McLean seminar

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5. Instrumentation and detectors

5.3 POLARIMETERS

Measure polarization properties of light (fraction polarized, direction of vibration, handedness of rotation).
→ Provides unique geometric information not obtainable from intensity alone.

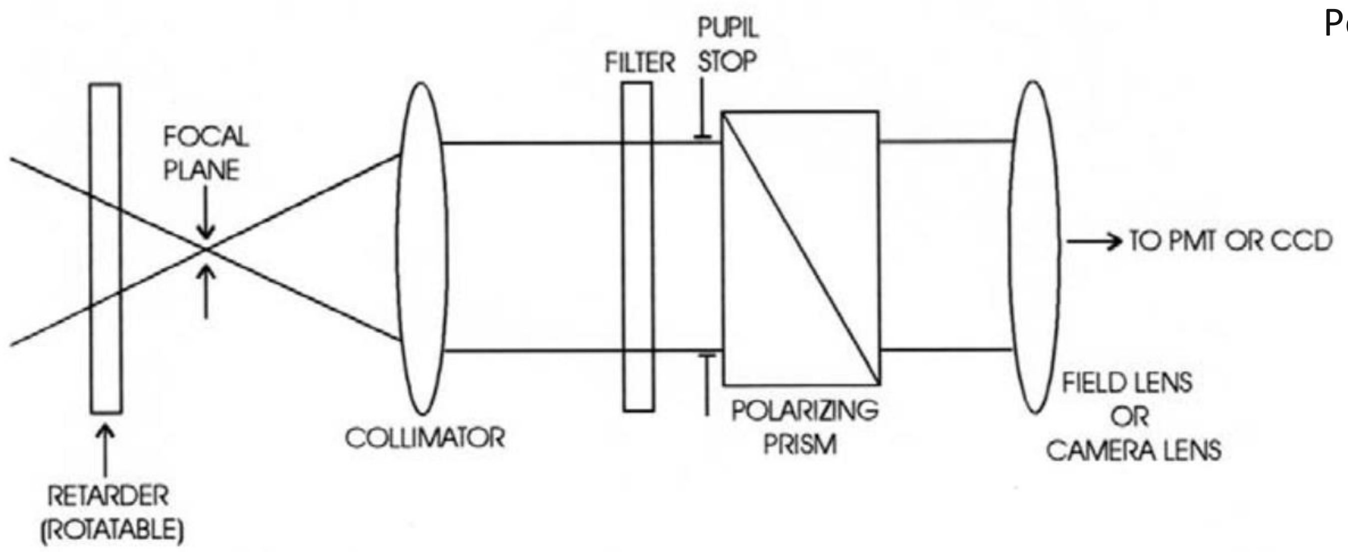
Targets:
- Reflection nebulae
- Synchrotron emission from supernova remnants
- Cyclotron emission from magnetic white-dwarf systems

Polarization Information is converted into brightness modulations.

Polarimeter Types:
- Photopolarimeter
- Imaging Polarimeter
- Spectropolarimeter

5.3.1 Modulators and polarizers

・Modulator: Rotatable plate (e.g. quartz and magnesium fluoride) or Pockels cell. Introduces birefringence, sensitive to light wave orientation.
・Polarizer: Typically glass components (e.g. Glan-Thompson or Wollaston prism). Allows controlled brightness variation based on polarization.
・Light from telescope passes through polarimeter (modulator + polarizer) then to detector.
・Modulation of brightness occurs due to polarized light.
・Detector records brightness variations.



