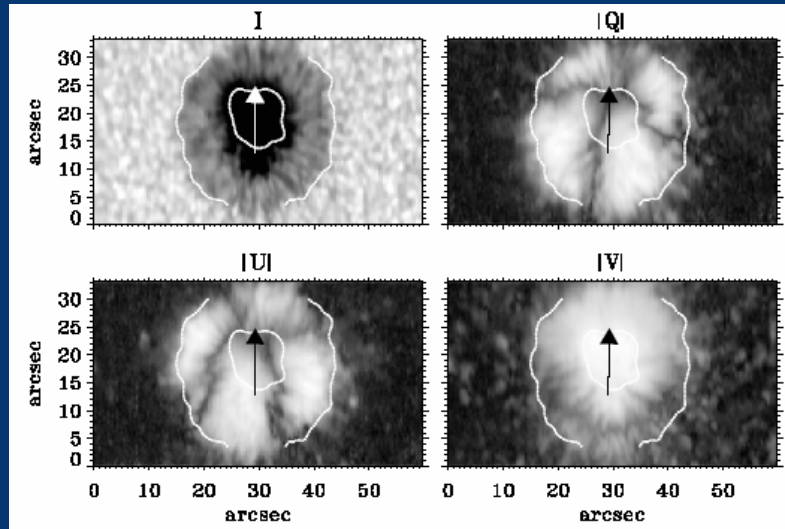
$$I = \xi_x^2 + \xi_y^2 \quad Q = \xi_x^2 - \xi_y^2$$

$$U = 2\xi_x \xi_y \cos \varepsilon \quad V = 2\xi_x \xi_y \sin \varepsilon$$

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Schlichenmaier and Collados (2002)

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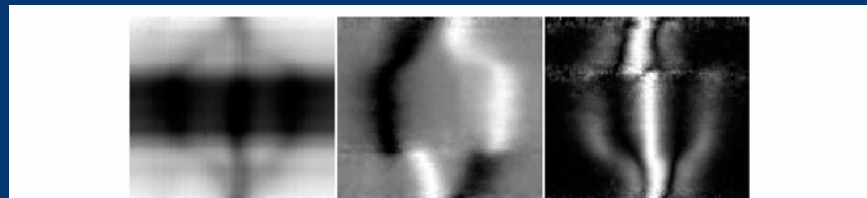


Fig. 2. Spatial variation of the intensity (left), circular polarization (middle) and linear polarization (right) profiles of the Fe I 1564.8 nm line in AR 8704 along the symmetry line connecting the disk center and the sunspot center. The horizontal and vertical axes represent the spectral and spatial directions, respectively. The center-side penumbra is at the top. The Stokes V and L profiles in each row have been normalized to their maximum absolute values for better visibility. Note that the maximum Doppler shifts occur near the spatial positions where Stokes V and Stokes L show discontinuities.

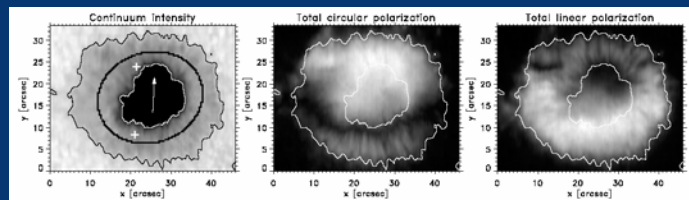


Fig. 1. Continuum intensity (left), total circular polarization (middle), and total linear polarization (right) maps of AR 8704 as observed with TIP on 1999 September 20 at 15:25 UT. The linear polarization L is defined as $L^2 = Q^2 + U^2$. The arrow indicates the direction to disk center. It also represents the positive y -axis of the local reference frame. Contour levels for the inner and outer penumbral boundaries are 0.75 and 0.90 of the quiet sun continuum intensity. The continuum map shows an azimuthal path at a normalized radial distance of 0.7. The crosses mark the position of the Stokes profiles displayed in Fig. 3.

