“Polarimetry of Solar System objects”

2a: Instrumentation

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Polarization

- $Q = Ip_{lin} \cos 2\chi$ and $U = Ip_{lin} \sin 2\chi$.
- $\chi = 0.5 \operatorname{atan} (U / Q)$.
- Q/I and U/I are cartesian components of the vector $(p_{lin}, 2\chi)$.
- The degree of linear polarization is $p_{lin} = (Q^2 + U^2)^{1/2} / I$.
- The degree of circular polarization is $p_{cir} = V / I$.

The linear polarization is a vectorial quantity

The circular polarization is a scalar quantity

Relevant points

• It is necessary to measure very small quantities, like $p < 0.1\%$.

•The light is not 100% monochromatic, then the result is obtained by integration over λ, ω, ϕ .

• Any asimmetry (in the physical process or instrument) produces polarization, so Coudé or Nasmyth focus are not recomended.

• Any reflection produces polarization, so it is necessary to use anti-reflection coatings in all the optical elements.

• It is necessary to apply an observational technique that is insensible to several errors, like transparency changes during the measurements.

Modulation technique

- This technique consists of making differential measurements quickly to compensate for errors due to changes in the observational conditions.

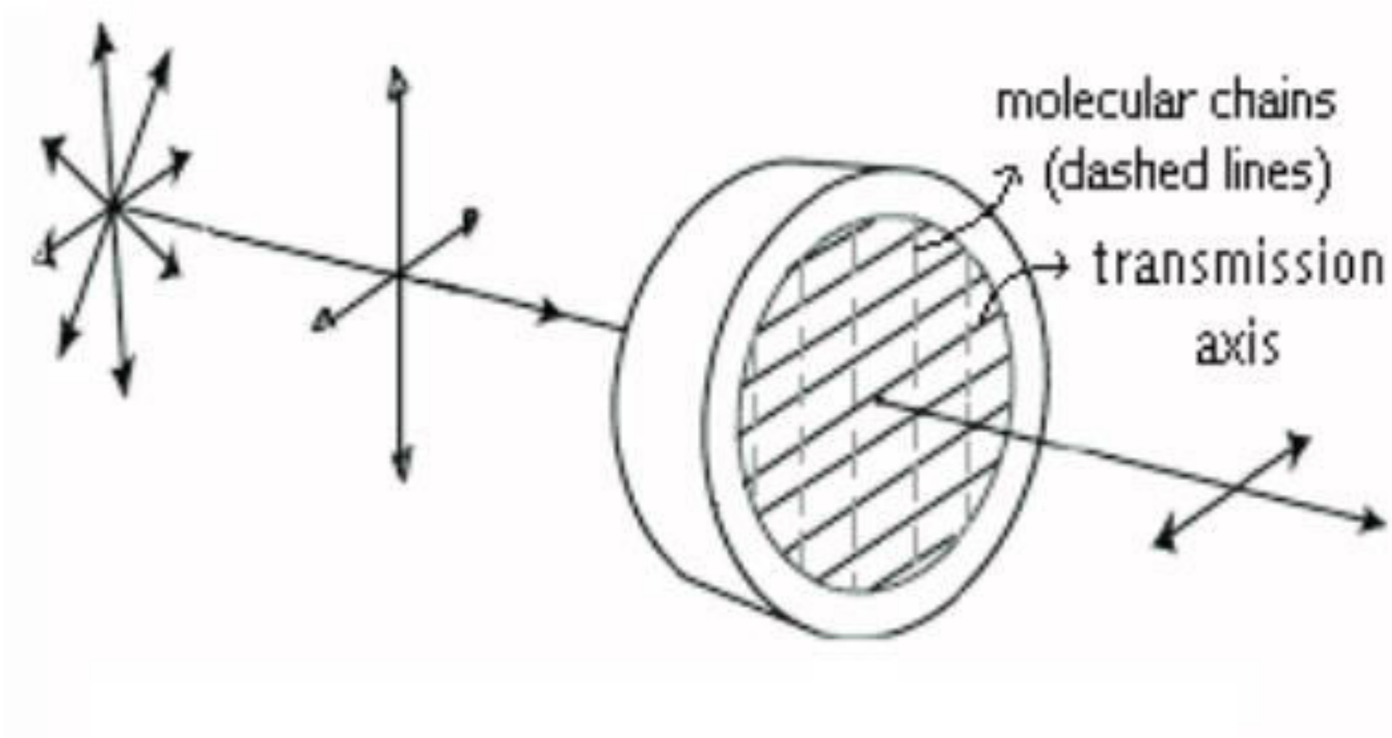
- The idea is to make simultaneous measurements at two orthogonal vibrational planes with different orientations.

- Modern polarimeters use CCD detectors and take advantage of the optical properties of birefringent materials.

- polarizers and retarders: quarter- and half-wave plates.

Dichroic polarizers

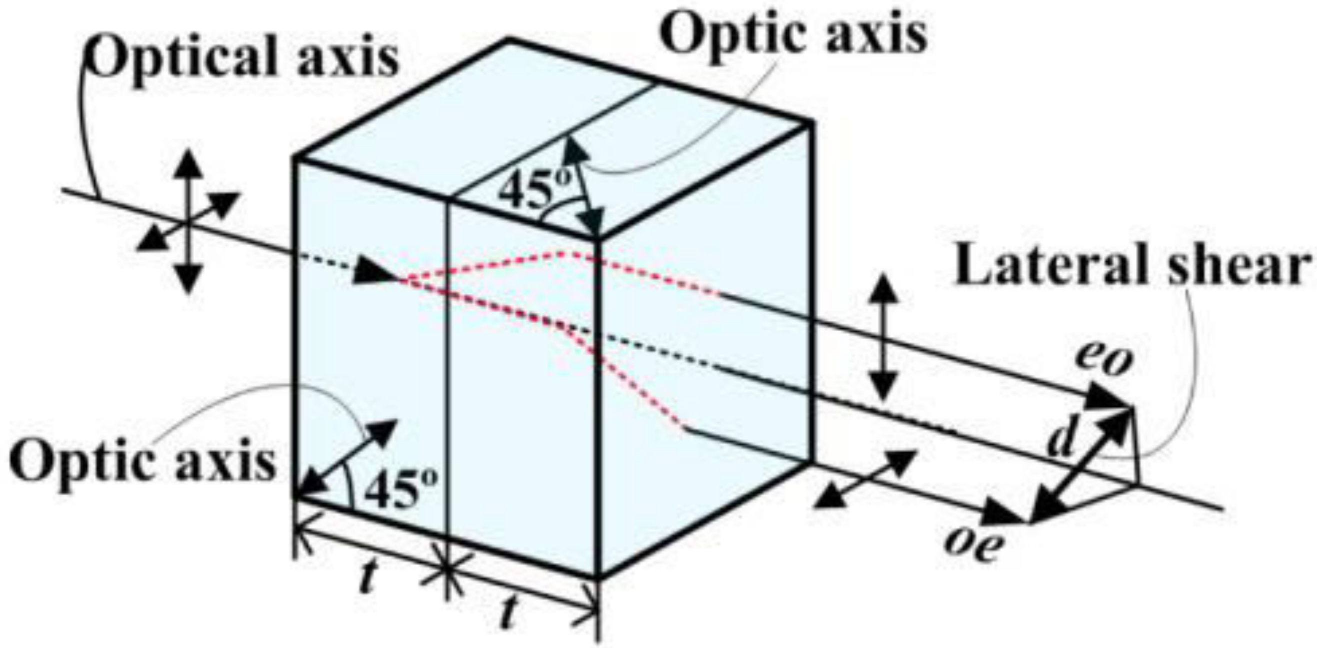
- Dichroic polarizers absorb all the components except the one that matches the axis of the polarizer (polarizing sheets).



