Light polarization and its use in retrievals of atmospheric particles

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Why this talk in the ROADMAP framework?

- Several activities within ROADMAP deal with the polarized state of scattered light.
  - Lab measurements of scattering matrices (see lecture **Olga Muñoz**)
  - Modelization of particle scatt./abs. (see lecture **Julia Martikainen**)
  - Retrievals of Martian dust using scattering matrices (see lecture **Yannick Williame**)
- Not everyone in the atmospheric community is aware of polarization
  - its effect on measurements (without you even knowing it)
  - its use in atmospheric research (aerosols/clouds/dust/haze, …)
- ROADMAP: Interesting things that have not yet been addressed

About me

- Physics degree (KULeuven), since 1996 at BIRA-IASB.
- Phd: retrievals + exploitation of the Occultation Radiometer (ORA) data (1992-1993). I naturally drifted into stratospheric aerosols (Pinatubo eruption, 1991)
- Aerosol dynamics modelling
- GOMOS/Envisat, ACE/SciSat-1
- Polar Stratospheric Clouds (PSCs), Polar Mesospheric Clouds (PMCs), PyroCumulonimbus clouds.
- Global long-term climatology of stratospheric aerosols (C. Bingen)
- ALTIUS (hyperspectral imager), VISION/PICASSO (solar occultation with Cubesat)
- Since COVID: planetary aeronomy! (A.C. Vandaele)

My past in Earth observation (1)

UV/VIS/NIR spectral observations

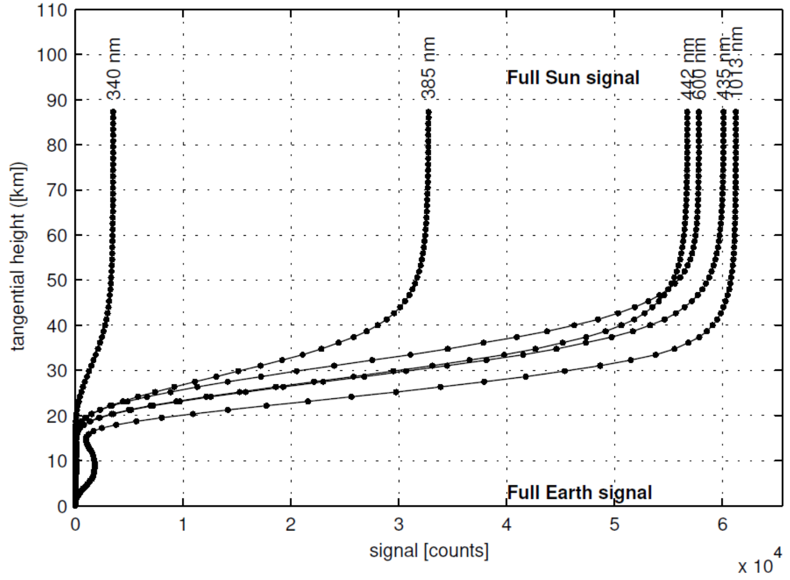


Figure 4.4: Measured occultation signals (Oct. 10, 1992, longitude = 13.58°, latitude = 27.06°). Notice the low sensitivity of the UV-channels, caused by the filter and window degradation.

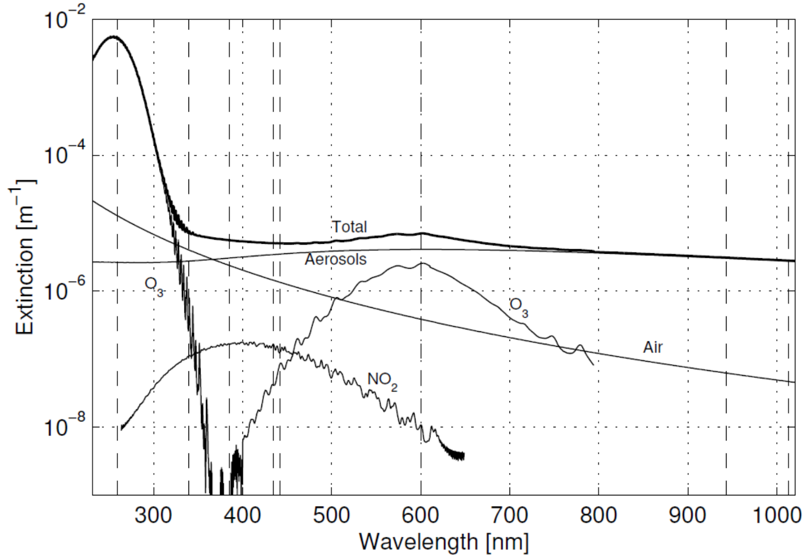


Figure 3.10: Extinction versus wavelength, calculated from gas densities and aerosol properties that are representative for an altitude of 22 km, in high-volcanic conditions. Total extinction is also shown (bold solid line) while ORA channels are indicated by dashed lines.

- Measurement to transmittance: $T(h,\lambda) = \frac{I(h,\lambda)}{I_0(h,\lambda)}$
- 'Vertical'/'spatial' inversion: Transmittance $T(h,\lambda) \rightarrow$ Total optical extinction $\beta_{tot}(z,\lambda)$
- 'Spectral' inversion: Total optical extinction $\beta_{tot}(z,\lambda) \rightarrow N_{air}(z), N_{O3}(z), N_{NO2}(z), \beta_{aero}(z,\lambda)$

My past in Earth observation (2)

The aerosols

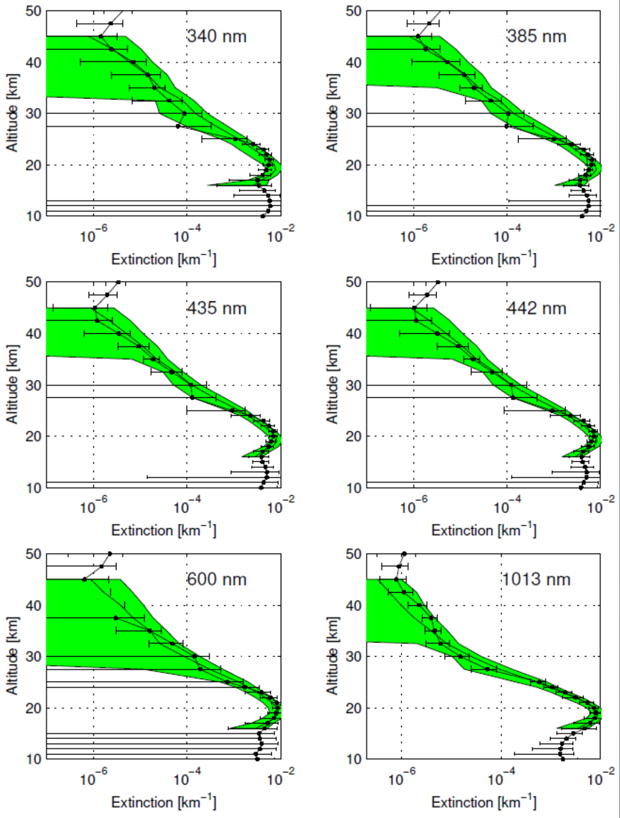


Figure 5.5: Mean aerosol extinction profiles (25 events). Shaded regions and solid lines: SAGE II. Solid lines with dots and error bars: ORA.

