Наблюдения магнитных полей с инстументами SOLIS и GONG.

Part I

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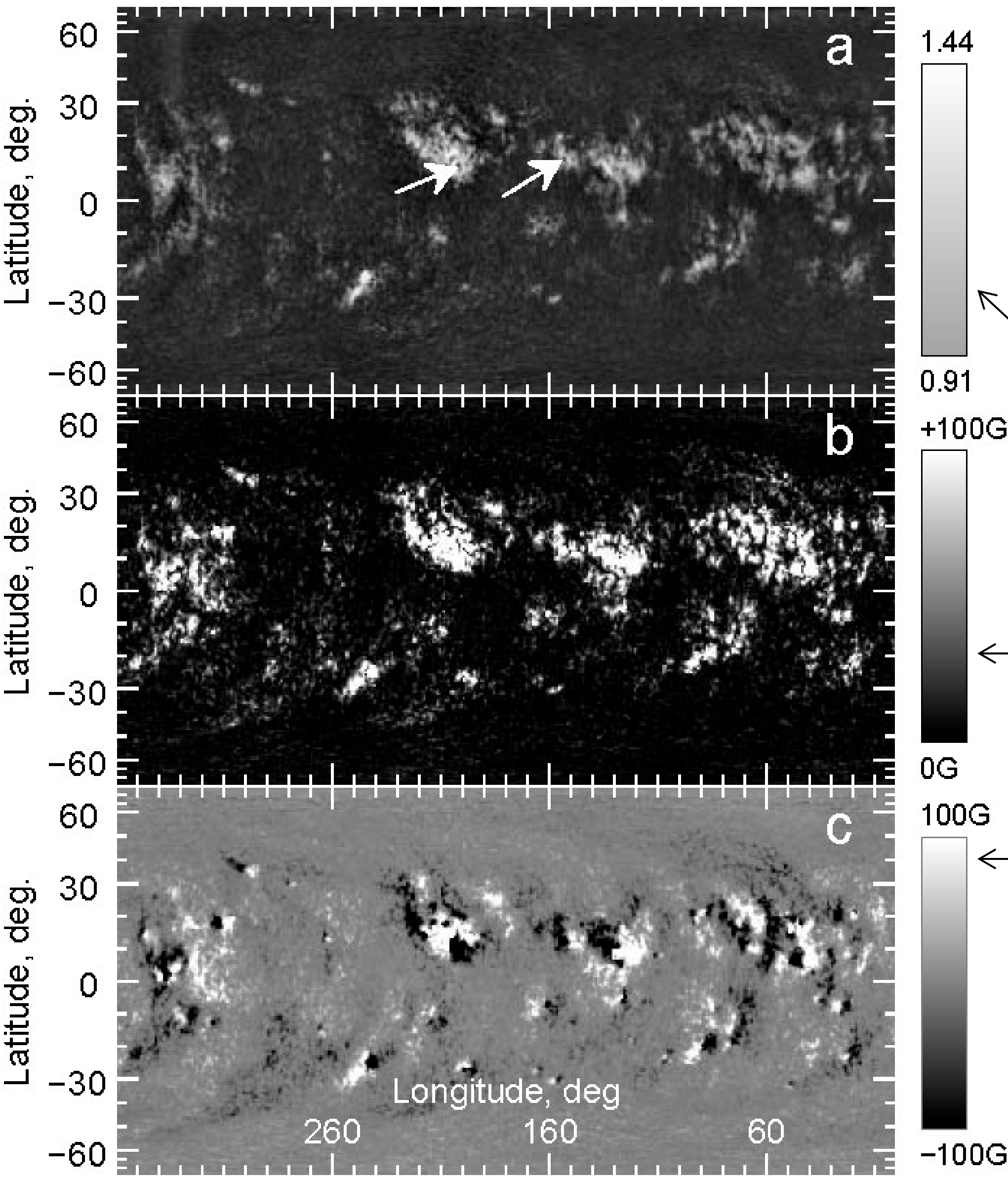
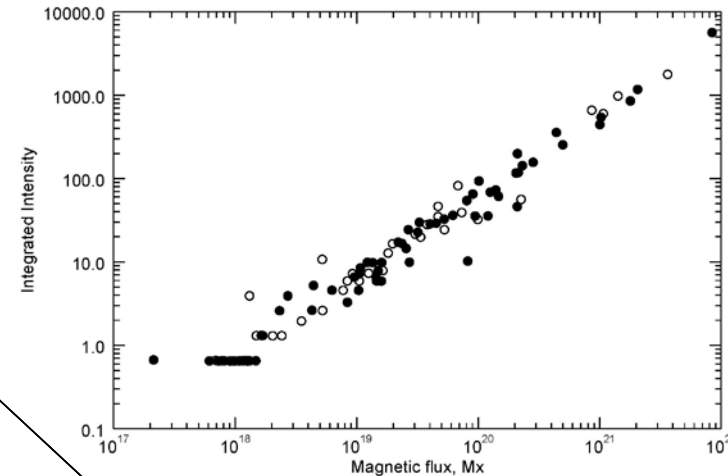
Outline

- History and basic principles of measuring magnetic fields
- SOLIS instruments
- SOLIS Data products

Methods of Inferring Properties of Magnetic Field in Stellar Atmospheres

- Zeeman and Hanle effects
- Observations in radio
- Via model-based interpretation of physical processes (e.g., oscillations in magnetic structures).
- Proxies of magnetic field.
- (Faraday rotation)





Ca II K intensity-gram

Map of absolute value of magnetic flux

Synoptic map of magnetic field

Pevtsov et al (2016)

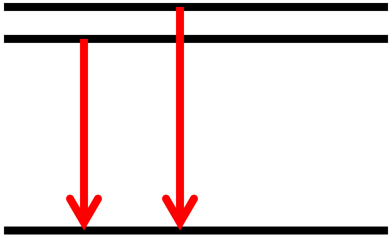
Inferring Properties of Magnetic Field in Stellar Atmospheres

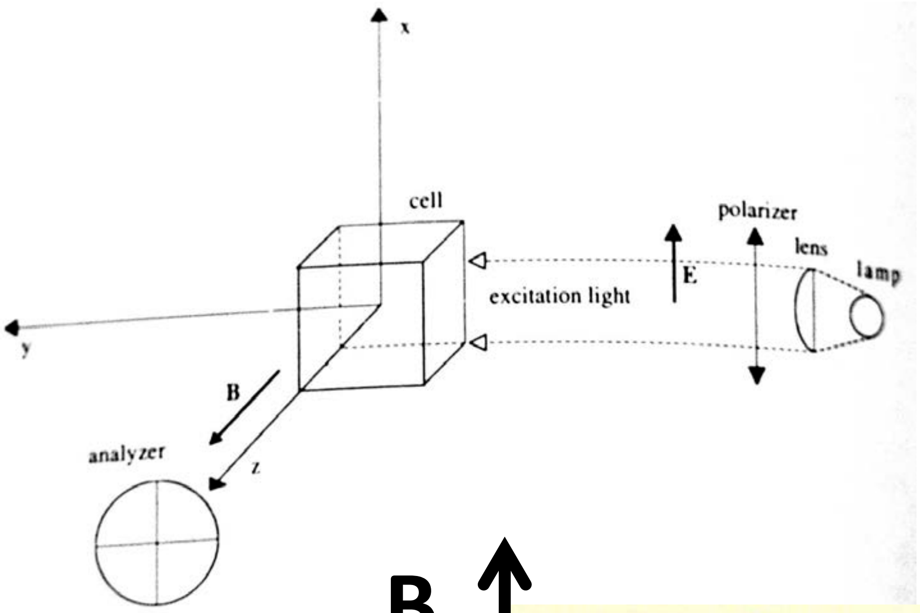
- Zeeman and Hanle effects (+Faraday rotation)
- Observations in radio
- Via model-based interpretation of physical processes (e.g., oscillations in magnetic structures).
- Proxies of magnetic field.
- (Faraday rotation)