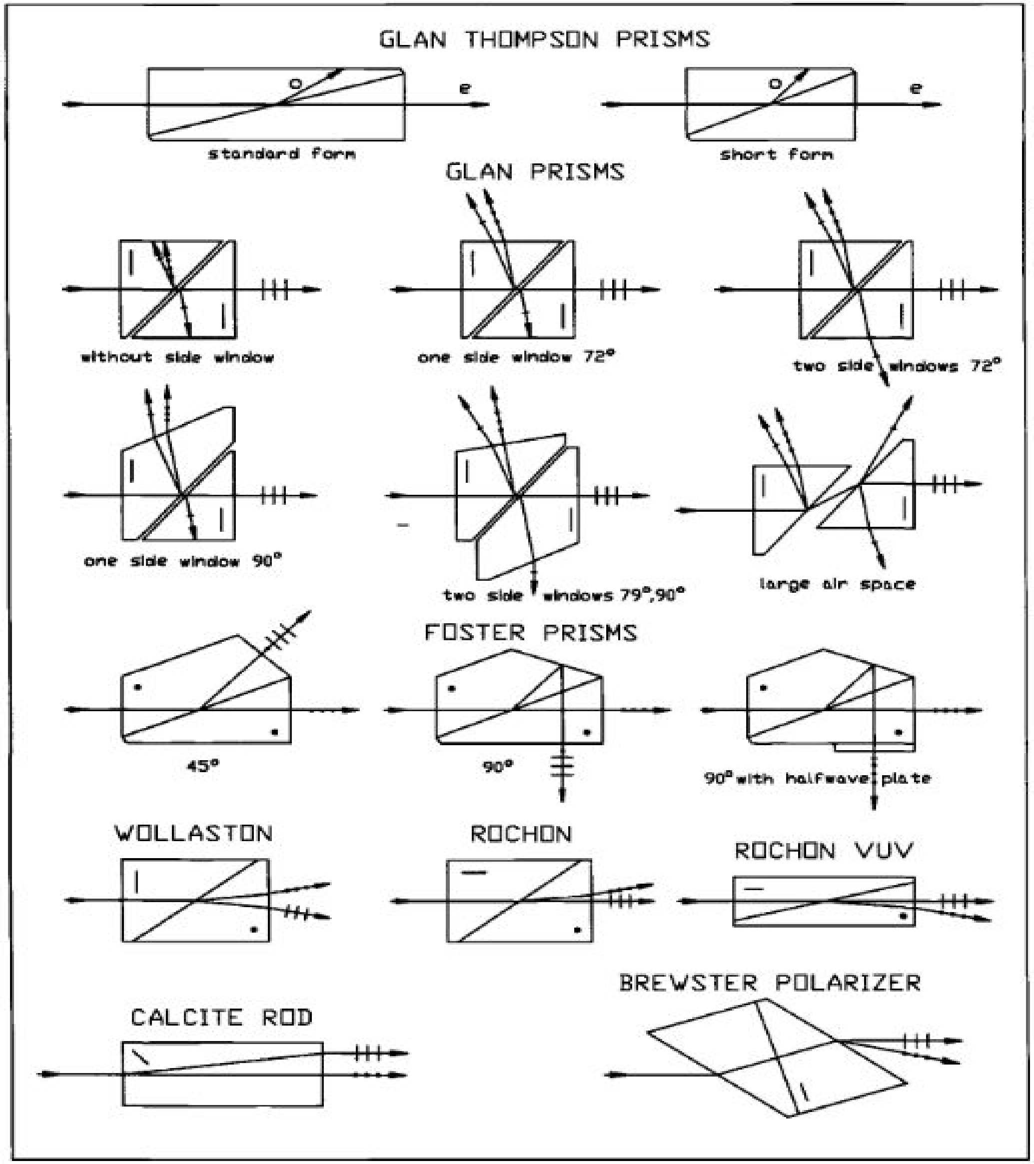
Birefringent polarizers

- Birefringent polarizers divide the beam in two orthogonal components called ordinary and extraordinary components
- There are several options (Savart plate, Wollaston prism, etc.)

Savart Plate



Birefringent polarizers



Some polarizers used in different instruments

Retarders or waveplates

- Resolve the incident light wave into two orthogonal linear polarization components by producing a phase shift between them.

- Depending on the induced phase difference, the transmitted light may have a different type of polarization than the incident beam.

- Retarders do not polarize unpolarized light.

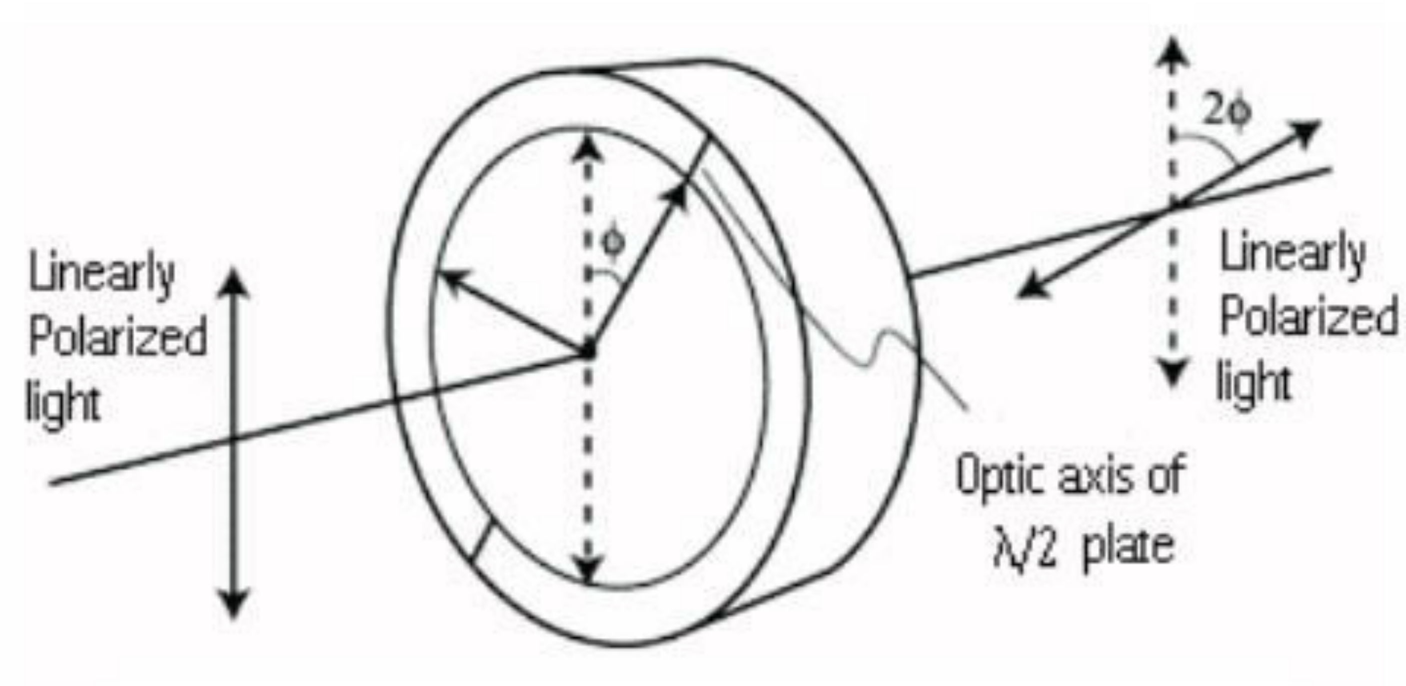
- Ideally, they do not reduce the intensity of the incident light beam.

- Retarders depends on wavelenght, so they must be achromatic.

- Retarders are made of birefringent materials producing a phase shift between the two orthogonal components.