Polarizer: A specific linear polarization can only pass
Rotator: Change the angle of polarization
Retarder: Make phase shift in the beam

5.3.2 The Stokes parameters

Stokes Parameters:
Linear Polarization: Intensity (I), degree (p), direction (θ).
Circular Polarization: Intensity (I), degree (q), handedness of the rotation of the elctric vector (+ or -).
A more onvenient way → use four Stokes Parameters: I, Q, U, V.
I: Total Intensity, Q, U: linear polarization, V: Circular polarization

degree of polarization p: linear, q: circular

$$p = \frac{[Q^2 + U^2]^{1/2}}{I}, \qquad q = \pm\frac{V}{I} \tag{5.30}$$

and the direction of vibration of the linearly polarized part is given by

$$\tan 2\theta = \frac{U}{Q} \tag{5.31}$$

and it follows that

$$\left.\begin{aligned} Q &= Ip\cos 2\theta \\ U &= Ip\sin 2\theta \\ V &= Iq \end{aligned}\right\} \tag{5.32}$$

$$I' = \tfrac{1}{2}[I \pm Q(G + H\cos 4\psi) \pm UH\sin 4\psi \mp V\sin\tau\sin 2\psi] \tag{5.33}$$

where

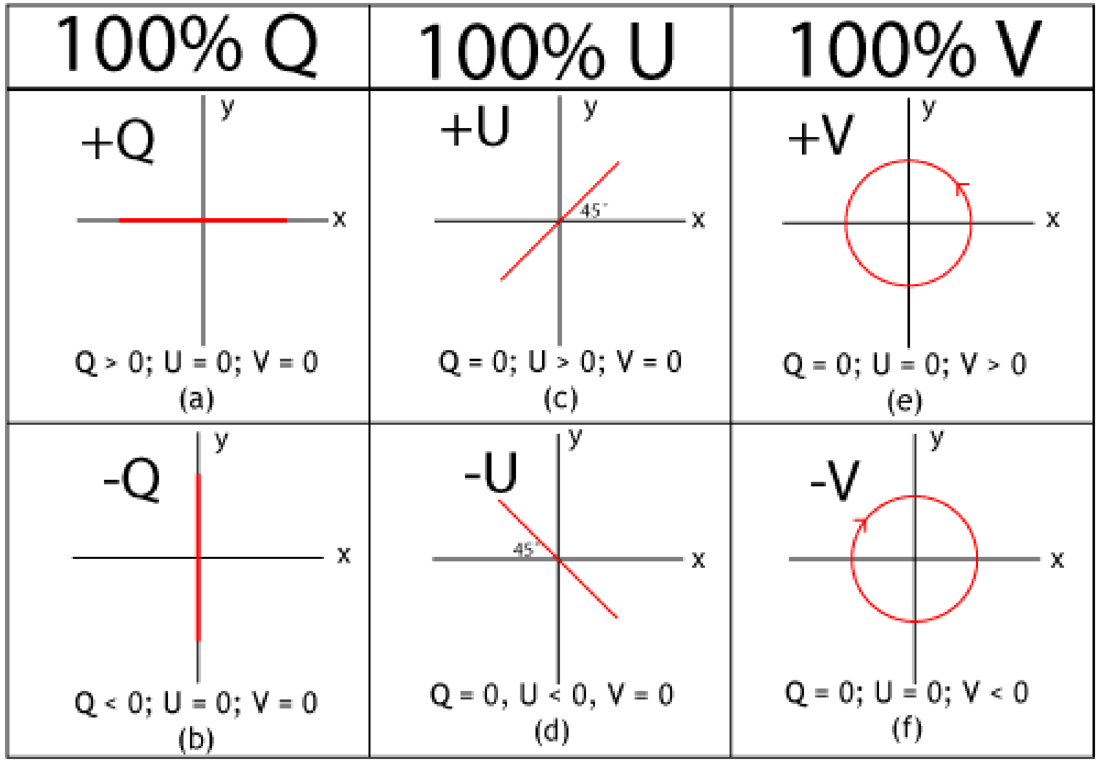
$$G = \tfrac{1}{2}(1 + \cos\tau), \qquad H = \tfrac{1}{2}(1 - \cos\tau), \qquad \tau = \frac{2\pi}{\lambda}\delta \tag{5.34}$$

5.3.2 The Stokes parameters

A more onvenient way → use four Stokes Parameters: I, Q, U, V.