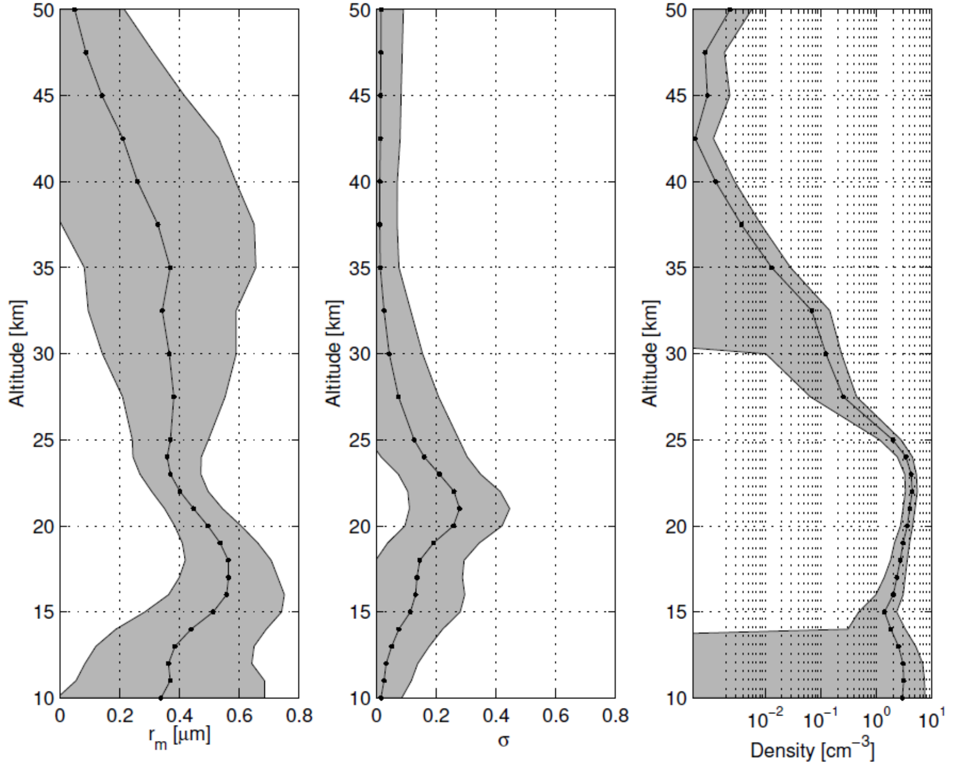


Figure 6.10: Altitude profiles for r_{m}, σ and $\mathcal{N}$, averaged over the entire ORA mission.

- 'Radial' inversion: aerosol ext. $\beta_{aero}(z,\lambda) \rightarrow$ Particle Size Distribution $n(r;\ a_1(z), \dots, a_n(z))$
- Examples: Normal, Log-normal, power law, Gamma, Modified Gamma, …

My past in Earth observation (3)

Scientific interpretation!

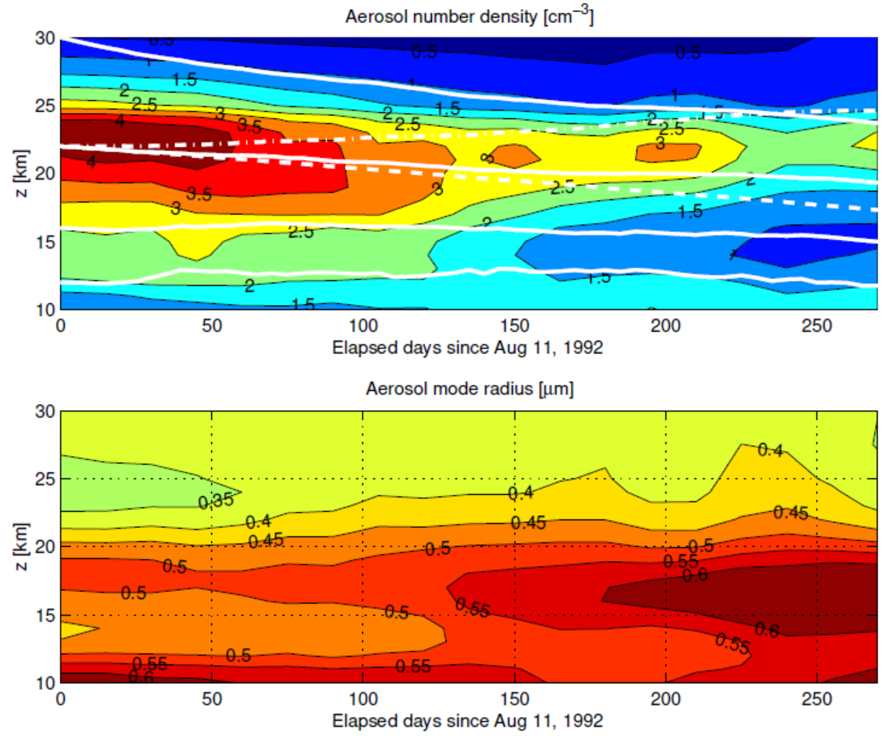
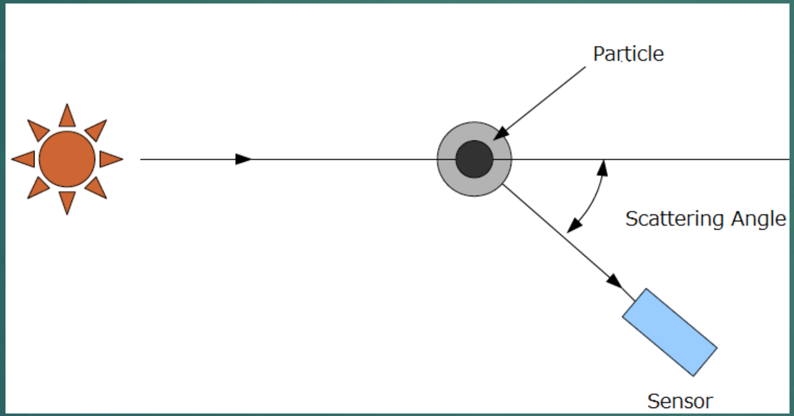


Figure 6.17: Top: latitude averaged time evolution of $\mathcal{N}(t, z)$. Full lines refer to vertical trajectories starting at 12, 16, 22 and 30 km, respectively. The dashed line is the $z = 22$ km trajectory, only accounting for sedimentation, while the dot-dashed line only includes vertical advection (see text). Bottom: time evolution for r_m.

Occultation data are limited
(and for aerosols: frustrating)

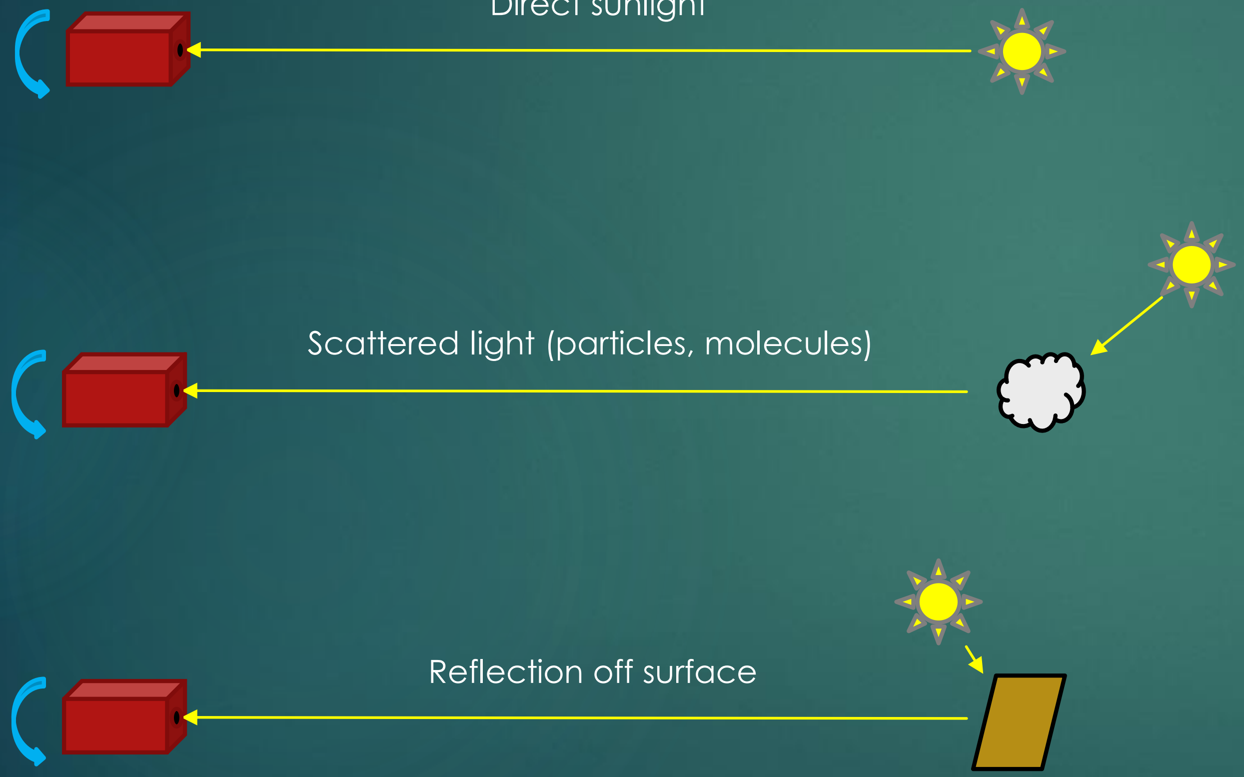
- We know particles scatter light in all directions. *Occultation instruments only observe in the forward direction: scattering angle θ is zero*. We're throwing away lots of information.