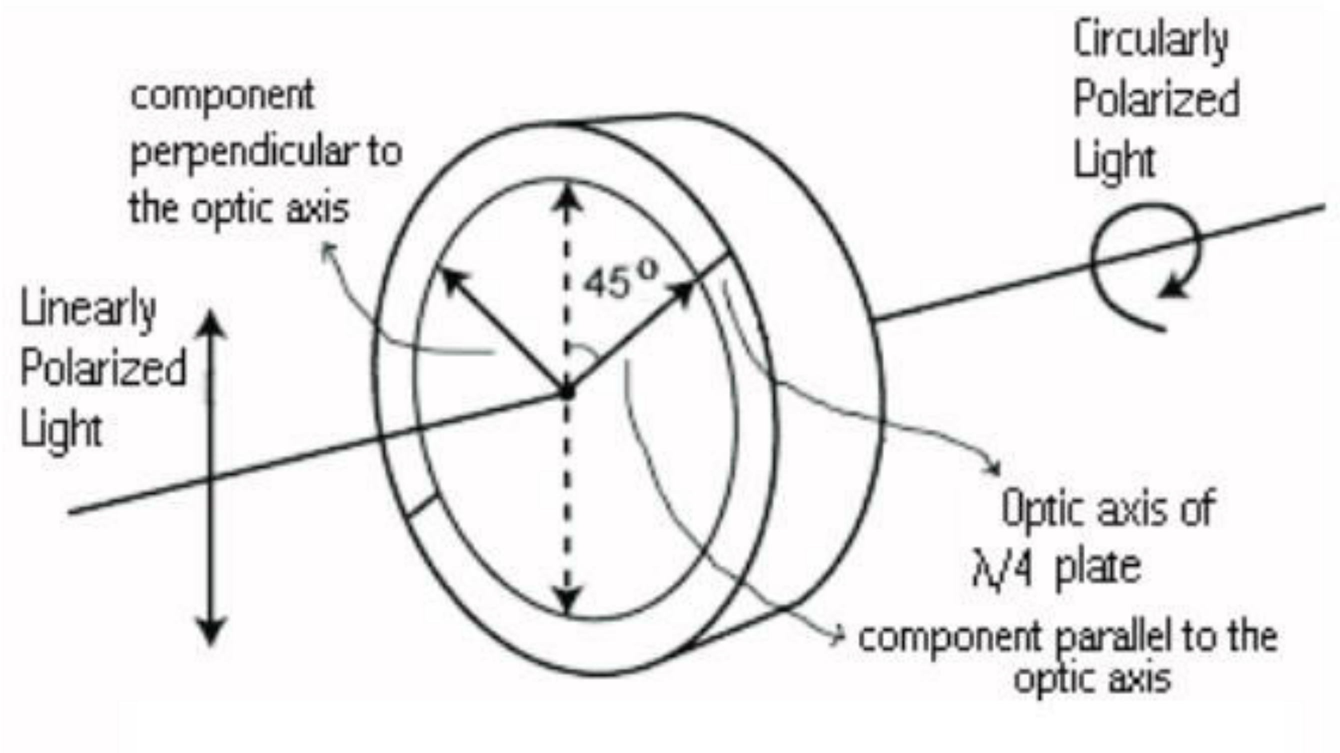
Half-wave plate

- Works as a polarization rotator for linearly polarized light.
- Rotates the polarization by twice the angle between its optical axis and the initial direction of polarization.

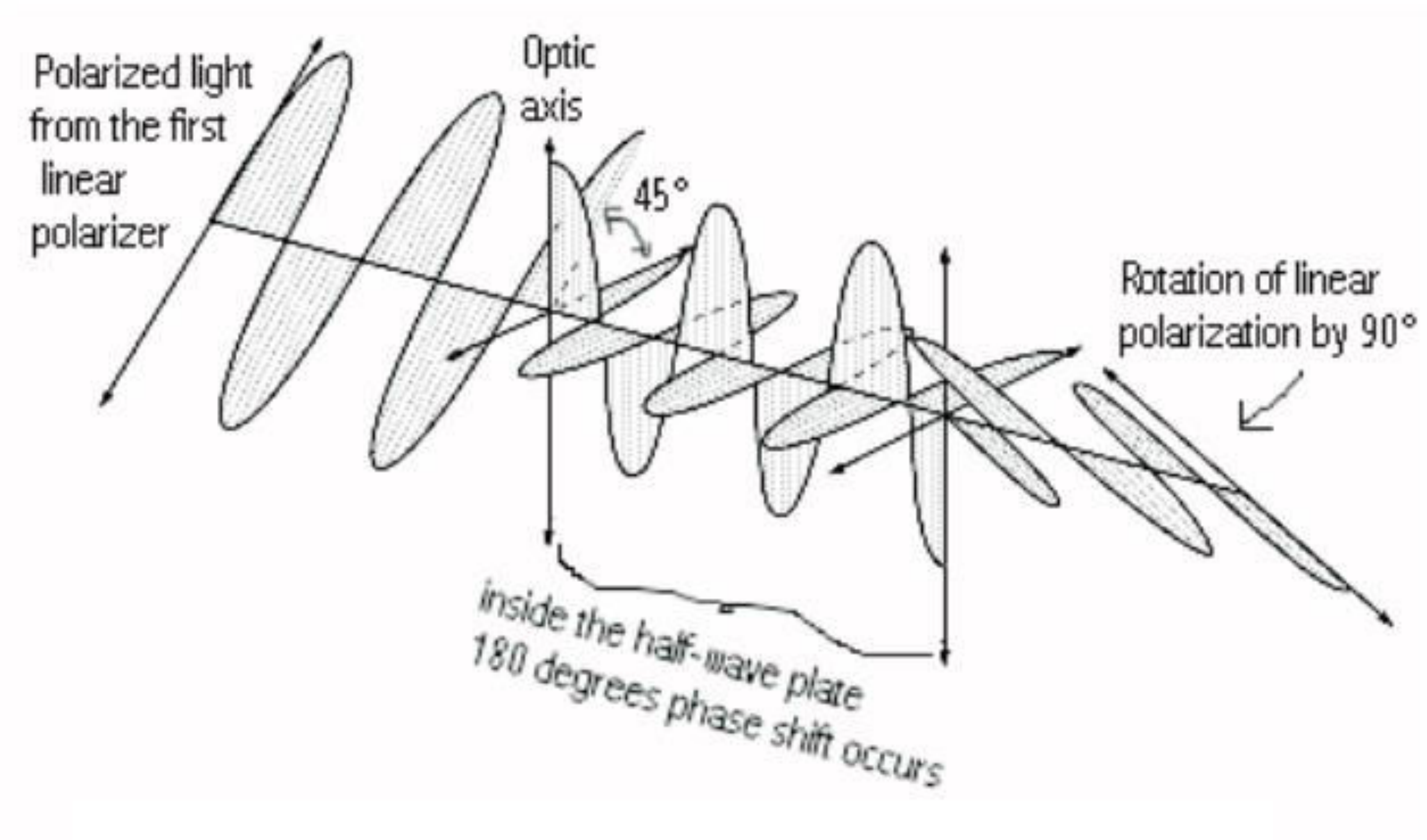


Quarter-wave plate

• Converts linear to circular polarization or vice-versa by a phase shift of 90º or 270º.