I: Total Intensity, Q, U: linear polarization, V: Circular polarization

(I, Q, U, V)
= (1, 1, 0, 0) : linear (horizontal)
= (1, -1, 0, 0) : linear (vertical)
= (1, 0, 1, 0) : linear (+45°)
= (1, 0, -1, 0) : linear (-45°)
= (1, 0, 0, -1) : circular (clockwise)
= (1, 0, 0, 1) : circular (counterclockwise)



5.3.2 The Stokes parameters

A more onvenient way → use four Stokes Parameters: I, Q, U, V.

I: Total Intensity, Q, U: linear polarization, V: Circular polarization

(1) *The Quarter-Wave Retarder*: $\delta = \lambda/4$, $\tau = 90°$, $G = H = \frac{1}{2}$ which gives

$$I' = \tfrac{1}{2}[I \pm \tfrac{1}{2}Q\cos 4\psi \pm \tfrac{1}{2}U\sin 4\psi \mp V\sin 2\psi] \quad (5.35)$$

Solar magnetographs must determine the circular component, and Method (1) is the basis for those instruments.

(2) *The Half-Wave Retarder*: $\delta = \lambda/2$, $\tau = 180°$, $G = 0$, $H = 1$ which gives

$$I' = \tfrac{1}{2}[I \pm Q\cos 4\psi \pm U\sin 4\psi] \quad (5.36)$$

V can not be determined by method 2 but is more efficient to derive Q and U = most often used for stellar polarimetry

case of linear polarization (Method 2)

$$\left.\begin{array}{ll} I'(0°) = \frac{1}{2}(I + Q) & I'(45°) = \frac{1}{2}(I - Q) \\ I'(22.5°) = \frac{1}{2}(I + U) & I'(67.5°) = \frac{1}{2}(I - U) \end{array}\right\} \quad (5.37)$$

and solving for I, Q, and U gives

$$\left.\begin{array}{ll} Q = I'(0°) - I'(45°) & U = I'(22.5°) - I'(67.5°) \\ I = I'(0°) + I'(45°) & I = I'(22.5°) + I'(67.5°) \end{array}\right\} \quad (5.38)$$

5.3.3 Mueller matrices

Handles all four Stokes parameters simultaneously.
Each optical element represented by a 4x4 matrix.
Light represented by a 1x4 Stokes vector.

$$S' = M_n M_{n-1} \cdots M_2 M_1 S \qquad\qquad M' = R(-\psi) M R(\psi)$$

$$R(\psi) = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos 2\psi & \sin 2\psi & 0 \\ 0 & -\sin 2\psi & \cos 2\psi & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

5.4 INTERFEROMETERS

・Collection method

Combining light from widely separated telescopes to overcome the diffraction limit of an individual telescope.
Applied in radio, but recently made the advancement of high-resolution interferometers in Opt+IR

・Detection method

Single-aperture telescopes with interferometer equipment for specific purposes. Several types of detection interferometers have been used for spectroscopy, such as the Fourier Transform Spectrometer(FTS) and the Fabry-Perot interferometer which is an imaging spectrometer.

5.4.1 The Fourier Transform Spectrometer (FTS)

・Scanning Michelson interferometer with collimated light input.
・Measures intensity variations due to path difference between fixed and scanning mirrors.
・Fourier Transform: Converts interferogram to spectral information.
・Advantages

- High Resolving Power: Example $4\Delta x_{\max}/\lambda$ and with $\Delta x_{\max} = 10$ cm
- R = 400,000 at 1 um wavelength with a 10 cm path difference.
- High Signal-to-Noise Ratio: All light falls on the detector.