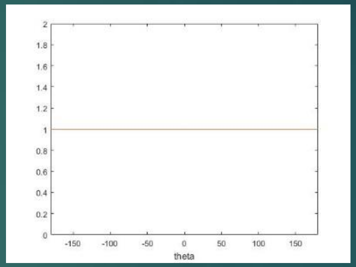


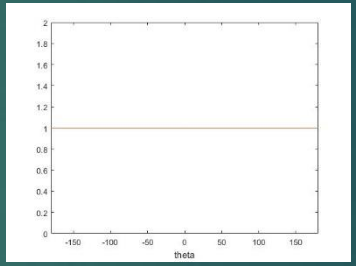
- Something else happens at $\theta \neq 0$: Initially unpolarized sunlight becomes **polarized**. The polarization depends on the properties of the particle (size, shape, composition)

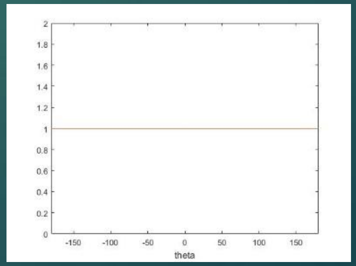
A simple experiment (1)

with a pinhole camera (camera obscura)



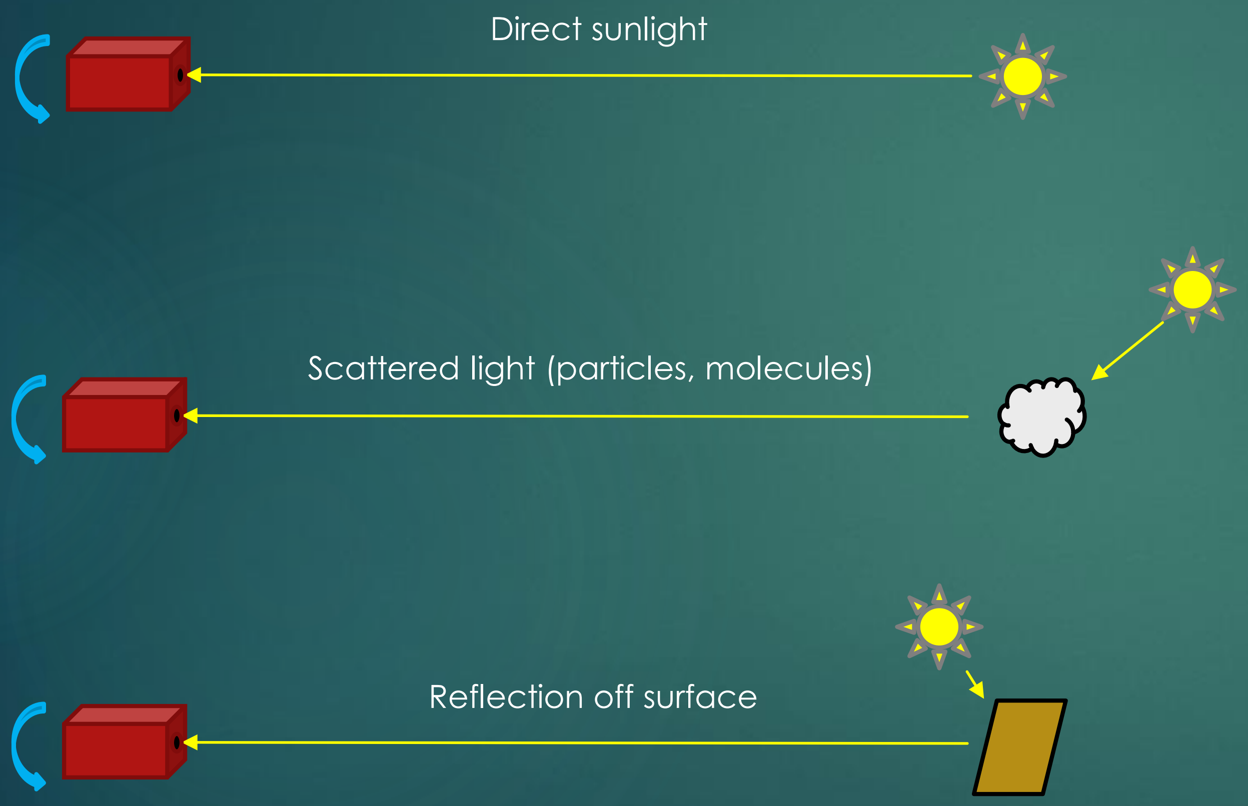


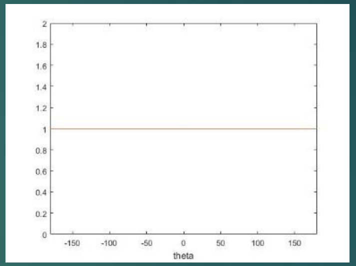


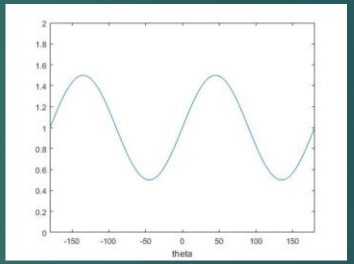


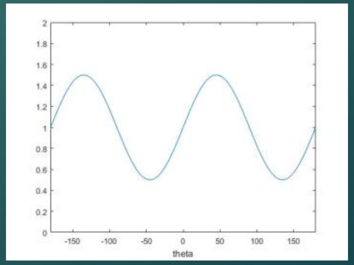
A simple experiment (2)

Now with a generic optical instrument









A simple experiment(3)
What do we learn from this?

- Apart from 'intensity' (flux, radiance, irradiance, …) and wavelength (frequency, period, wavenumber), light has another property that is sometimes manifest, sometimes not.
- Sunlight doesn't have it
- Light acquires it after having been scattered or reflected.
- Optics (mirrors, lenses, gratings, prisms, tunable filters, …) are sensitive to it, a pinhole camera is not.
- It's called **polarization** (unfortunately)
- *It contains information on molecules/particles (scattering) and surfaces (reflection)!*
- *Preview: It's annoying or wonderful, depending on your point of view!*

Observations from orbit

Geometries vs. polarization

Geometry	Resolution Vertical	Resolution Horizontal	Forward model	Coverage	Polarization?
Occultation: • Solar • Stellar • Planetary • Lunar	 Very good Good Good Very good	 Bad Bad Bad Bad	 Very simple Very simple OK OK	 Terminator Night side Night side Night side	 NO NO YES YES
Limb: • Scatter • Emission	 OK Good	 Bad Bad	 Very complex OK	 Day side Night side	 YES (YES)
Nadir: • Reflection • Emission	 Bad Bad	 Very good Very good	 Very Complex OK	 Day side Night side	 YES (YES)
LIDAR	x	x	OK	Night side	YES
….					