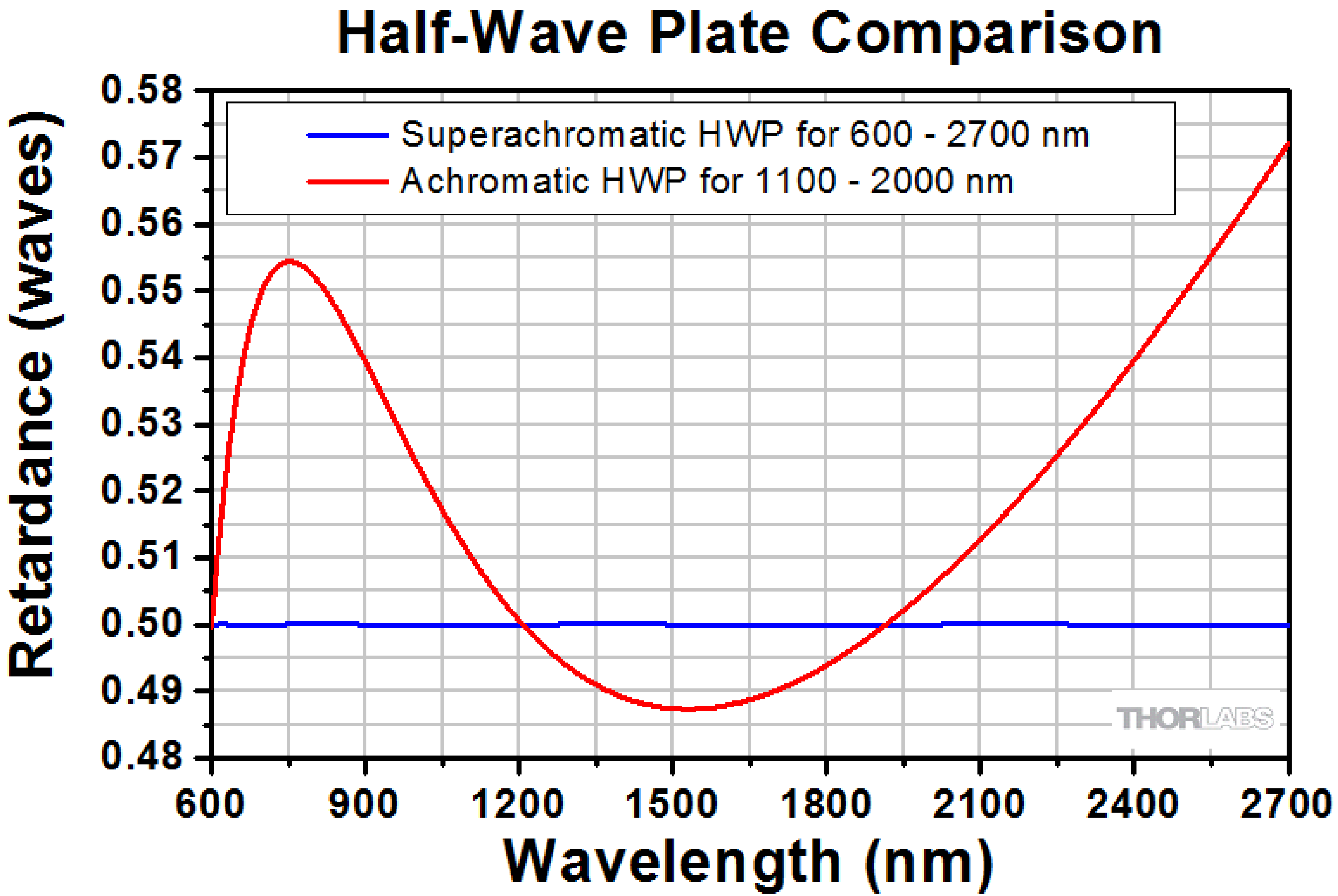


Waveplates

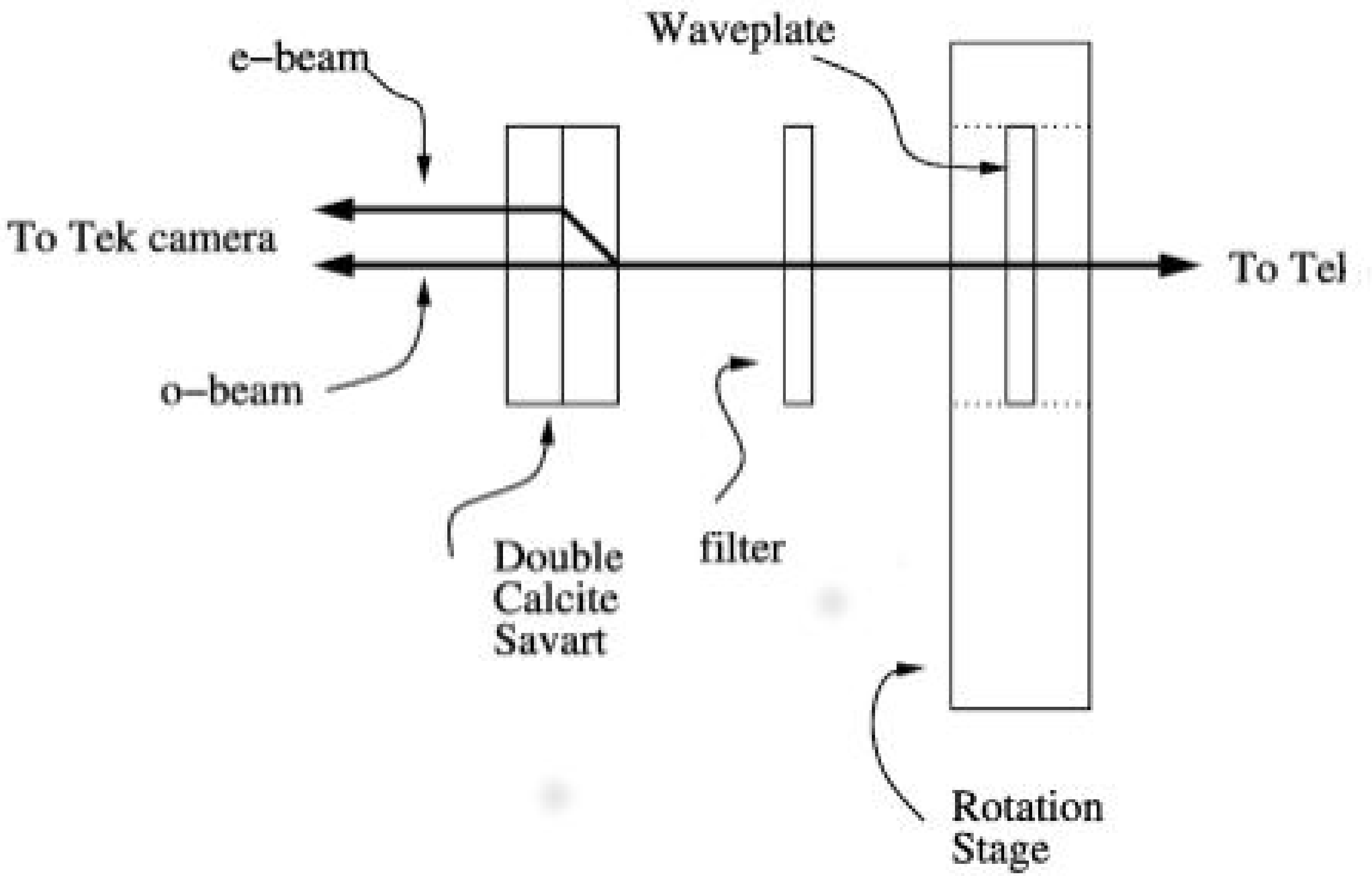


Polarized light from the first linear polarizer
Optic axis
45°
Rotation of linear polarization by 90°
inside the half-wave plate
180 degrees phase shift occurs

Waveplates


Half-Wave Plate Comparison
Superachromatic HWP for 600 - 2700 nm
Achromatic HWP for 1100 - 2000 nm
Retardance (waves)
0.58
0.57
0.56
0.55
0.54
0.53
0.52
0.51
0.50
0.49
0.48
600
900
1200
1500
1800
2100
2400
2700
Wavelength (nm)
THORLABS

Polarimeter



Polarimeter

CASPOL unit
+
CCD

CASLEO
Argentina

Reduction process

- Images for several positions of the retarder (α) are obtained.

- The images are reduced following the usual process (bias, dark, flat).

- The intensity of the ordinary and extraordinary images for each object (I_o and I_e) are obtained.

- The objective is to obtain the polar coordinates of the vector using their orthogonal components. →

$$(Q, U) \rightarrow (p, 2\chi)$$

$$p = \sqrt{(Q^2 + U^2)}$$

$$\chi = \frac{1}{2} \arctan\left(\frac{U}{Q}\right)$$

Reduction process

- We assume that we only have linear polarization.

$$\begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix} = \begin{pmatrix} I_{UP} \\ 0 \\ 0 \\ 0 \end{pmatrix} + \begin{pmatrix} I_P \\ Q \\ U \\ 0 \end{pmatrix}$$

Unpolarized component
~90-99%

Polarized component
~1-10%

Reduction process

- If α is the position angle of the retarder, the ordinary and extraordinary components are:

$$I_o = \frac{I_{UP}}{2} + I_P \cos^2(\chi - 2\alpha)$$

$$I_e = \frac{I_{UP}}{2} + I_P \sin^2(\chi - 2\alpha)$$

- Using these components it is possible to define a relation between them:

$$R_\alpha = \left(\frac{I_o - I_e}{I_o + I_e}\right)_\alpha$$

Reduction process

$$
\begin{aligned}
R_\alpha &= \left(\frac{I_o - I_e}{I_o + I_e}\right)_\alpha \\
&= \frac{I_P[\cos^2(\chi - 2\alpha) - \sin^2(\chi - 2\alpha)]}{I_{UP} + I_P} \\
&= \frac{I_P}{I_{UP} + I_P}\cos(2\chi - 4\alpha) \\
&= p\cos(2\chi - 4\alpha) \\
&= p[\cos(2\chi)\cos(4\alpha) + \sin(2\chi)\sin(4\alpha)] \\
&= Q\cos(4\alpha) + U\sin(4\alpha)
\end{aligned}
$$

Reduction process

- If the measurements are made at particular values of α it is possible to solve easily for Q and U:

$$
\begin{aligned}
R_0 &= p\cos(2\chi) &= Q \\
R_{22,5} &= p\sin(2\chi) &= U \\
R_{45} &= -p\cos(2\chi) &= -Q \\
R_{67,5} &= -p\sin(2\chi) &= -U
\end{aligned}
$$

$$p = \sqrt{(Q^2 + U^2)}$$

$$\chi = \frac{1}{2}\arctan\left(\frac{U}{Q}\right)$$

Zero points

- Since the instrument add polarization to any measurement, it is necessary to substract it. The Q and U instrumental components are obtained observing unpolarized standard stars.

- The zero point for α is arbitrary, so it is considered as zero the direction to the north equatorial pole.

- This choise is not valid for solar system objects because there is a scattering plane clearly defined.

- To find the zero point of the polarization angle, high polarization standards stars must be observed.

“Polarimetry of Solar System objects”

2b: Theory and laboratory studies

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Polarimetry of solar system bodies

- The source of unpolarized light is the Sun.