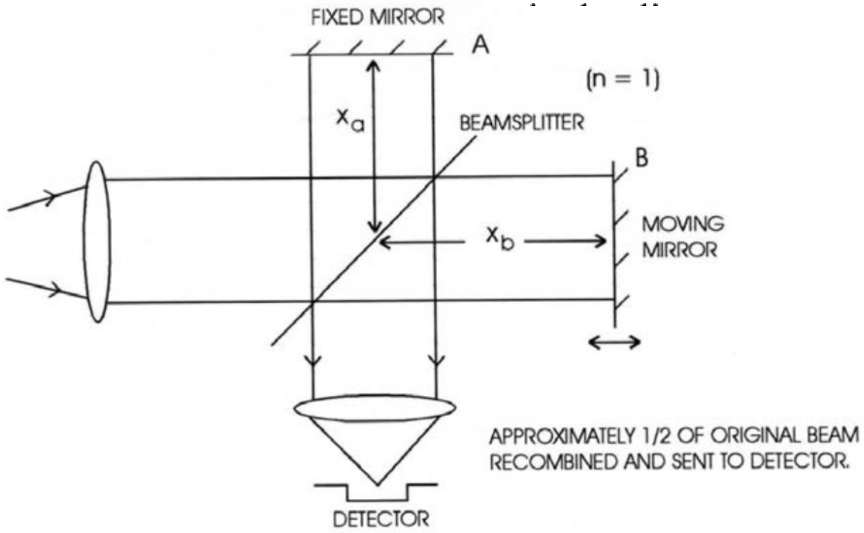
・Disadvantages

Time-Dependent Measurements: Atmospheric conditions may vary during measurement sequence.

$$T(k, \Delta x) = \tfrac{1}{2}[I + \cos(2k\Delta x)] \tag{5.41}$$

$$F(\Delta x) = c\int I(k)T(k, \Delta x)\, dk = \text{constant} + \frac{c}{2}\int I(k)\cos(2k\Delta x)\, dk \tag{5.42}$$

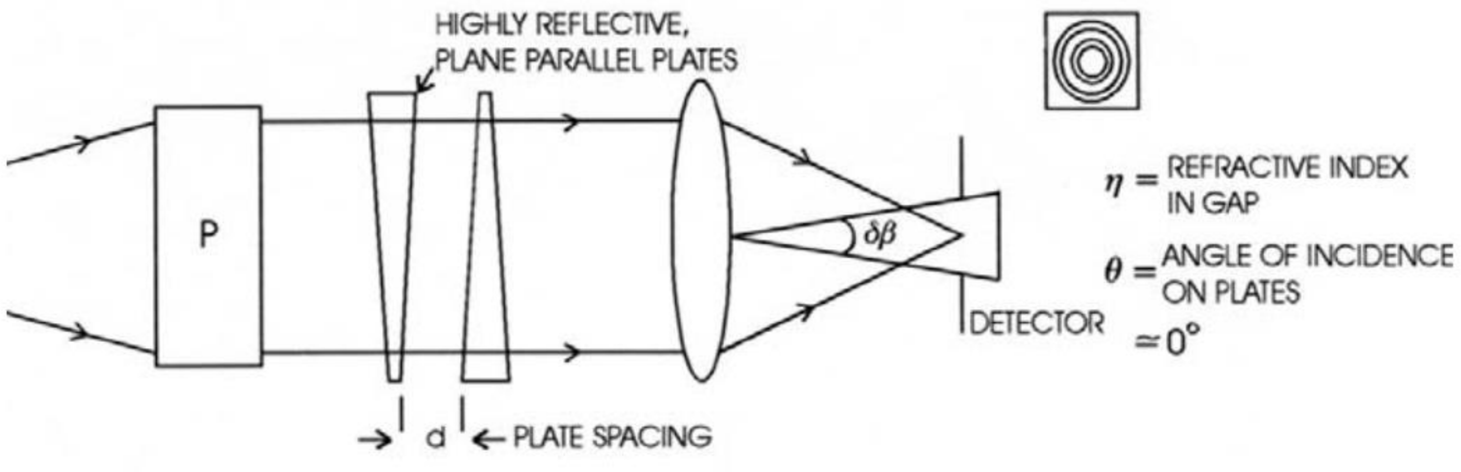
$\Delta x = 2(x_b - x_a),$



5.4.2 The Fabry-Perot etalon

The Fabry-Perot interferometer = imaging spectrometer which is formed by placing a device called an "etalon" (French étalon, meaning "measuring gauge" or "standard") in the collimated beam of a typical camera system.