A brief history
Polarization of light

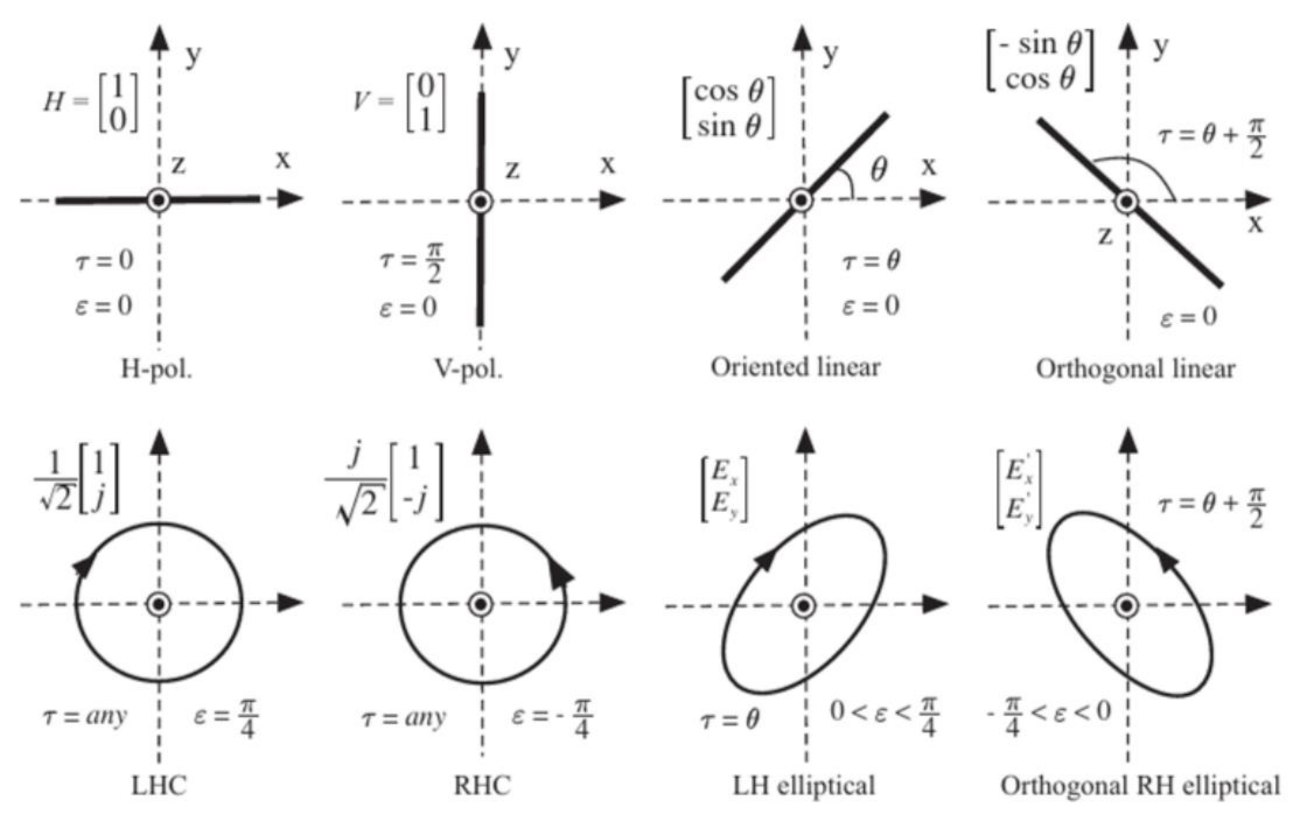
- **Vikings!** 'Sunstones' for marine navigation (probably Iceland spar (calcite))
- **Erasmus Bartholin (1669)**: first publication on double refraction in Icelandic spar
- **Christiaan Huygens (1690)**: First wave theory of light; an early explanation of double refraction
- **Thomas Young (1803)**: light is most definitely a wave (double-slit experiment)
- **Etienne-Louis Malus (1809)**: polarization by reflection, cosine-squared law.
- **Dominique François Jean Aragon(1809)**: the sky light is polarized.
- **David Brewster (1815)**: polarization angle vs. refractive index
- **Augustin-Jean Fresnel**: theoretical explanation (light = transversal wave); laws for reflectance and transmittance
- **Michael Faraday (1845)**: discovers Faraday rotation
- **George Gabriel Stokes (1852)**: theory in terms of observable quantities (Stokes parameters)
- **Jules Henry Poincaré (1892)**: Alternative parameterization, Poincaré sphere
- **R. Clark Jones (1941)**: introduces Jones matrices acting on electric field vectors.
- **Hans Mueller (1943)**: teaches Mueller matrices acting on Stokes vectors at MIT.
- **Subrahmanyan Chandrasekhar (1950)**: 'Radiative Transfer theory', popularizes Stokes vectors.

Physics of light polarization (1)

Some mathematical insight

- The fundamental origin of polarization: a photon = a spin 1 boson
  - $s = 1$, # spin states = $2s + 1 = 3$, $sz = -1, 0, 1$, of which $sz = 0$ does not occur $\rightarrow$ 2 base states. E.g.: $\Psi\rangle = \langle LH|\Psi\rangle\ LH\rangle + \langle RH|\Psi\rangle\ RH\rangle$
- Classical Maxwell theory: transversal electromagnetic waves!
- Here's a monochromatic plane wave solution of the Maxwell equations in free space travelling in the $+z$ direction:
  - $\bar{E} = \begin{pmatrix} E_x(z,t) \\ E_y(z,t) \end{pmatrix} = \begin{pmatrix} E_{x0}e^{i\delta_x} \\ E_{y0}e^{i\delta_y} \end{pmatrix} e^{i(\omega t - kz)}$ with the vector () a **Jones vector**.
  - Intensity: $I \sim \bar{E}.\bar{E}^* = E_{x0}^2 + E_{yo}^2$
  - A highly idealized description of light! (monochromatic, coherent):
    - Spectral width $\Delta\nu = 0$, coherence time $T_c = \frac{1}{\Delta\nu} = \infty$

Physics of light polarization (2)
Graphical representation

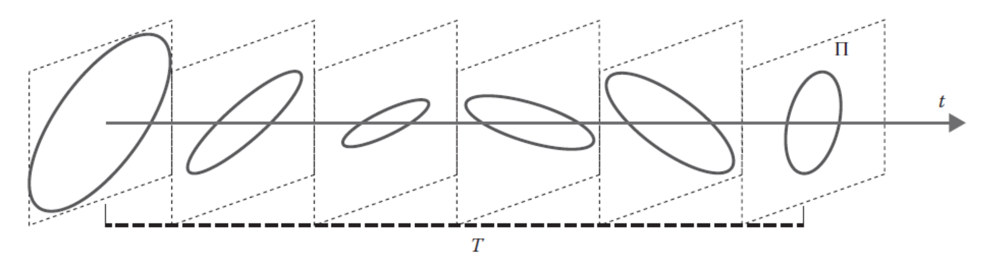


- The general case: elliptical polarization, linear and circular polarization are degenerate cases! → **‘Polarization ellipse’**
- All these are examples of light in a pure polarization state!

What about real, natural light?

Coherency, quasi-monochromatic light

- Result of large amounts of moving atoms, molecules, particles that emit or scatter light at different positions and times → we are dealing with a stochastic process, with some level of 'incoherency'.