No polarity information

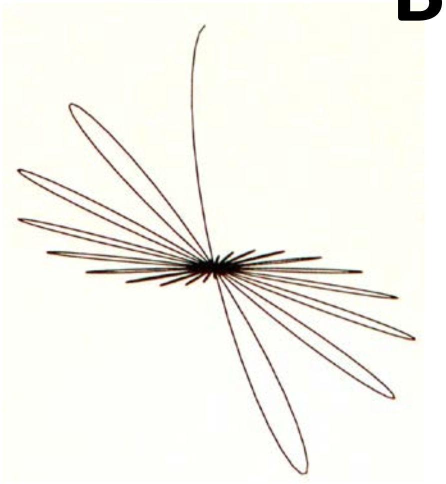
Zeeman and Hanle

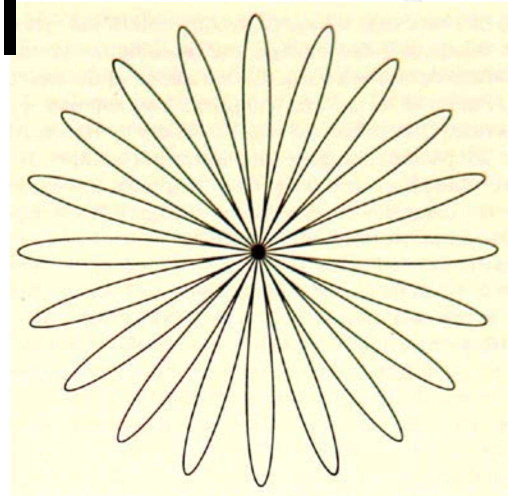
+B



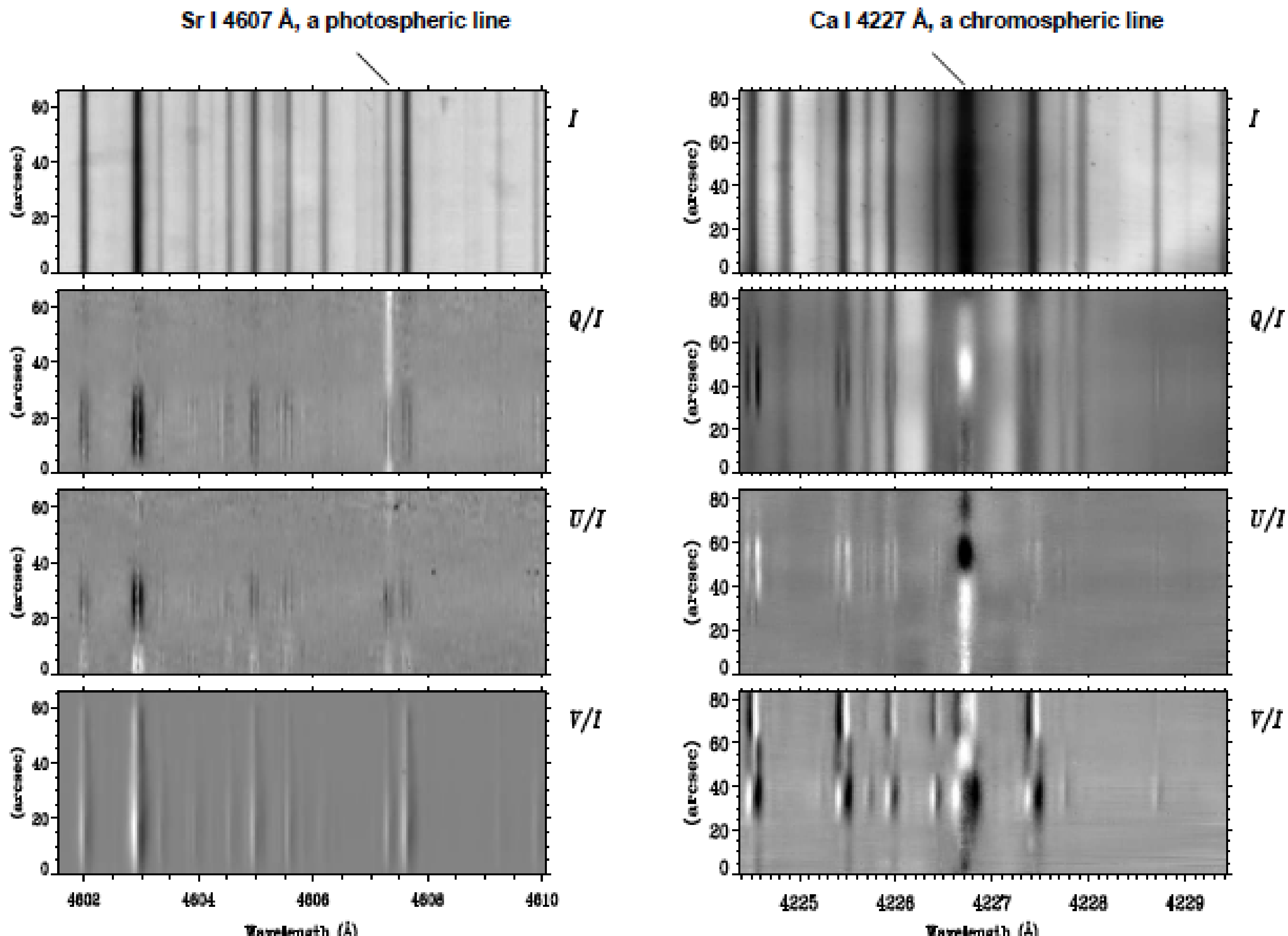


B ↑





Zeeman and Hanle



Stenflo (2010)

Zeeman and Hanle Effects

- Strong magnetic fields
- Unresolved fields will cancel out polarization
- Absorption and emission lines
- Scales with λ^2

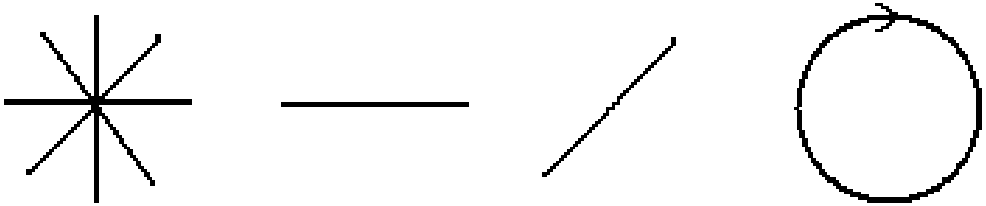
- Weak field -1-300 Gauss
- Detects unresolved fields
- coherent scattering plays a significant role in the formation of the spectral line (resonance lines)
- the scattering polarization has observable amplitude (incident radiation field of the scattering process is significantly anisotropic)

First Observations of magnetic fields in Astrophysics

- 1896 - Zeeman effect discovered by Dutch physicist Pieter Zeeman
- 1908 – first measurements in astrophysics by G.E. Hale (Mount Wilson Observatory)
- Since 1917 – regular daily observations of magnetic fields in sunspots