- Two plane-parallel plates with highly reflective coatings.
- Wavelengths transmitted with maximum intensity follow the relation $m\lambda=2nd\cos\theta$.
- Etalon in the collimated beam of a camera system.
- Set of concentric rings for monochromatic light.
- Pre-Filtering: Narrow band interference filter to ensure narrow light band.
- Resolving Power: Determined by the finesse of the etalon.



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The Fabry-Perot interferometer = imaging spectrometer which is formed by placing a device called an "etalon" (French étalon, meaning "measuring gauge" or "standard") in the collimated beam of a typical camera system. Two plane-parallel plates with highly reflective coatings.

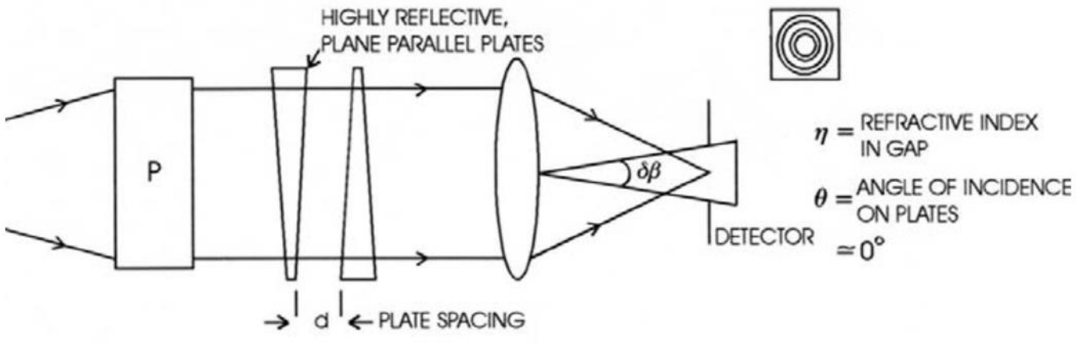
・Wavelengths transmitted with maximum intensity follow the relation $m\lambda=2nd\cos\theta$.
・Etalon in the collimated beam of a camera system. Set of concentric rings for monochromatic light.
・Pre-Filtering: Narrow band interference filter to ensure narrow light band.
・Taurus Tunable Filter: Wide-field narrow-band imaging in the CCD range (370 nm to 1,000 nm).
・Finesse (F): Measure of plate quality and reflectance.
・Resolving Power (R): $R=\lambda/\Delta\lambda$, dependent on the finesse and spacing of the etalon plates.
・Charge shuffling synchronized to frequency (band) switching is used to suppresses systematic errors, enhancing image quality.

a circular aperture isolates the central order which has an angular diameter $\delta\beta = \sqrt{(8/R)}$ and the free spectral range is given by

$$\Delta\lambda_{FSP} = \frac{\lambda}{m} = \frac{\lambda^2}{2nd} \tag{5.44}$$

The resolving power ($R = \lambda/\delta\lambda$) is

$$R = \frac{2Fnd}{\lambda} \tag{5.45}$$



5.4.3 Interference filters

- Multi-layer thin-film devices operate with the same principle as Fabry-Perot etalon.
- Produces transmission maxima when wavefronts are in phase.Construction
- Two quarter-wave stacks separated by a half-wave spacer.
- Can have 3-4 layers for steeper band slopes and near square "tophat" profiles.
- Continuous vacuum deposition run to create multiple layers.
- Base width where transmission is 1% of peak is 1.9-2.2 times the FWHM.
- Tilt-Scanning: Shifts center wavelength to the blue with increasing angle of incidence.

$$\lambda = \lambda_0 \sqrt{[1 - (n_o/n_e)^2 \sin^2 \varphi]} \tag{5.46}$$