- In general, polarized light appears due to reflection on opaque bodies and produce linear polarization.

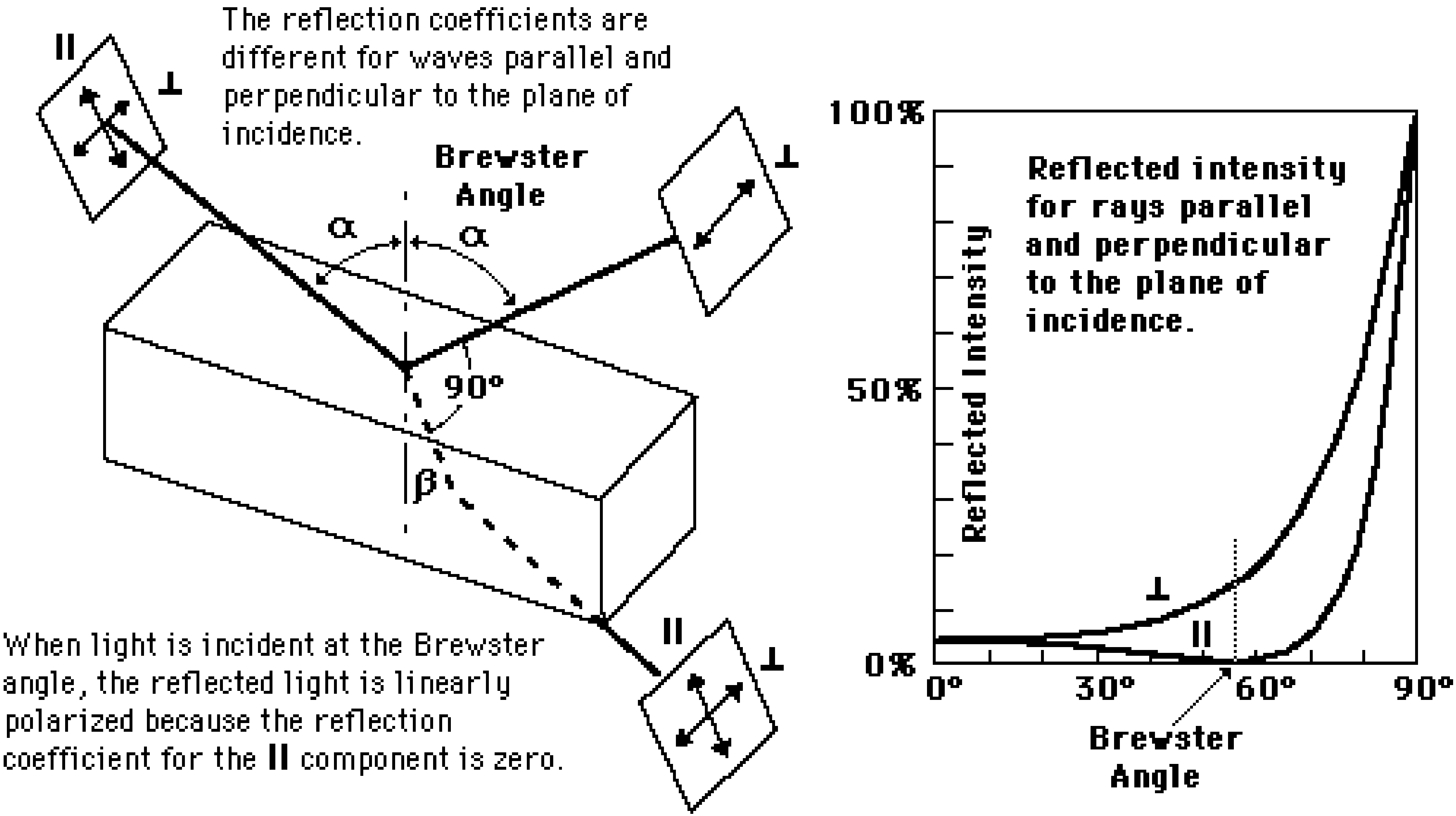
- The scattering plane is the plane containing the observer, the Sun and the object, then:

$$P_r = \frac{(I_\perp - I_\parallel)}{(I_\perp + I_\parallel)}$$

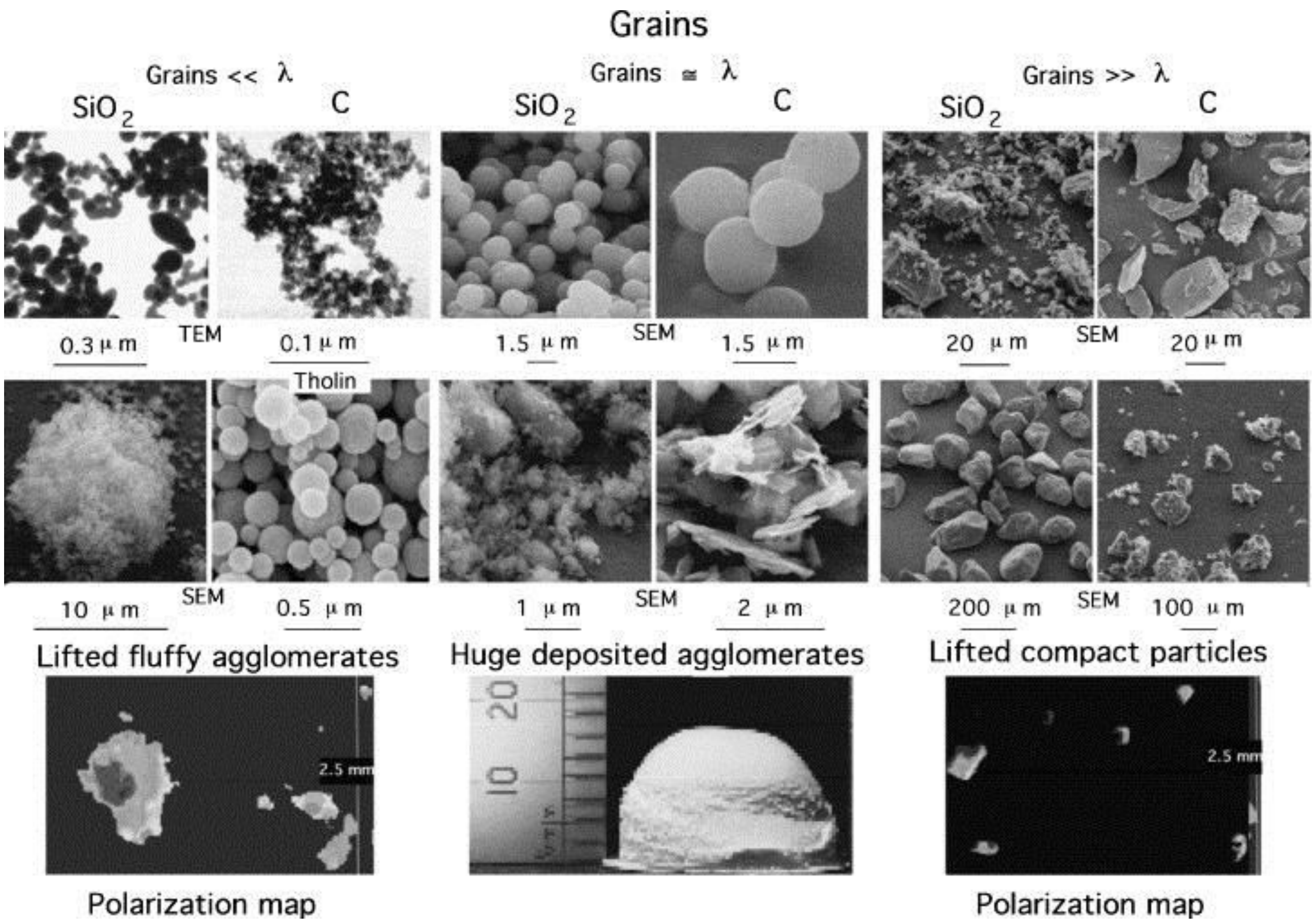
- Usually, the scattering medium is interplanetary dust or a dusty surface.

- The objective is to obtain information about the scattering medium (particle sizes, shapes, composition, albedo, etc.).