Representation of PL

F_0 F_1 F_2 F_3



unpolarized 0^o 45^o right-hand

linear circular polarization

$$\begin{bmatrix} F_0 \\ F_1 \\ F_2 \\ F_3 \end{bmatrix} \rightarrow \begin{bmatrix} I \\ Q \\ U \\ V \end{bmatrix}$$

$$\begin{bmatrix} I \\ Q \\ U \\ V \end{bmatrix} = \begin{bmatrix} \langle a_x^2 + a_y^2 \rangle \\ \langle a_x^2 - a_y^2 \rangle \\ \langle 2 a_x a_y \cos\gamma \rangle \\ \langle 2 a_x a_y \sin\gamma \rangle \end{bmatrix}$$

$Q=U=V=0$ - unpolarized light

$I=(Q^2+U^2+V^2)^{1/2}$ – 100% polarized

$P= (Q^2+U^2+V^2)^{1/2} /I$ - polarization degree

Mueller Calculus

$$\begin{bmatrix} I \\ Q \\ U \\ V \end{bmatrix}_{OUT} = \begin{bmatrix} m_{11} & m_{12} & m_{13} & m_{14} \\ m_{21} & m_{22} & m_{23} & m_{24} \\ m_{31} & m_{32} & m_{33} & m_{34} \\ m_{41} & m_{42} & m_{43} & m_{44} \end{bmatrix} \cdot \begin{bmatrix} I \\ Q \\ U \\ V \end{bmatrix}_{IN} = \begin{bmatrix} m_{11}I + m_{12}Q + m_{13}U + m_{14}V \\ m_{21}I + m_{22}Q + m_{23}U + m_{24}V \\ m_{31}I + m_{32}Q + m_{33}U + m_{34}V \\ m_{41}I + m_{42}Q + m_{43}U + m_{44}V \end{bmatrix}$$

$$\begin{bmatrix} I \\ Q \\ U \\ V \end{bmatrix}_{OUT} = \frac{1}{2} \begin{bmatrix} 1 & 1 & 0 & 0 \\ 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \cdot \begin{bmatrix} 1 \\ 0 \\ 0 \\ 0 \end{bmatrix}_{IN} = \begin{bmatrix} 0.5 \\ 0.5 \\ 0 \\ 0 \end{bmatrix}$$

→ 50% of light

→ 100% P

Linear polarizer

$I=(Q^2+U^2+V^2)^{1/2}$ – 100% polarized

$P= (Q^2+U^2+V^2)^{1/2} /I$ - polarization degree

Mueller Calculus

$$[S]_{out} = [M_4][M_3][M_2][M_1][S]_{IN}$$

Ex: P(0°)+R(δ=90°, ρ=45°)+ R(δ=90°, ρ=45°)

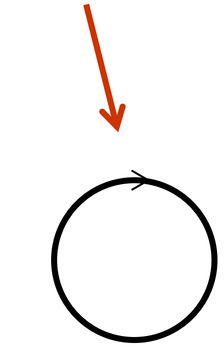
Light in: (light polarized horizontally)

$$\begin{bmatrix} I \\ Q \\ U \\ V \end{bmatrix}_{OUT} = \frac{1}{2}\begin{bmatrix} 1 & 1 & 0 & 0 \\ 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \cdot \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix} \cdot \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix} \cdot \begin{bmatrix} 1 \\ 1 \\ 0 \\ 0 \end{bmatrix}_{IN} =$$

Mueller Calculus

$$\begin{bmatrix} I \\ Q \\ U \\ V \end{bmatrix}_{OUT} = \frac{1}{2}\begin{bmatrix} 1 & 1 & 0 & 0 \\ 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \cdot \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix} \cdot \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix} \cdot \begin{bmatrix} 1 \\ 1 \\ 0 \\ 0 \end{bmatrix}_{IN} =$$

$$\begin{bmatrix} 1 \\ 0 \\ 0 \\ 1 \end{bmatrix}$$



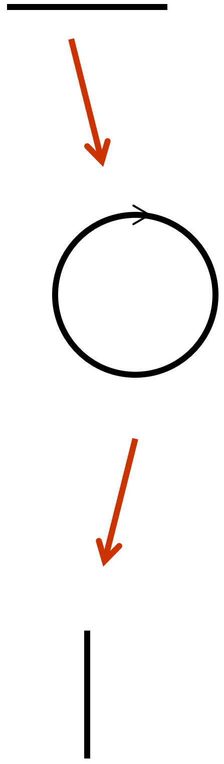
Left circular polarization

Mueller Calculus

$$\begin{bmatrix} I \\ Q \\ U \\ V \end{bmatrix}_{OUT} = \frac{1}{2}\begin{bmatrix} 1 & 1 & 0 & 0 \\ 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \cdot \underbrace{\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & -1 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix} \cdot \begin{bmatrix} 1 \\ 0 \\ 0 \\ 1 \end{bmatrix}}$$

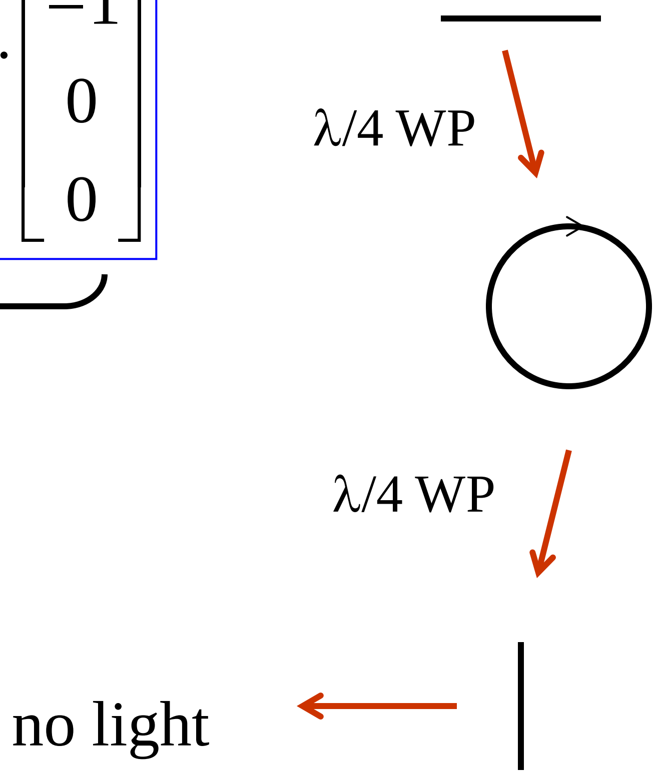
$$\begin{bmatrix} 1 \\ -1 \\ 0 \\ 0 \end{bmatrix}$$

Linear polarization



Mueller Calculus

$$\begin{bmatrix} I \\ Q \\ U \\ V \end{bmatrix}_{OUT} = \frac{1}{2}\underbrace{\begin{bmatrix} 1 & 1 & 0 & 0 \\ 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \cdot \begin{bmatrix} 1 \\ -1 \\ 0 \\ 0 \end{bmatrix}}_{\begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \end{bmatrix}}$$