Bellot Rubio et al. (2004)

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- Superposition of a large number of independent waves

$$I = \langle \xi_x^2 + \xi_y^2 \rangle \quad Q = \langle \xi_x^2 - \xi_y^2 \rangle$$

$$U = 2 \langle \xi_x \xi_y \cos \varepsilon \rangle \quad V = 2 \langle \xi_x \xi_y \sin \varepsilon \rangle$$

- Degree of polarization

$$P = \left(\frac{Q^2 + U^2 + V^2}{I^2} \right)$$

- Stokes profiles $I(\lambda)$, $Q(\lambda)$, $U(\lambda)$, and $V(\lambda)$
- Longitudinal Zeeman triplet

$$I = I_C (1 - \tau) - I_C \tau (\eta^+ + \eta^-) / 2$$

$$\eta^\pm = \eta(\lambda \pm \Delta\lambda_B) \quad \text{with} \quad \eta(\lambda) = \kappa_l(\lambda) / \kappa_C$$

$$V(\lambda) = -I_C \tau (\eta^+ - \eta^-) / 2$$



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Unno's Equations

$\Delta \mathbf{I} = -\tau \mathbf{I} - \tau \boldsymbol{\eta} \mathbf{I}$ with

$$\mathbf{I} = \begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix} \quad \boldsymbol{\eta} = \begin{pmatrix} \eta_I & \eta_Q & \eta_U & \eta_V \\ \eta_Q & \eta_I & 0 & 0 \\ \eta_U & 0 & \eta_I & 0 \\ \eta_V & 0 & 0 & \eta_I \end{pmatrix}, \quad \text{where}$$

$$\eta_I = \frac{1}{2} \eta \sin^2 \gamma + \frac{1}{4} (\eta^+ + \eta^-) (1 + \cos^2 \gamma)$$

$$\eta_Q = \left(\frac{1}{2} \eta - \frac{1}{4} (\eta^+ + \eta^-) \right) \sin^2 \gamma \cos 2\phi$$

$$\eta_U = \left(\frac{1}{2} \eta - \frac{1}{4} (\eta^+ + \eta^-) \right) \sin^2 \gamma \sin 2\phi$$

$$\eta_V = \frac{1}{2} (\eta^+ - \eta^-) \cos \gamma$$



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Transfer of Polarized Light

$$\cos\theta \frac{dI}{d\tau} = (1 + \eta)(I - B_\lambda)$$

- Longitudinal magnetic field

$$\gamma = 0 \Rightarrow \eta_Q = 0, \eta_U = 0, \eta_I = \frac{1}{2}(\eta^+ + \eta^-), \text{ and } \eta_V = \frac{1}{2}(\eta^+ - \eta^-)$$

- Radiative transfer equations

$$\mu \frac{dI}{d\tau} = (1 + \eta_I)(I - B_\lambda) + \eta_V V \quad \mu \frac{dQ}{d\tau} = (1 + \eta_I)Q$$

$$\mu \frac{dV}{d\tau} = (1 + \eta_I)V + \eta_V(I - B_\lambda) \quad \mu \frac{dU}{d\tau} = (1 + \eta_I)U$$



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- Transverse magnetic field

$$\gamma = 90^\circ \text{ and } \phi = 0 \Rightarrow \eta_U = \eta_V = 0 \text{ and } U \equiv 0$$

$$\eta_I = \frac{1}{2}\eta + \frac{1}{4}(\eta^+ + \eta^-)$$

$$\eta_Q = \frac{1}{2}\eta - \frac{1}{4}(\eta^+ + \eta^-)$$

- Radiative transfer equations

$$\mu \frac{dI}{d\tau} = (1 + \eta_I)(I - B_\lambda) + \eta_Q Q$$

$$\mu \frac{dQ}{d\tau} = (1 + \eta_I)Q + \eta_Q(I - B_\lambda)$$

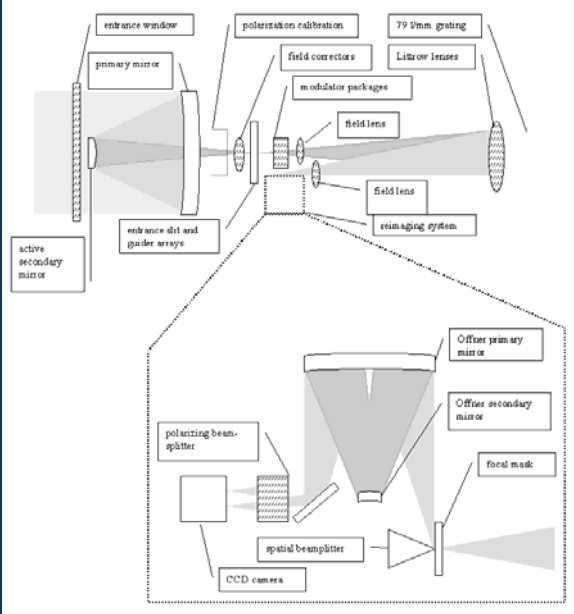
$$\mu \frac{dV}{d\tau} = (1 + \eta_I)V$$



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