- There are 3 time scales to consider:
  - Natural period $T_0 = 1/\nu$ (IR to UV: $10^{-12} - 10^{-16}$ seconds)
  - Coherence time scale $T_c = 1/\Delta\nu_c$
  - Measurement time scale T (milliseconds to seconds)
- This beam has a 'bandwidth'
- 'Quasi-monochromatic light': $\Delta\nu_c \ll \nu$ or $T_c \gg T_0$

Real, natural light (2)

Statistics, Coherency matrix, Stokes parameters

- Let's average over the measurement time: $\langle f \rangle = \frac{1}{T}\int_0^T f(t)\, dt$
- **Coherency matrix** (the 'complex covariance'): $C = \begin{pmatrix} \langle E_x E_x^* \rangle & \langle E_x E_y^* \rangle \\ \langle E_y E_x^* \rangle & \langle E_y E_y^* \rangle \end{pmatrix}$
- Decomposition: the 3 Pauli matrices + the identity matrix:
  - $C = \frac{1}{2}\left[\boldsymbol{I}\begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} + \boldsymbol{Q}\begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} + \boldsymbol{U}\begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} + \boldsymbol{V}\begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}\right] = \frac{1}{2}\begin{pmatrix} I+Q & U-iV \\ U+iV & I-Q \end{pmatrix}$
- **Stokes parameters:**
  - $I = \langle E_x E_x^* + E_y E_y^* \rangle$
  - $Q = \langle E_x E_x^* - E_y E_y^* \rangle$
  - $U = \langle E_x E_y^* + E_y E_x^* \rangle$
  - $V = i\langle E_x E_y^* - E_y E_x^* \rangle$

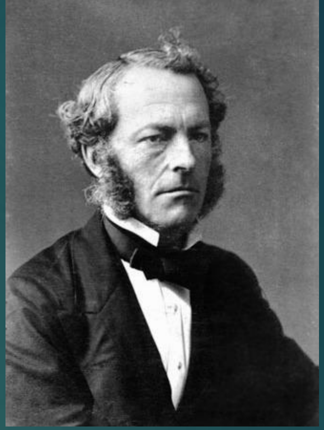
$I^2 \geq Q^2 + U^2 + V^2$

$P^2 I^2 = Q^2 + U^2 + V^2$

P: 'degree of polarization'

Real, natural light (3)

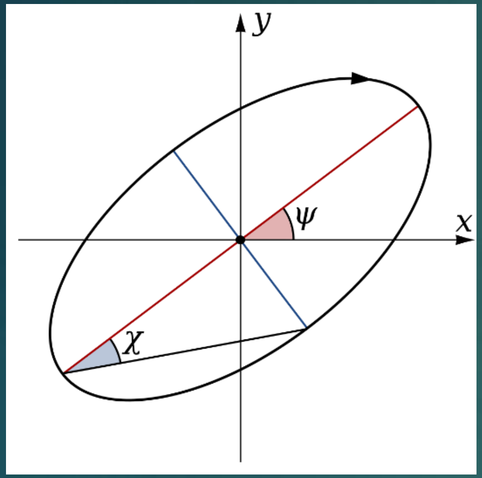
How G.G. Stokes did it (1852)



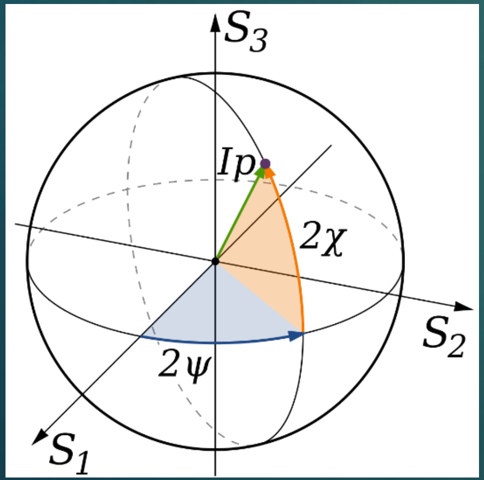
- Stokes used the transversal waves of the Fresnel theory. He wanted a theory in terms of observables (intensity measurements).
- He theoretically investigated the combination of:
  - A waveplate ('retarder'): birefringent material, 'slow axis' and 'fast axis', inducing a phase difference δ. *Kitchen cellophane*.
  - A linear polarizer ('diattenuator'): 'transmission axis' at angle θ. *Polaroid*
- He squared the amplitude vector to $I(\theta, \delta)$, and imagined 6 measurements to derive:
  - $I = I(0°, 0°) + I(90°, 0°) = I_{\parallel} + I_{\perp}$
  - $\mathrm{Q} = I(0°, 0°) - I(90°, 0°) = I_{\parallel} - I_{\perp}$
  - $U = I(+45°, 0°) - I(-45°, 0°) = I_{45} - I_{-45}$
  - $V = I(0°, 90°) - I(0°, -90°) = I_{RH} - I_{LH}$ $\rightarrow \delta = \delta_y - \delta_x = 90°$ or $-90°$: quarter-waveplate!
- Operational definition in terms of measurements!
- Quarter-waveplate + linear polarizer is at present still a very potent polarimetric solution!

Real natural light (4)

An alternative formulation (Henri Poincaré, 1892)



$$I$$
$$Q = I\,P\cos 2\psi\cos 2\chi$$
$$U = I\,P\sin 2\psi\cos 2\chi$$
$$V = I\,P\sin 2\chi$$



- These are (almost) spherical coordinates for a sphere with radius IP!
- So, two descriptions ('coordinate systems'):

  $$(I, Q, U, V) \leftrightarrow (I, P, \psi, \chi)$$

- When $V = 0$ ($\chi = 0$):

  $$(I, Q, U) \leftrightarrow (I, P, \psi)$$

Real natural light (5)

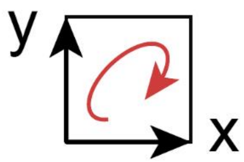
The Poincaré sphere

$$S_0 = I = E_x^2 + E_y^2$$

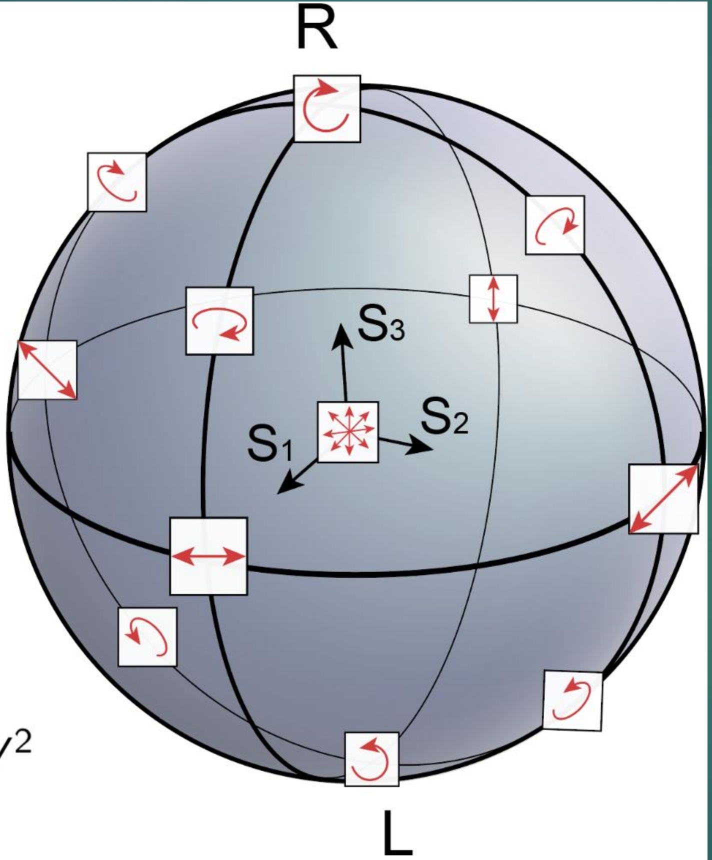
$$S_1 = Q = E_x^2 - E_y^2$$

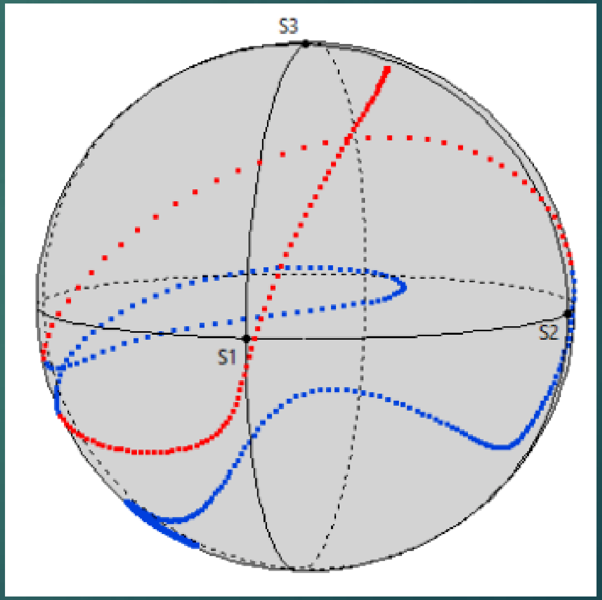
$$S_2 = U = 2E_xE_y\cos\delta$$

$$S_3 = V = 2E_xE_y\sin\delta$$



$$radius = I^2 \geq Q^2 + U^2 + V^2$$





From manual: optical fiber polarization modulator device

Stokes parameters (1)