Rotating ¼ WP

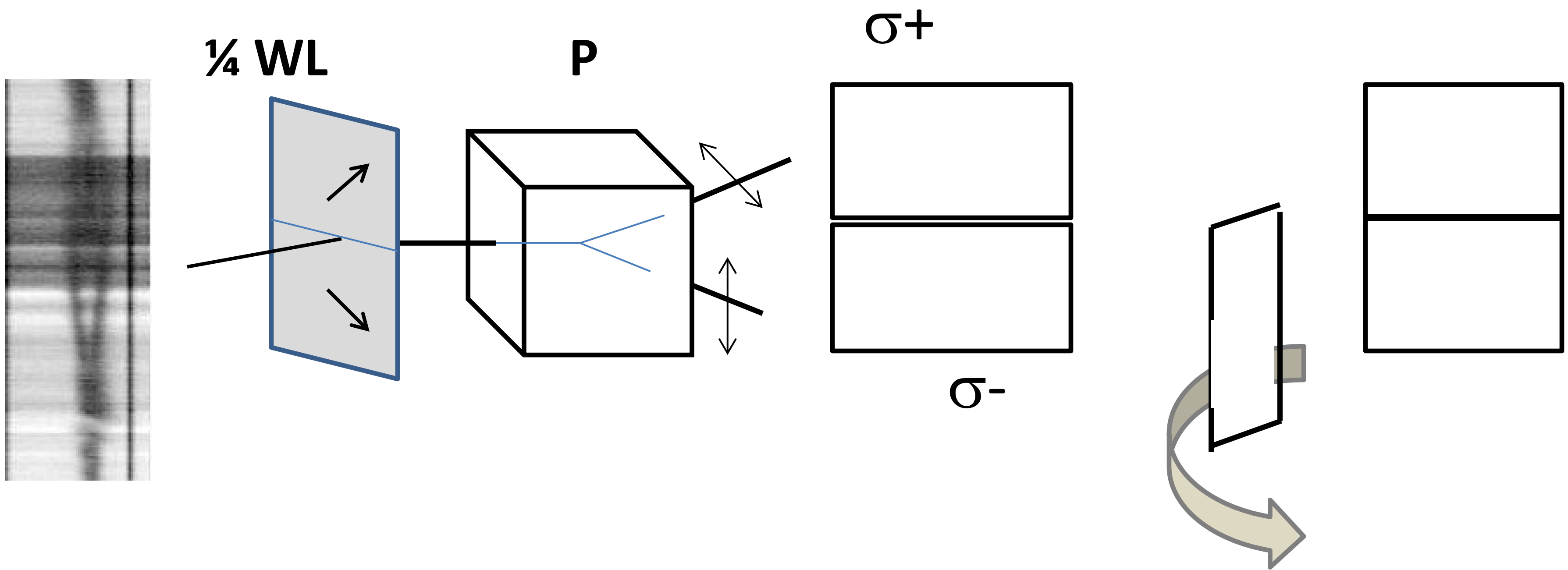
$$\begin{bmatrix} S_I \\ S_Q \\ S_U \\ S_V \end{bmatrix} = \frac{1}{2}\begin{bmatrix} 1 & 1 & 0 & 0 \\ 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}\begin{bmatrix} I \\ Q\cos^2(2\rho) + U\cos(2\rho)\sin(2\rho) - V\sin(2\rho) \\ Q\cos(2\rho)\sin(2\rho) + U\sin^2(2\rho) + V\cos(2\rho) \\ Q\sin(2\rho) - U\cos(2\rho) \end{bmatrix}$$

$$S_I \xrightarrow{0\,\mathrm{deg}} \frac{1}{2}(I+Q) \xrightarrow{45\,\mathrm{deg}} \frac{1}{2}(I-V) \xrightarrow{90\,\mathrm{deg}} \frac{1}{2}(I+Q) \xrightarrow{135\,\mathrm{deg}} \frac{1}{2}(I+V)$$

$$S_I \xrightarrow{0\,\mathrm{deg}} \frac{1}{2}(I-Q) \xrightarrow{45\,\mathrm{deg}} \frac{1}{2}(I+V) \xrightarrow{90\,\mathrm{deg}} \frac{1}{2}(I-Q) \xrightarrow{135\,\mathrm{deg}} \frac{1}{2}(I-V)$$