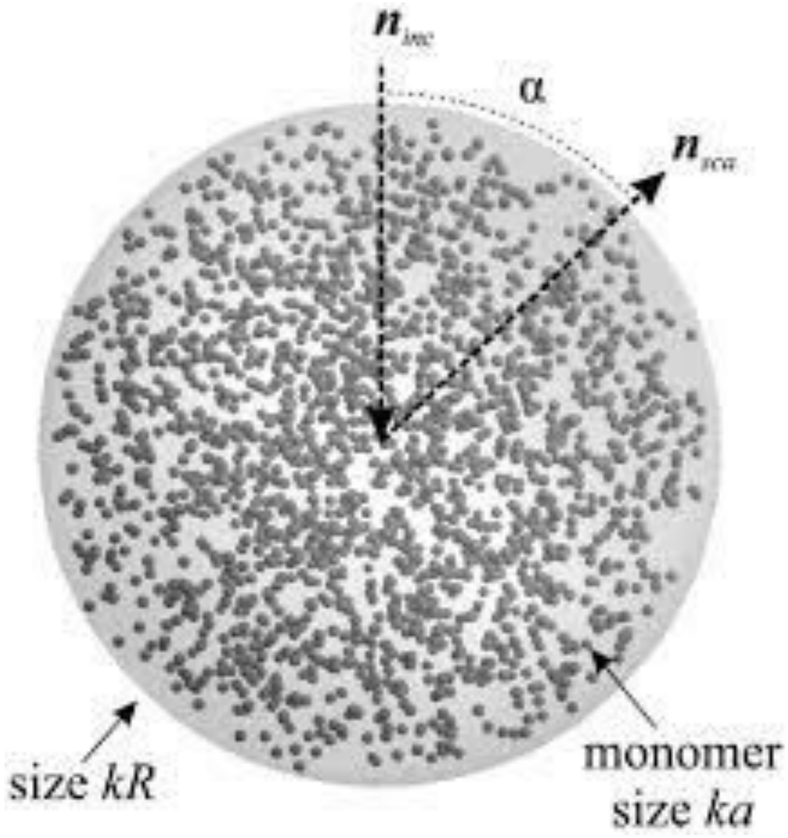
Polarimetry of solar system bodies



Polarimetry of solar system bodies

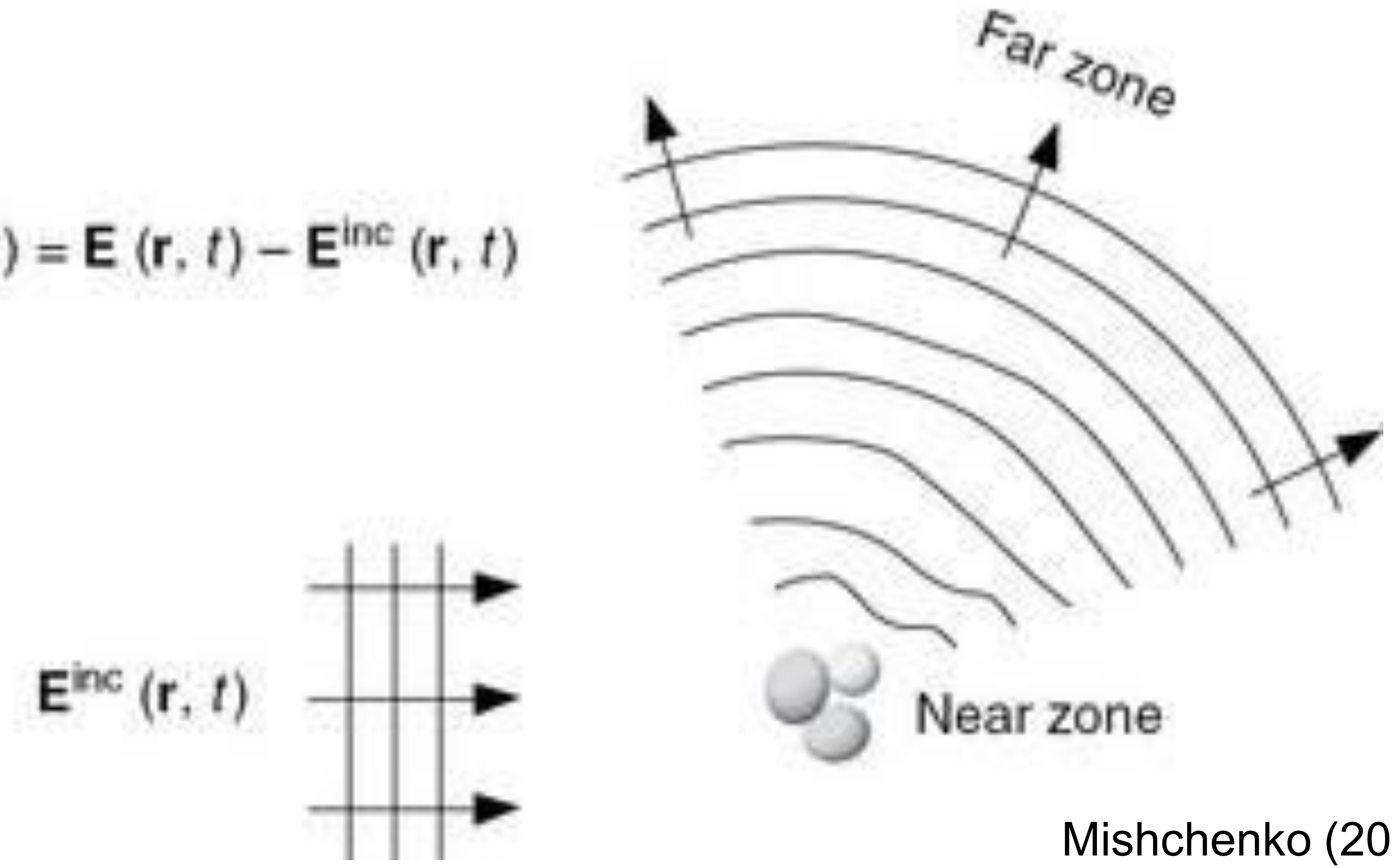


Polarimetry of solar system bodies



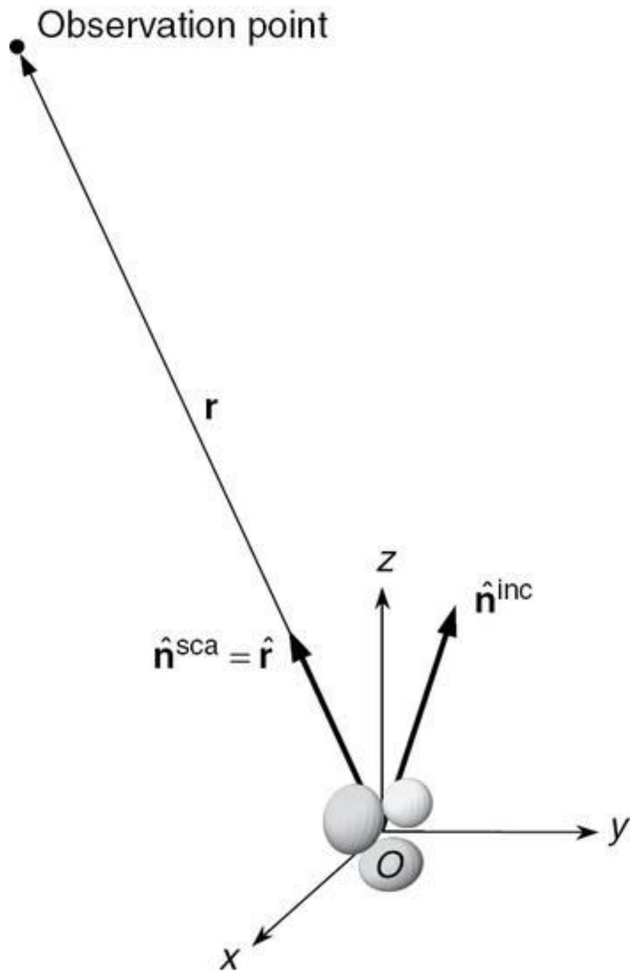
Polarimetry of solar system bodies

$$\mathbf{E}^{sca}(\mathbf{r}, t) = \mathbf{E}(\mathbf{r}, t) - \mathbf{E}^{inc}(\mathbf{r}, t)$$



Mishchenko (2015)

Polarimetry of solar system bodies



$$\mathbf{E}^{\mathrm{sca}}(\mathbf{r}) \underset{r\to\infty}{\longrightarrow} \frac{\exp(\mathrm{i}k_1 r)}{r}\mathbf{E}_1^{\mathrm{sca}}(\hat{\mathbf{n}}^{\mathrm{sca}})$$