The Stokes 'vector'

- At present, two notations: $\boldsymbol{S} = \begin{pmatrix} S_0 \\ S_1 \\ S_2 \\ S_3 \end{pmatrix} \leftrightarrow \boldsymbol{S} = \begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix}$
- These things are not elements of a standard vector space. E.g.: $-2\,\boldsymbol{S}$ is not a valid Stokes 'vector'.
- (For the interested: mathematical isomorphism with Minkowski 4-vector space with pseudo-Euclidean metric …)
- Mnemonic: "**I Q**uestion, **U V**erify"

Stokes parameters (2)

Natural light is a binary cocktail

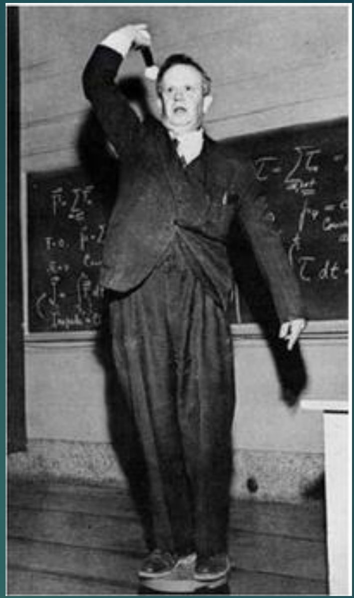
- Gin-Tonic: 2 parts of tonic, 1part of Gin:
  - Gin-Tonic = (1-1/3) Gin-Tonic + 1/3 Gin-Tonic = 'Tonic' + 'Gin'
- Natural light with degree of polarization P:
  - $I = (1-P)\,I + P\,I = I_u + I_p$
- Generalization to Stokes vectors:
  - $\begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix} = \begin{pmatrix} (1-P)I \\ 0 \\ 0 \\ 0 \end{pmatrix} + \begin{pmatrix} PI \\ Q \\ U \\ V \end{pmatrix} = \begin{pmatrix} I_u \\ 0 \\ 0 \\ 0 \end{pmatrix} + \begin{pmatrix} I_p \\ Q \\ U \\ V \end{pmatrix}$ with $I_p^2 = Q^2 + U^2 + V^2$
- Don't take this for granted, there's nothing obvious about it! (see Stokes, 1852)

Spectropolarimetry
(it's like getting an extra pair of eyes)

- Spectroscopy:
  - $I(\lambda)$ (or $I(\sigma)$)
- Spectropolarimetry:
  - $\big(I(\lambda), Q(\lambda), U(\lambda), V(\lambda)\big)$ (Stokes)
  - $\big(I(\lambda), P(\lambda), \psi(\lambda), \chi(\lambda)\big)$ (Poincaré)
- For usual atmospheric observations, we can neglect circular polarization:
  - $\big(I(\lambda), Q(\lambda), U(\lambda)\big)$ (Stokes)
  - $\big(I(\lambda), P(\lambda), \psi(\lambda)\big)$ (Poincaré)

Mueller matrices (1)

Describing changes in the state of polarization



$$\begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix}_{out} = \begin{pmatrix} m_{11} & m_{12} & m_{13} & m_{14} \\ m_{21} & m_{22} & m_{23} & m_{24} \\ m_{31} & m_{32} & m_{33} & m_{34} \\ m_{41} & m_{42} & m_{43} & m_{44} \end{pmatrix} \begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix}_{in}$$

- Polarization calculations now become straightforward: multiplication of matrices and vectors!
- There are Mueller matrices for just about every optical component: polarizers, waveplates, spectral filters, scramblers, mirrors, prisms …
- The scattering matrix for particles or molecules is a Mueller matrix.
- Surface reflection has a Mueller matrix
- How does it work? Just multiply them **in the correct order**!
- $\boldsymbol{S}_{detector} = \boldsymbol{M}_{grating}\boldsymbol{M}_{mirror}\boldsymbol{M}_{rotation}\boldsymbol{M}_{scatt2}\boldsymbol{M}_{rotation}\boldsymbol{M}_{scatt1}\ \boldsymbol{S}_{source}$

- This wonderful machinery doesn’t work with the Poincaré formulation. That’s why the (unintuitive) Stokes vectors are still being used!

Measuring the Stokes vector

How many independent measurements do you need?

- It may seem that you need 6 (remember the Stokes definition)
- No! You need 4. There are 4 Stokes parameters.
- If $V = 0$, then you need 3! Using linear polarizer at 3 angles θ:
  - $$\begin{pmatrix} I \\ Q \\ U \\ 0 \end{pmatrix}_{out} = \frac{1}{2}\begin{pmatrix} 1 & \cos 2\theta & \sin 2\theta & 0 \\ \cos 2\theta & \cos^2 2\theta & \sin 2\theta \cos 2\theta & 0 \\ \sin 2\theta & \sin 2\theta \ \cos 2\theta & \sin^2 2\theta & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}\begin{pmatrix} I \\ Q \\ U \\ 0 \end{pmatrix}_{in}$$ (Mueller)
  - $$\begin{pmatrix} I_{out}(\theta_1) \\ I_{out}(\theta_2) \\ I_{out}(\theta_3) \end{pmatrix} = \frac{1}{2}\begin{pmatrix} 1 & \cos 2\theta_1 & \sin 2\theta_1 \\ 1 & \cos 2\theta_2 & \sin 2\theta_2 \\ 1 & \cos 2\theta_3 & \sin 2\theta_3 \end{pmatrix}\begin{pmatrix} I_{in} \\ Q_{in} \\ U_{in} \end{pmatrix}$$
  - Invert this matrix, and bingo. Remember to optimize the angles!
- However, if (1) you know the instrument orientation (attitude), and certain atmospheric conditions (only single scattering) then you need only 2!

What alters the polarization state?