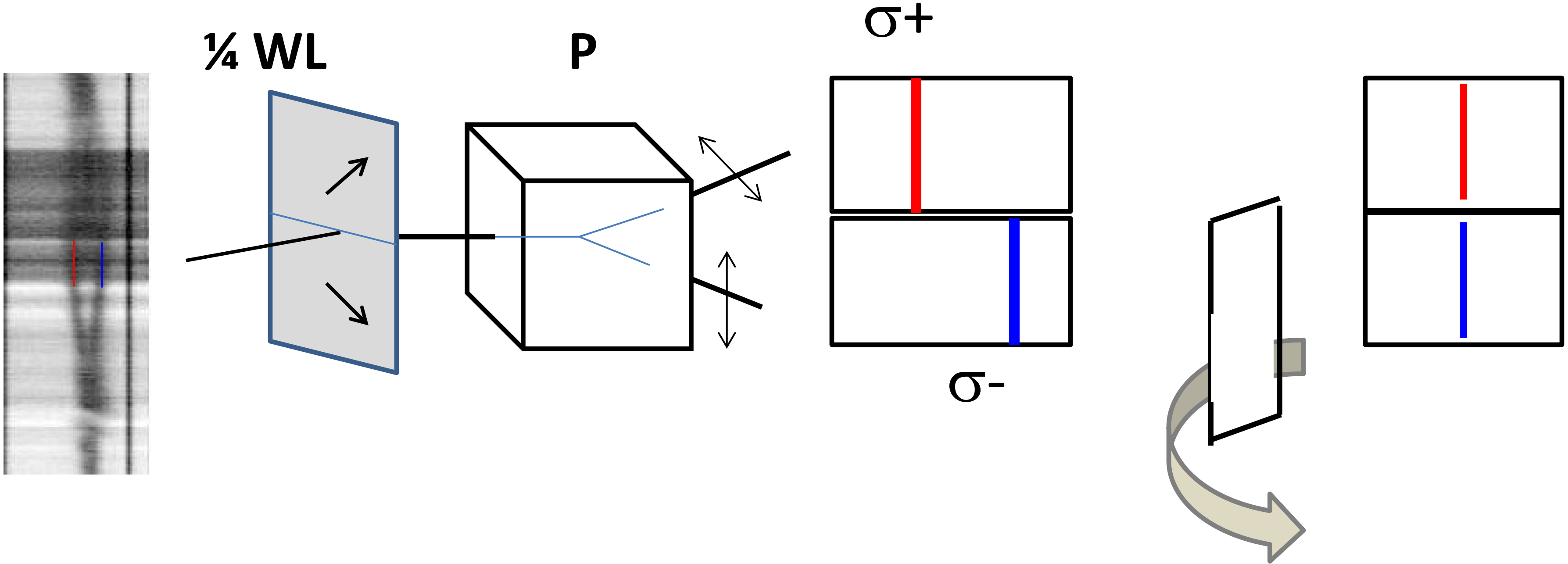
Simple MF Analyzer

$$\Delta\lambda_H = 4.67 \times 10^{-5} g \cdot H \cdot \lambda_0^2$$

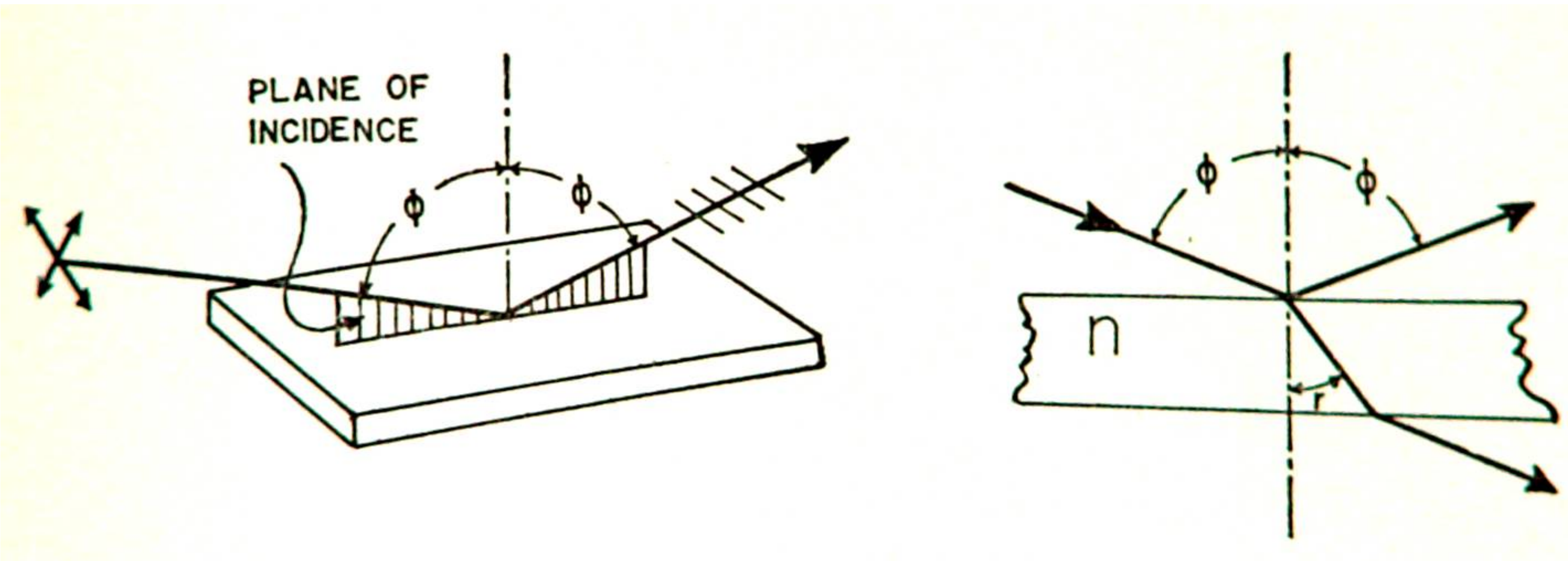


Simple MF Analyzer

$$\Delta\lambda_H = 4.67\times10^{-5} g \cdot H \cdot \lambda_0^2$$



Instrumental Polarization



$$\rho_{90} = \frac{\sin^2(\phi - r)}{\sin^2(\phi + r)}; \quad \rho_0 = \frac{\tan^2(\phi - r)}{\tan^2(\phi + r)}$$

$$P = \frac{\rho_{90} - \rho_0}{\rho_{90} + \rho_0}$$

(P=0, ϕ=0, 90 deg; P~1, Brewster’s angle)

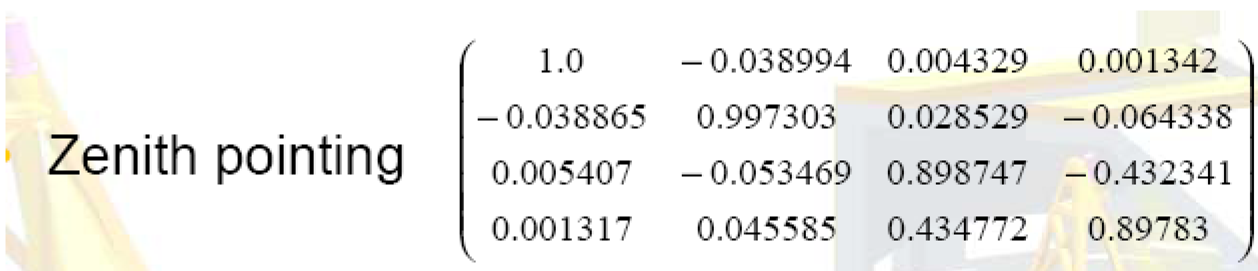
Instrumental Polarization

$$\vec{I} = \begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix}$$

$$\vec{I}^{\,'} = M \cdot \vec{I}$$

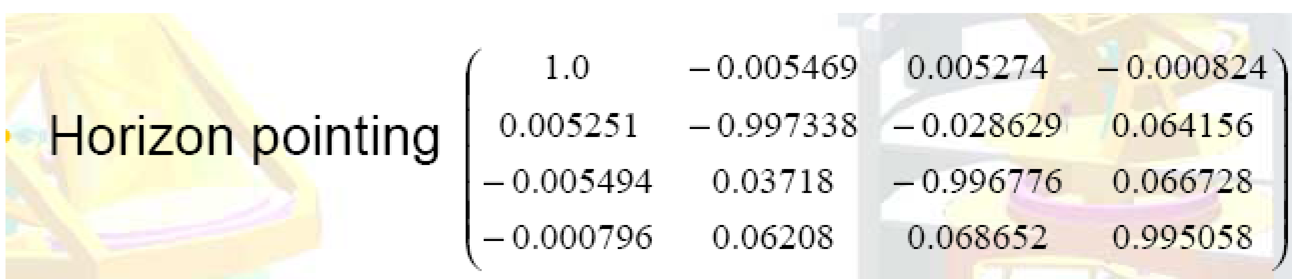
Mueller matrix

$$M = \begin{pmatrix} 1.0 & 0.04318 & -0.000836 & -0.00002 \\ 0.004318 & 0.999946 & -0.000382 & 0.009329 \\ -0.000837 & -0.000163 & 0.998507 & 0.048196 \\ -0.00002 & -0.009336 & -0.048196 & 0.998453 \end{pmatrix}$$



Zenith pointing

$$\begin{pmatrix} 1.0 & -0.038994 & 0.004329 & 0.001342 \\ -0.038865 & 0.997303 & 0.028529 & -0.064338 \\ 0.005407 & -0.053469 & 0.898747 & -0.432341 \\ 0.001317 & 0.045585 & 0.434772 & 0.89783 \end{pmatrix}$$



Horizon pointing

$$\begin{pmatrix} 1.0 & -0.005469 & 0.005274 & -0.000824 \\ 0.005251 & -0.997338 & -0.028629 & 0.064156 \\ -0.005494 & 0.03718 & -0.996776 & 0.066728 \\ -0.000796 & 0.06208 & 0.068652 & 0.995058 \end{pmatrix}$$