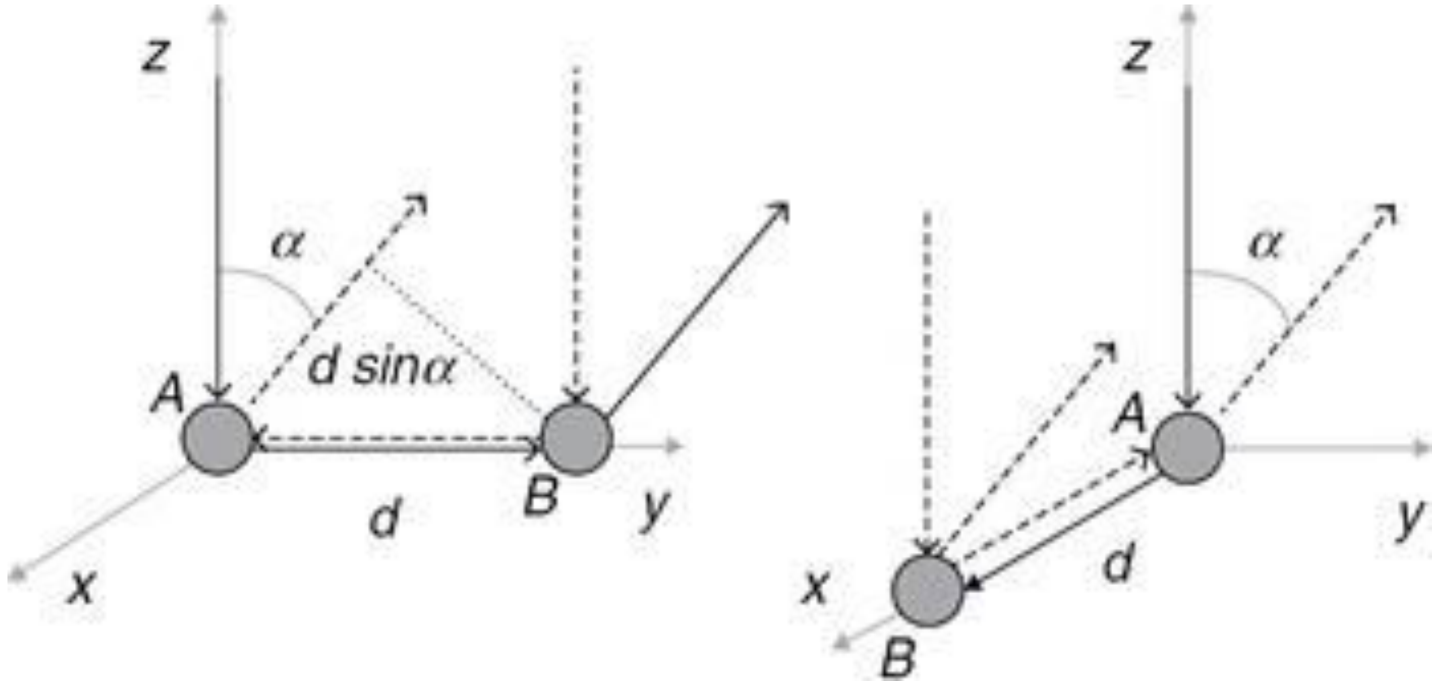
$$= \frac{\exp(\mathrm{i}k_1 r)}{r}\overset{\leftrightarrow}{A}(\hat{\mathbf{n}}^{\mathrm{sca}}, \hat{\mathbf{n}}^{\mathrm{inc}}) \cdot \mathbf{E}_0^{\mathrm{inc}},$$

$$\hat{\mathbf{n}}^{\mathrm{sca}} \cdot \mathbf{E}_1^{\mathrm{sca}}(\hat{\mathbf{n}}^{\mathrm{sca}}) = 0.$$

Mishchenko (2015)

Polarimetry of solar system bodies

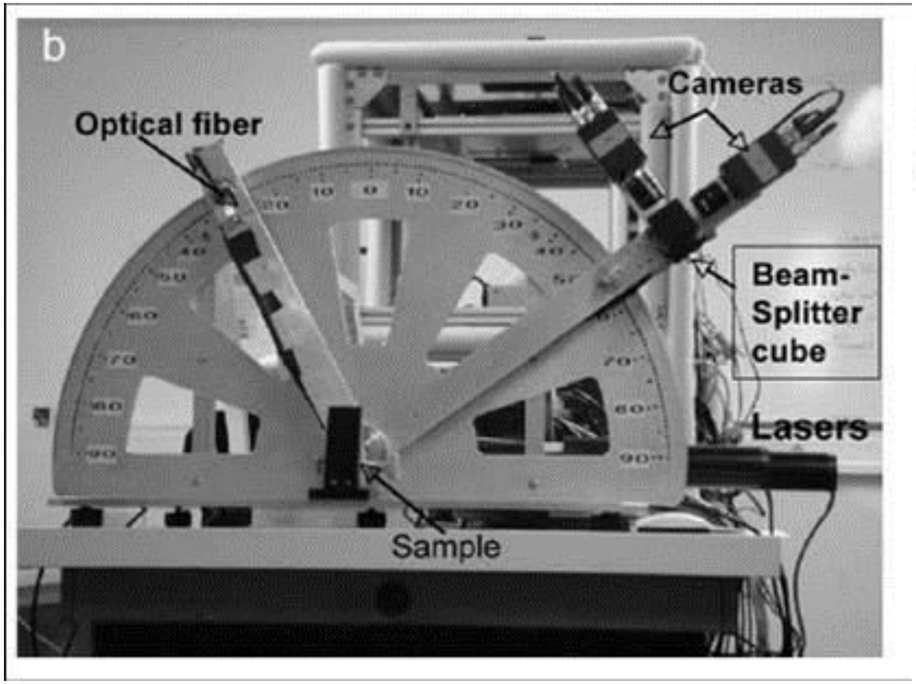
Multiple scattering of light

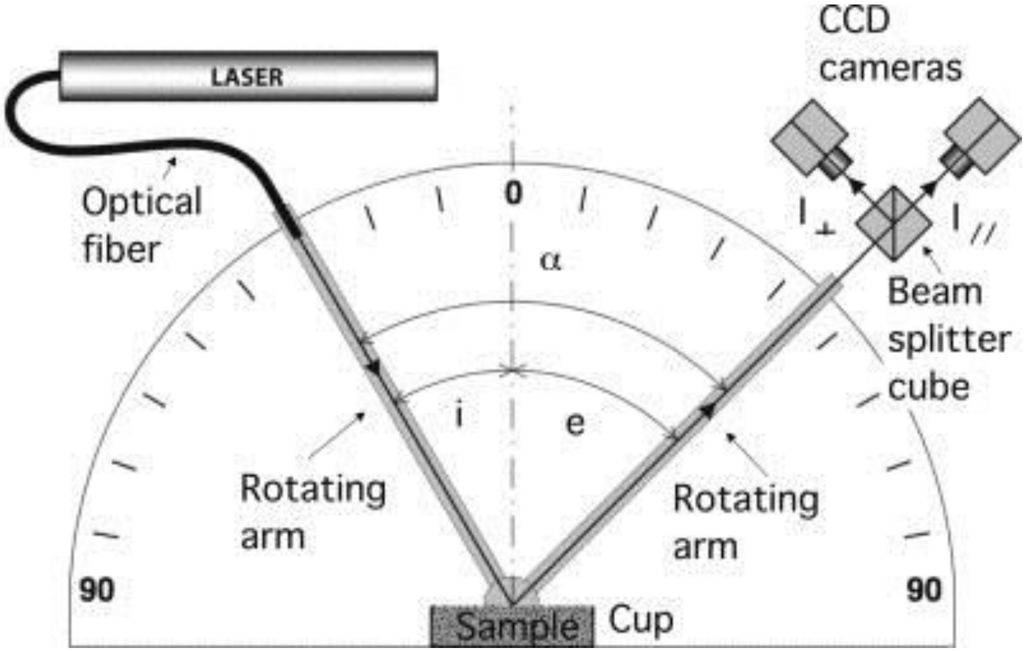


Muinonen et al. (2015)