C. Keller

Measuring Instrumental Polarization

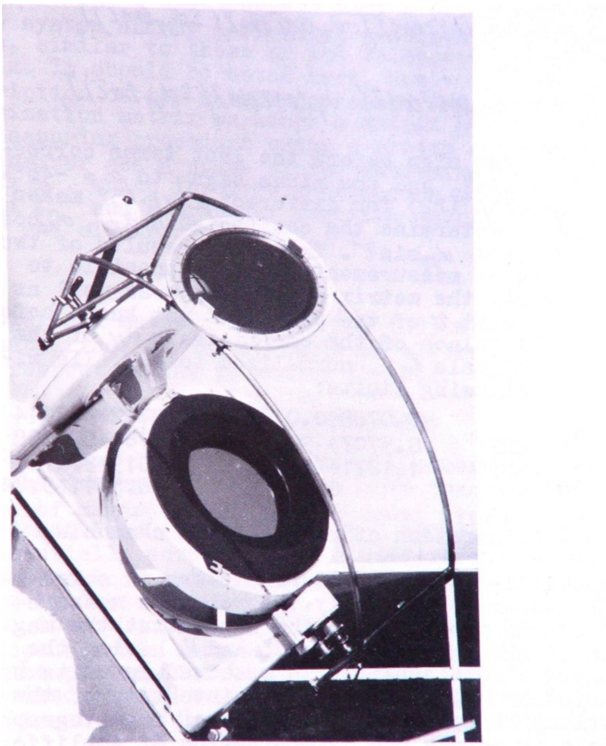


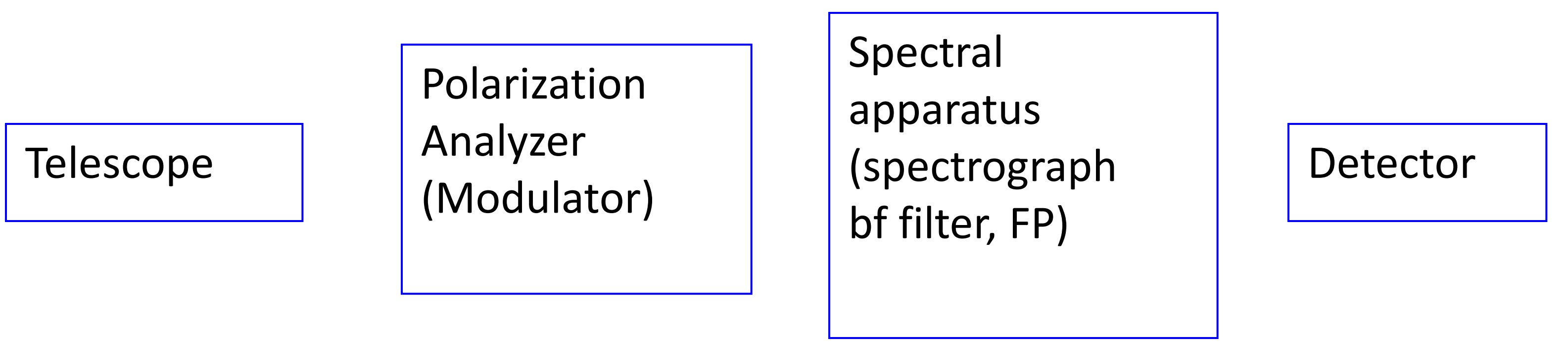
Fig. 6. Device for measuring the telescope instrumental matrix

1. Creating known polarization in front of a telescope
2. Using assumptions about object's polarization
3. Polarization compensators
4. Using selected spectral lines that have no linear but only circular polarization

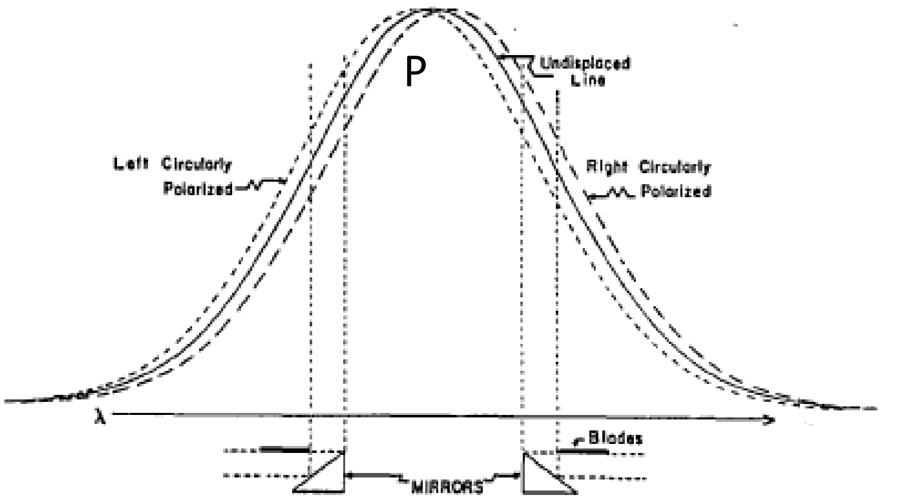
(S. Almeida & V. Villahoz, A&A, 1993, 280, 688)

Magnetographs

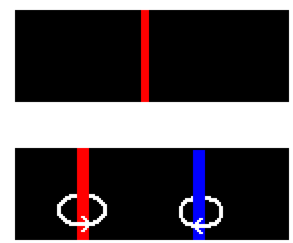
-Babcock-type magnetograph
-Imaging magnetograph
-Stokes Polarimeter



Babcock-type magnetograph

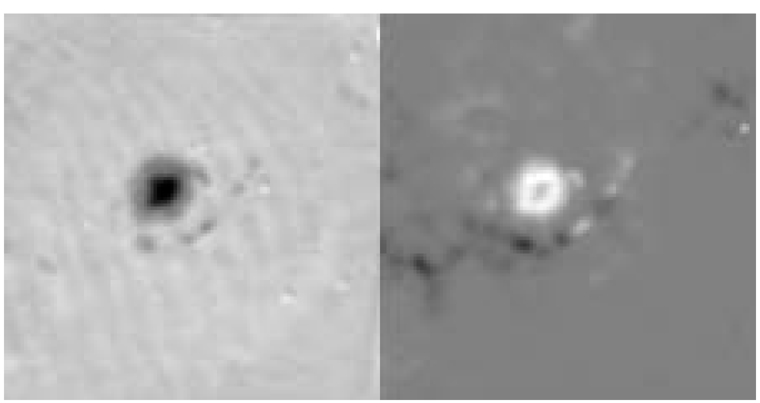


$$\Delta\lambda_H = 4.67 \times 10^{-5} g \cdot H \cdot \lambda_0^2$$

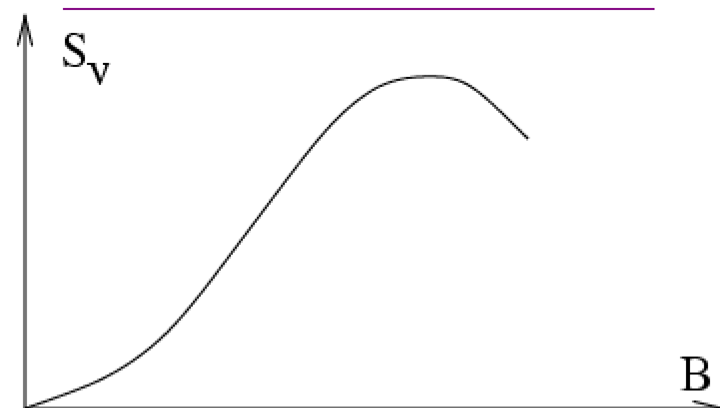


spetral line

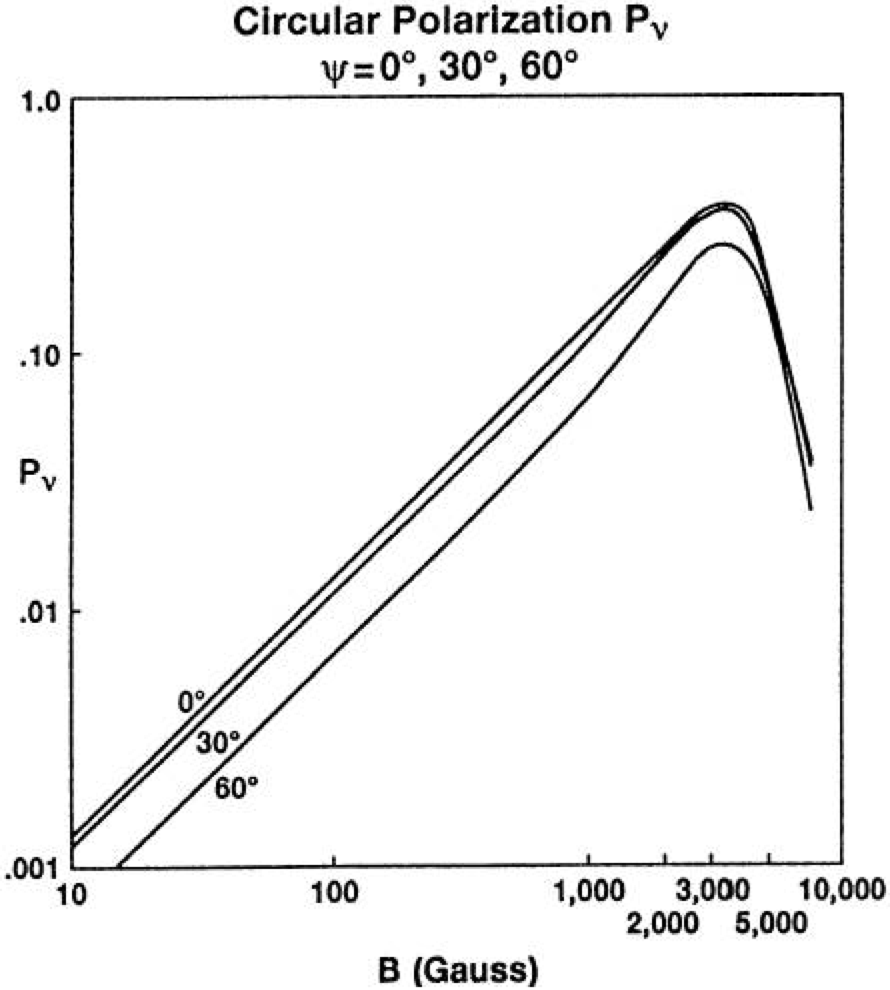
B-lonitudinal

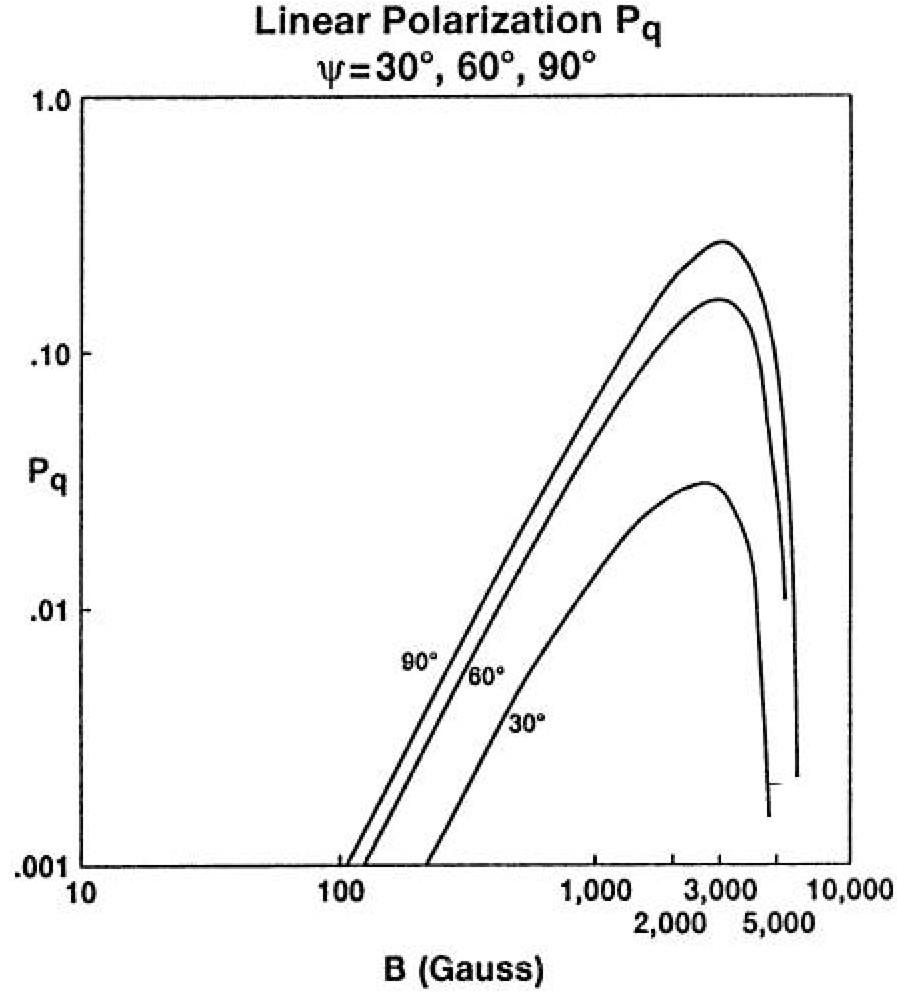


I-continuum B-longitudinal



Saturation





$$|B|\cos\gamma = C_1(\Delta\lambda)k(\Delta\lambda)(S_V(\Delta\lambda)-S_{V0})$$

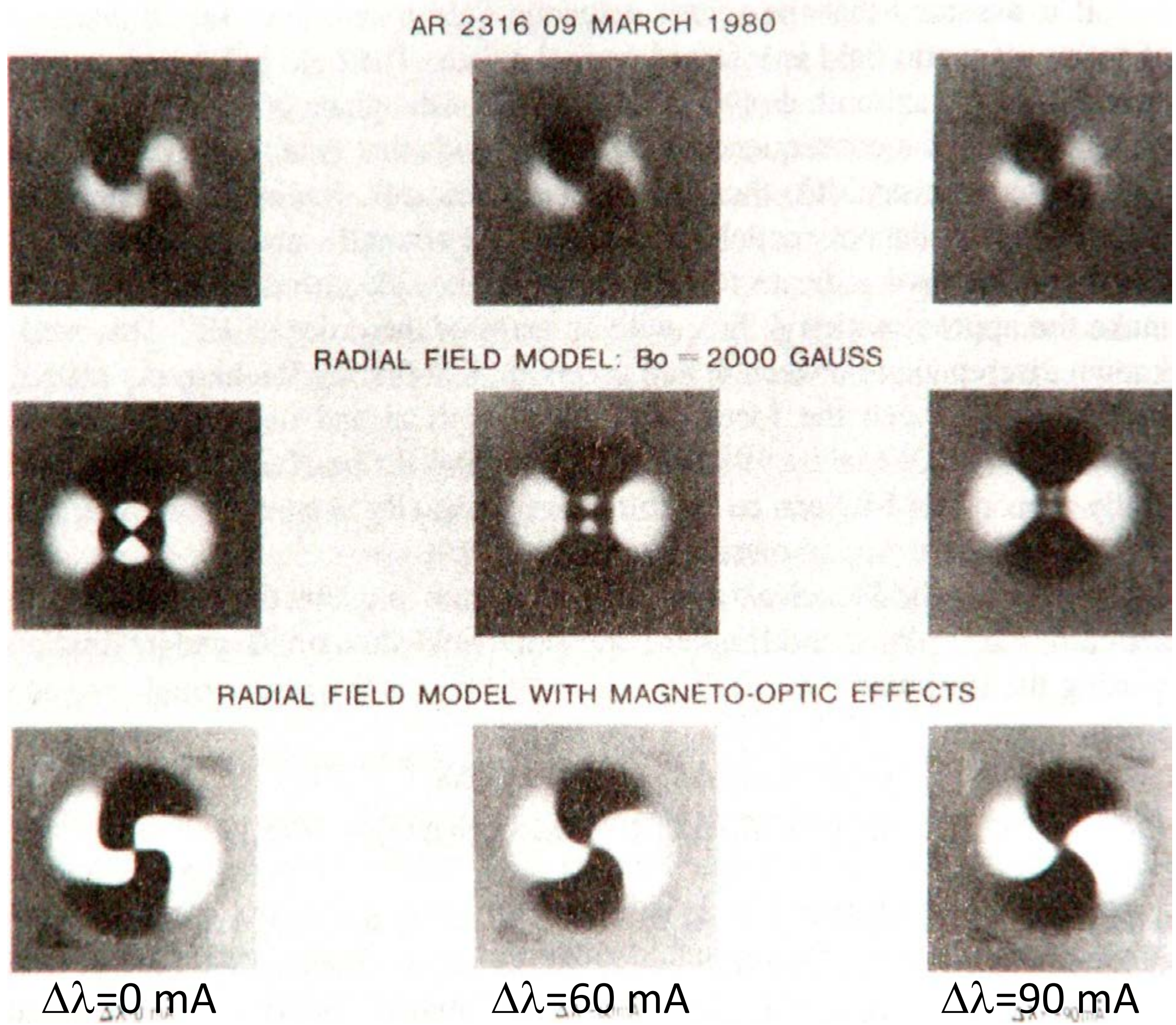
$$|B|\sin\gamma = C_2(\Delta\lambda)\sqrt{k(\Delta\lambda)(S_Q(\Delta\lambda)-S_{Q0})}$$