Polarimetry of solar system bodies

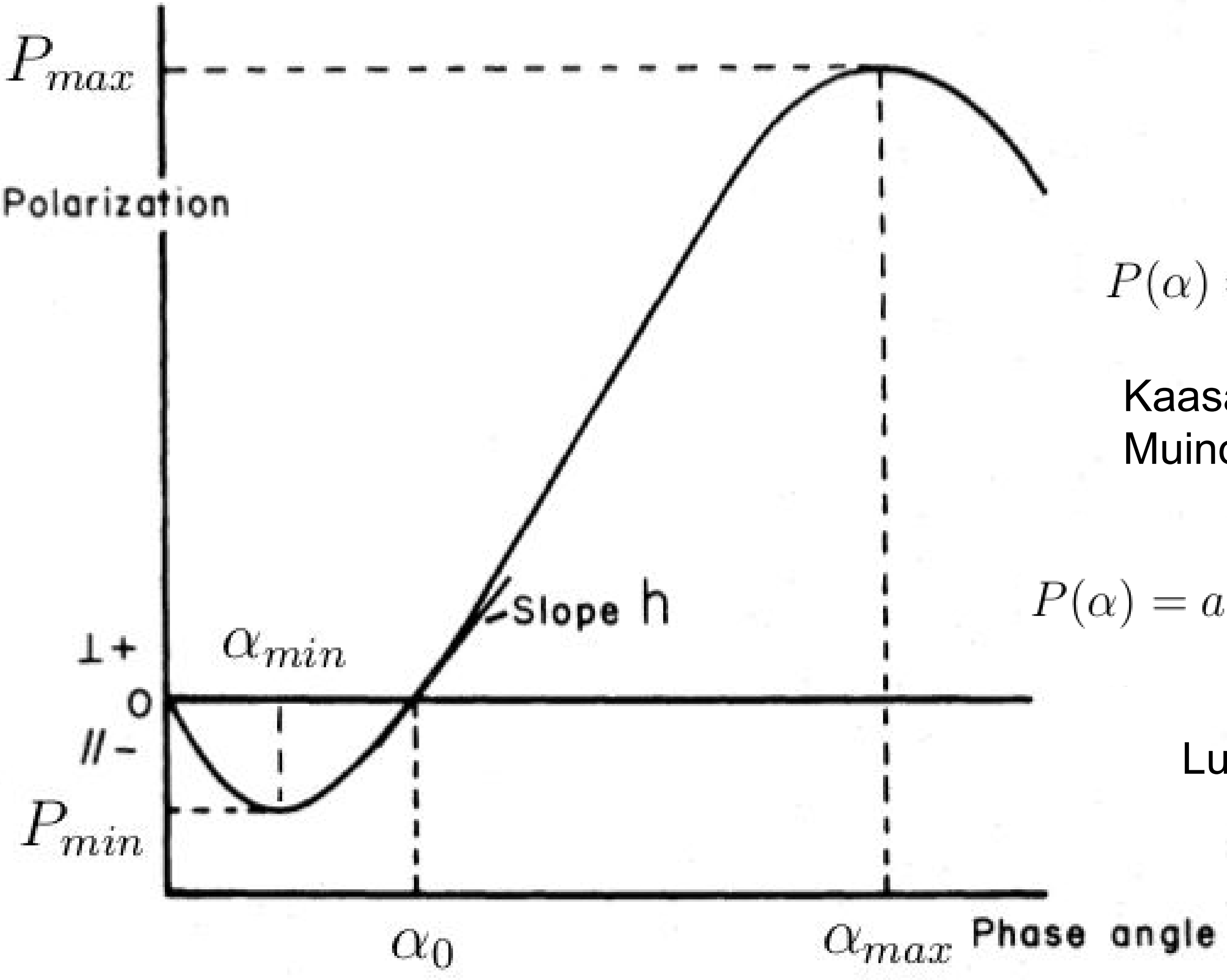
PROGRA2-Surf imaging photopolarimeter





Levasseur-Regourd et al. (2015)

Polarimetry of solar system bodies



$$P_r = \frac{(I_\perp - I_\parallel)}{(I_\perp + I_\parallel)}$$

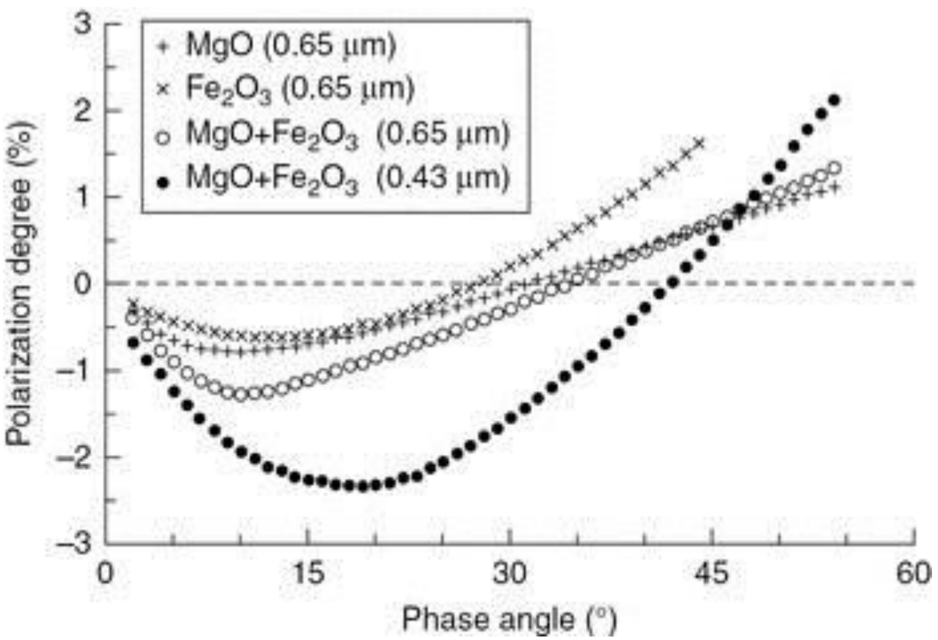
$$P(\alpha) = A_0 \left[\exp\left(-\frac{\alpha}{A_1}\right) - 1\right] + A_2\alpha$$

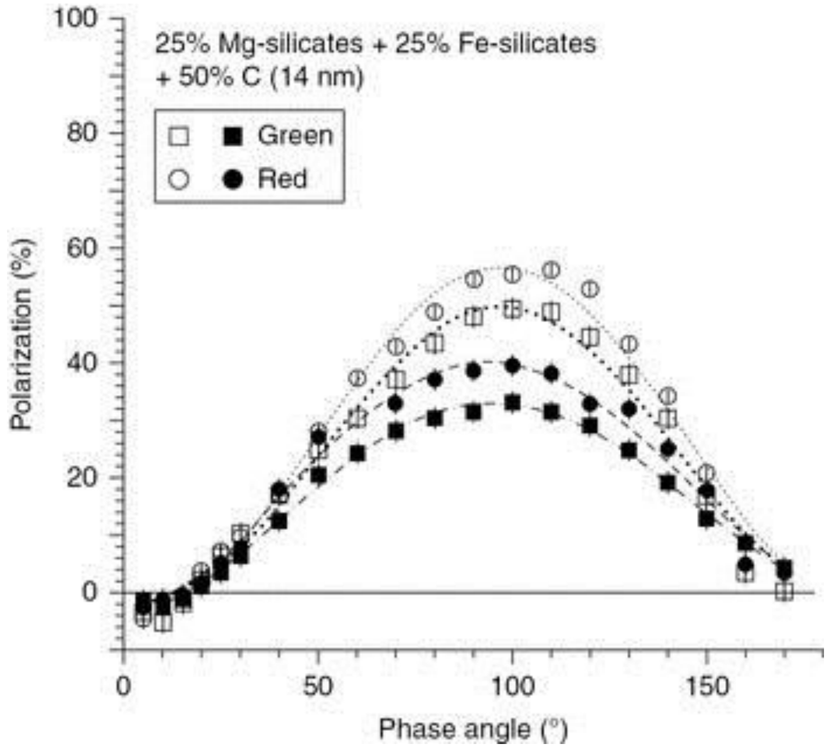
Kaasalainen et al. (2001, 2003)
Muinonen et al. (2009)

$$P(\alpha) = a[\sin(\alpha)]^b \sin\left(\frac{\alpha - c}{2}\right)\left[\cos\left(\frac{\alpha}{2}\right)\right]^d$$

Lumme & Muinonen (1993)

Polarimetry of solar system bodies





Levasseur-Regourd et al. (2015)

Polarimetry of solar system bodies

- The degree of polarization is a function of the phase angle.

- Multiple scattering in particulate media is the fundamental process to understand.

- In any simulation of the scattering process the number of free parameters is huge.

- The scattering in a macroscopic medium composed of microscopic particles constitutes an open computational problem.

- The results of laboratory studies help to reach a theoretical understanding of the physical mechanisms at work.

- The general idea is to relate in some way polarimetric and physical parameters.

Polarimetry of solar system bodies