$$S_Q = \sqrt{\left(\left\langle\frac{Q}{I}\right\rangle\right)^2 + \left(\left\langle\frac{U}{I}\right\rangle\right)^2}$$

$$S_V = \left\langle\frac{V}{I}\right\rangle$$

Hagyard & Kineke (1995)

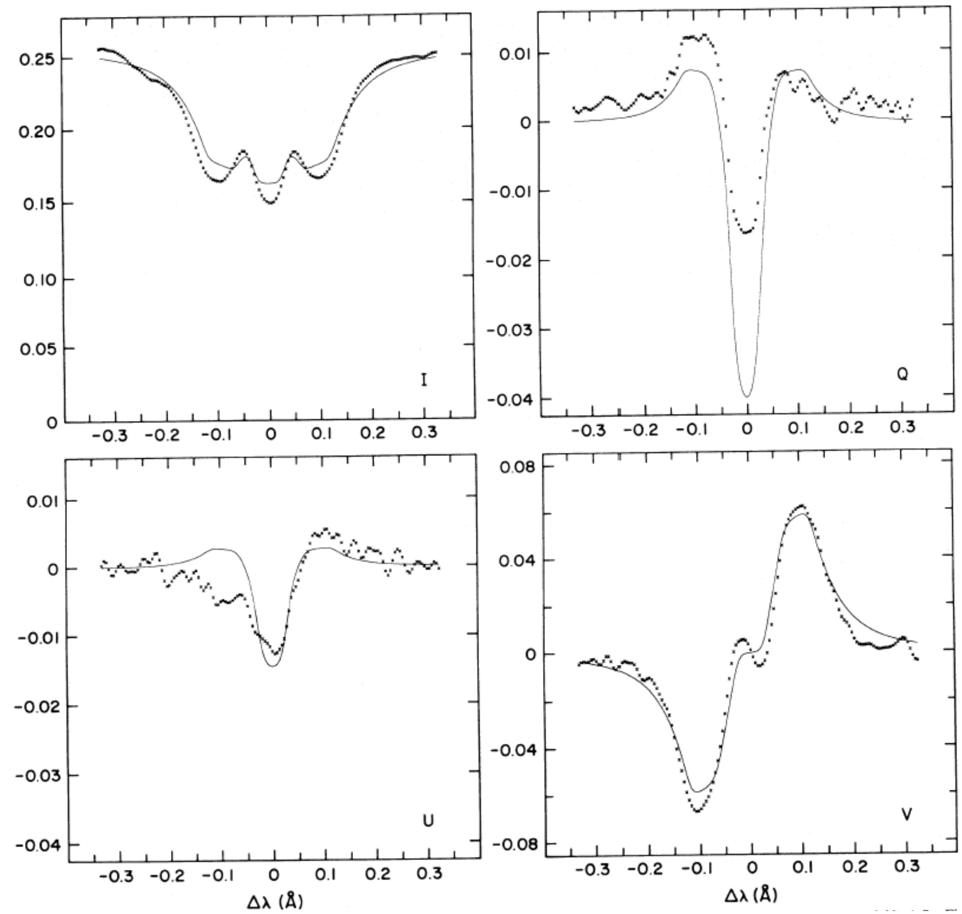
Magneto-Optical Effects



Hagyard et al (2000)

Stokes Polarimeter

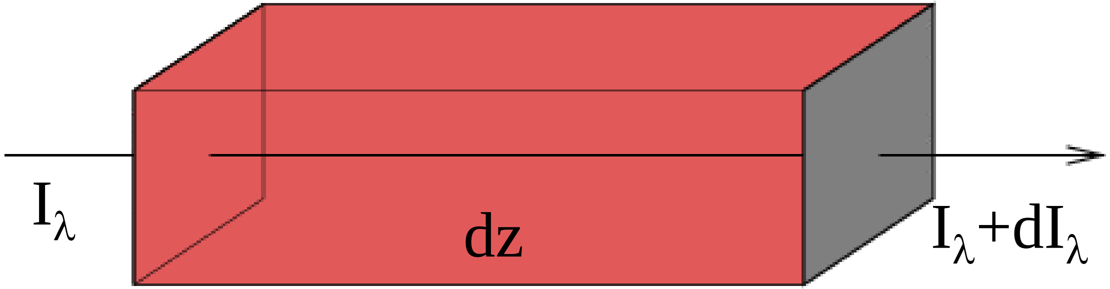
-Spectral synthesis
 (difficult to automate)
-Spectral inversion
 (restrict number of parameters)
$|B|, \gamma, \chi, \lambda_c, \Gamma, \Delta\lambda_D, B_1, \eta_0$



Skumanich & Lites (1987)

Radiative Transfer Equation

- Radiation is the primary mode of energy transport through the surface of a star.
- The interaction of the matter with the radiation is described by the radiative transfer equation (I_λ – specific intensity, κ_λ (ε_λ) – absorption (emission) coefficients:



$$dI_\lambda = -\kappa_\lambda \rho I_\lambda dz + \varepsilon_\lambda \rho dz$$

$$\frac{dI_\lambda}{d\tau} = -I_\lambda + S_\lambda$$

$$\tau = \int_z^\infty k_\lambda \rho dz - optical\ depth$$

$$S_\lambda = \frac{\varepsilon_\lambda}{\kappa_\lambda} - source\ \ function$$

Radiative Transfer Equation

- Radiation is the primary mode of energy transport through the surface of a star.
- The interaction of the matter with the radiation is described by the radiative transfer equation (I_λ – specific intensity, κ_λ (ε_λ) – absorption (emission) coefficients:

Plane-parallel atmosphere, κ, κ_0, $\Delta\lambda_D$, Γ, V_{los} = const over the region of line formation; Milne-Eddington model (LTE)

$$dI_\lambda = -\kappa_\lambda \rho I_\lambda dz + \varepsilon_\lambda \rho dz$$

$$\frac{dI_\lambda}{d\tau} = -I_\lambda + S_\lambda$$

$$\tau = \int_z^\infty k_\lambda \rho dz - optical\ depth$$

$$S_\lambda = \frac{\varepsilon_\lambda}{\kappa_\lambda} - source\ function$$