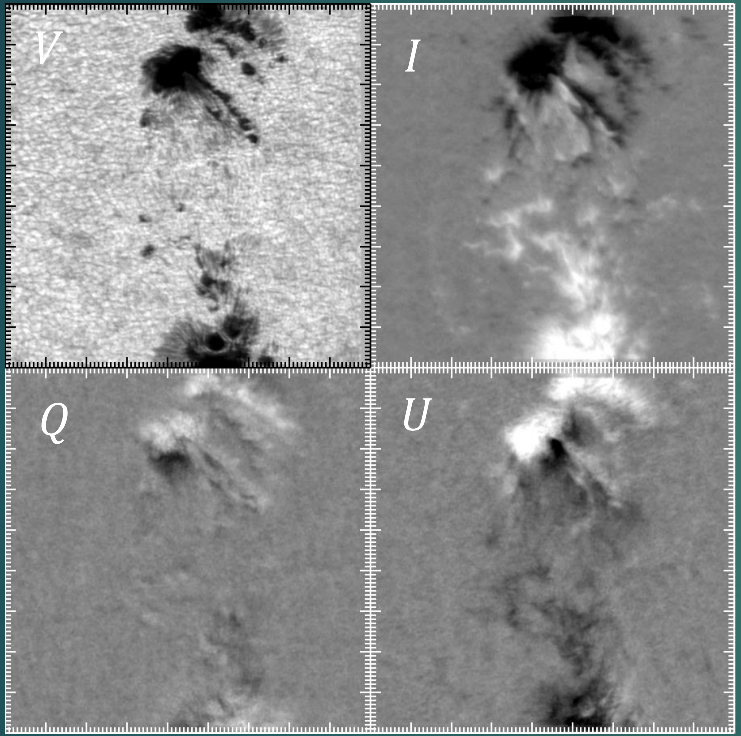
A selective list

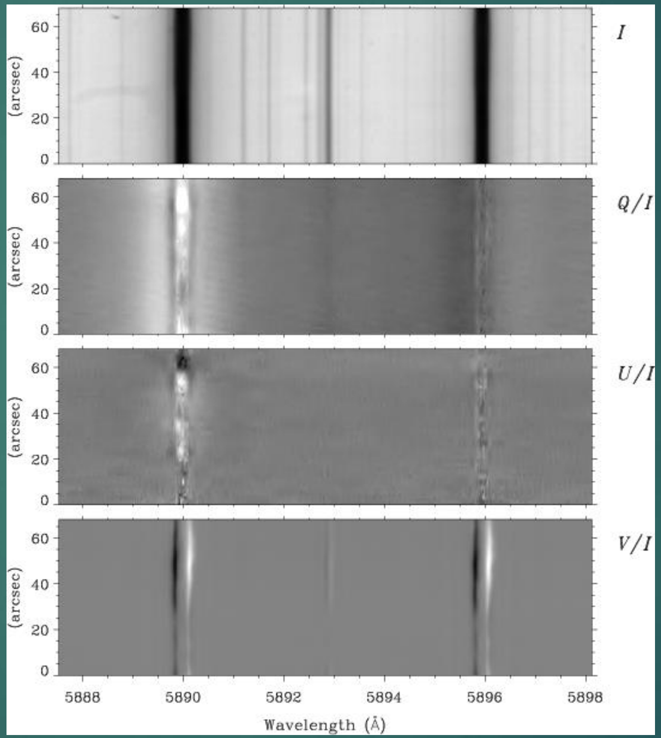
- Molecular and particle scattering
- Surface reflection
- Refraction
- Birefringence (retarders = waveplates)
- Diattenuation (linear polarizers)
- Depolarization (thick clouds, scramblers, ‘randomizers’)
- Magnetic fields:
  - Zeeman effect (Solar polarimetry)
  - Faraday effect (rotation of pol. direction)
  - Hanle effect
- ***Rule of thumb: when there’s scattering, anisotropic materials or magnetic fields, polarization comes into play!***

Solar light is unpolarized (1)

Or is it?

Flare Genesis Experiment, Jan. 2000 balloon flight (John Hopkins Univ.)



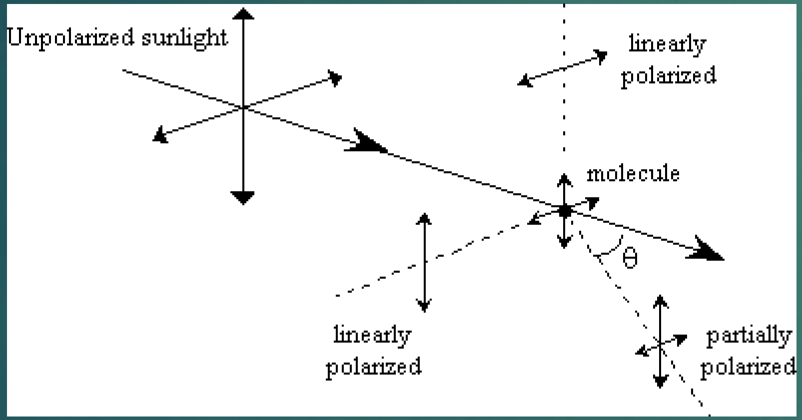


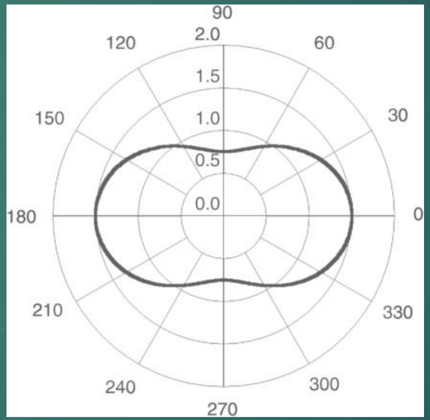
Basis of Solar Polarimetry. 'Invert' these images and you get the magnetic field.
For our purposes: Full solar disk has polarization $\sim 10^{-6}$! So no worries ...

Molecular (Rayleigh) scattering (1)

A reminder

- Physics:
  - $\bar{E}_{in}(t)$ → charge separation → dipole moment $\bar{p}(t) = \alpha \bar{E}_{in}(t)$
  - $\bar{E}_{sca}(t) \sim \frac{1}{r}\ddot{\bar{p}} = \frac{-\omega^2}{r}\bar{p} \rightarrow I \sim \frac{\omega^4}{r^2}|\alpha|^2 I_{in}$ (blue sky, etc...)





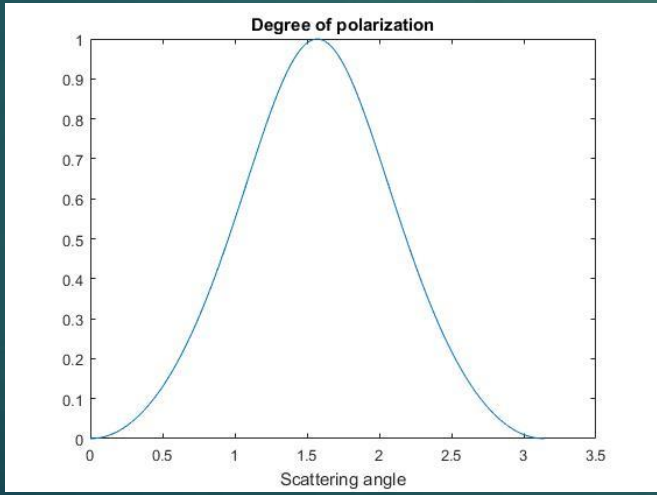
- Mueller matrix (scattering matrix): $\frac{3}{2}\begin{pmatrix} \frac{1}{2}(1+\cos^2\theta) & -\frac{1}{2}(1-\cos^2\theta) & 0 & 0 \\ -\frac{1}{2}(1-\cos^2\theta) & \frac{1}{2}(1+\cos^2\theta) & 0 & 0 \\ 0 & 0 & \cos\theta & 0 \\ 0 & 0 & 0 & \cos\theta \end{pmatrix}$

Molecular (Rayleigh) scattering (2)

Degree of polarization

- For unpolarized solar light:

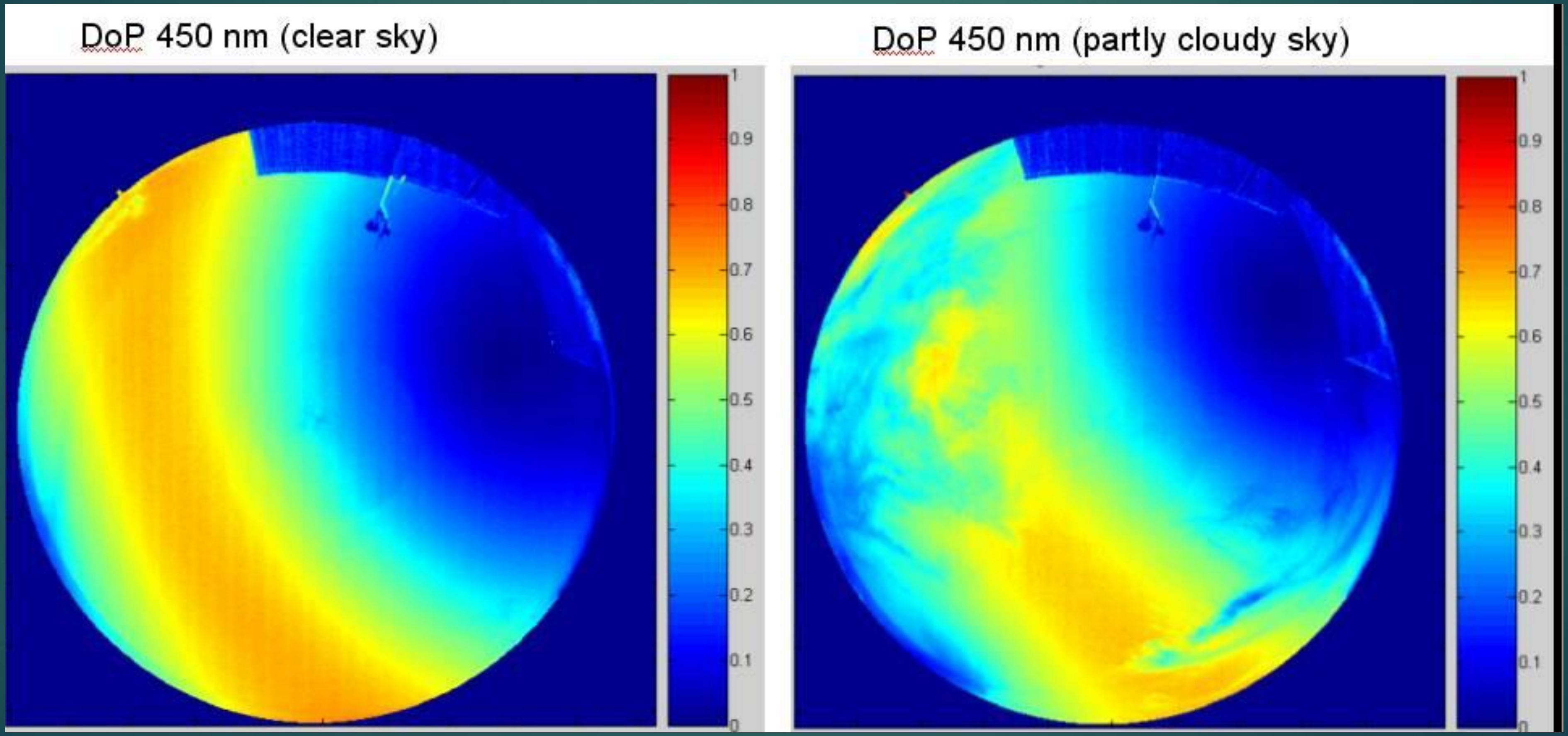
- $$\begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix}_{out} = \mathrm{M}. \begin{pmatrix} I_{in} \\ 0 \\ 0 \\ 0 \end{pmatrix} = \frac{3}{4} \begin{pmatrix} 1+\cos^2\theta \\ -1+\cos^2\theta \\ 0 \\ 0 \end{pmatrix} I_{in} \rightarrow P = \left| \frac{1-\cos^2\theta}{1+\cos^2\theta} \right|$$



- For a gas (mixture): $P(\theta)$ is always the same!
- You can't do spectroscopic polarimetry with Rayleigh scattering:
  - $I(\lambda) \sim\lambda^{-4}$ (always)
  - $P(\lambda)$ = constant (always)
- Rayleigh scattering is a 'baseline' scenario.
  → a deviation indicates the presence of particles (or something else!)

Molecular (Rayleigh) scattering (3)

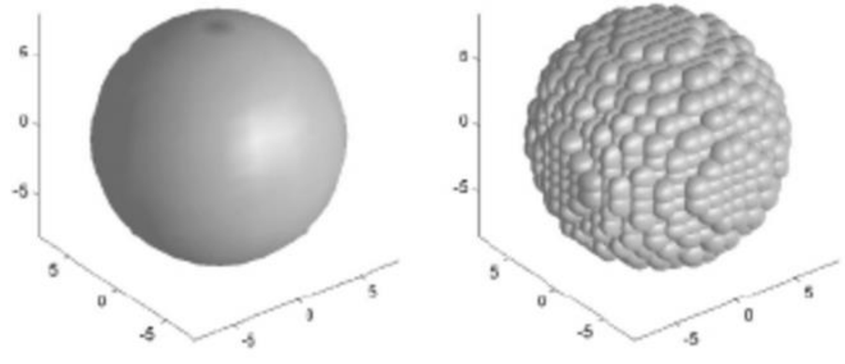
Sky polarimetry

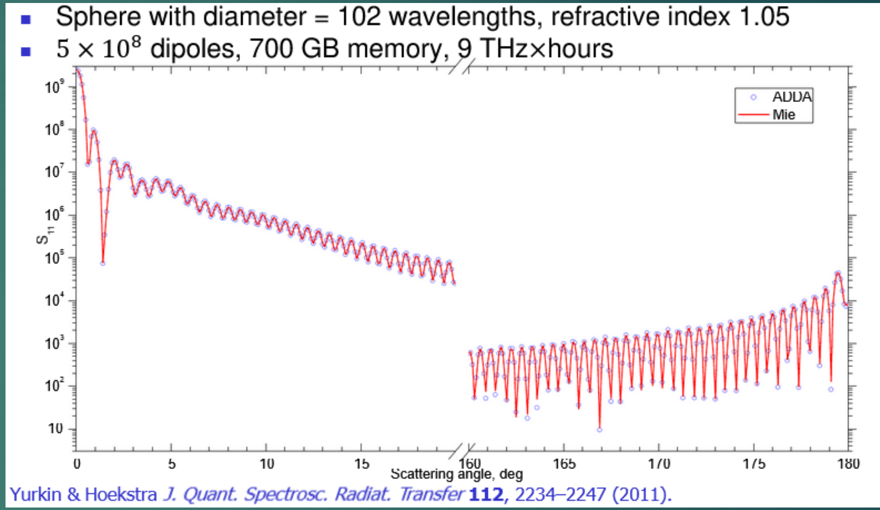


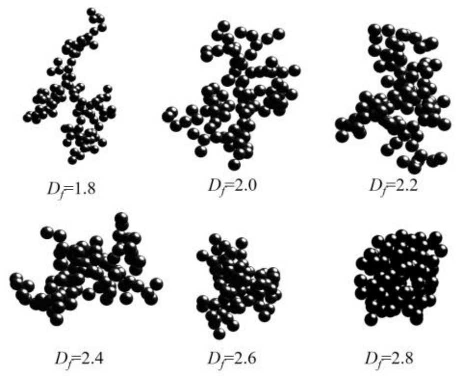
Scattering by particles (1)

such as Martian dust

- Physics: same principle as Rayleigh scattering (induced dipoles)
  - → Discrete Dipole Approximation.







- If it works for spheres …
- it likely works for other stuff as well…

Scattering by particles (2)

Some theory (in a nutshell)

- In general: $\boldsymbol{S}_{out} = \frac{1}{k^2r^2}\boldsymbol{M}\,\boldsymbol{S}_{in}$
- A bunch of randomized particles with mirror symmetry:
  - $$\begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix}_{out} = \frac{1}{k^2r^2}\begin{pmatrix} F_{11} & F_{12} & 0 & 0 \\ F_{21} & F_{22} & 0 & 0 \\ 0 & 0 & F_{33} & F_{34} \\ 0 & 0 & -F_{43} & F_{44} \end{pmatrix}\begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix}_{in}$$
- A bunch of spheres (from Mie theory):
  - $$\begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix}_{out} = \frac{1}{k^2r^2}\begin{pmatrix} F_{11} & F_{12} & 0 & 0 \\ F_{12} & F_{11} & 0 & 0 \\ 0 & 0 & F_{33} & F_{34} \\ 0 & 0 & -F_{34} & F_{33} \end{pmatrix}\begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix}_{in}$$
- Notice: $1 - {}^{F_{22}}/_{F_{11}}$ is a measure of the deviation of sphericity (depolarization ratio)

Scattering by particles (3)

Hansen&Travis, Space Science Reviews (1974)

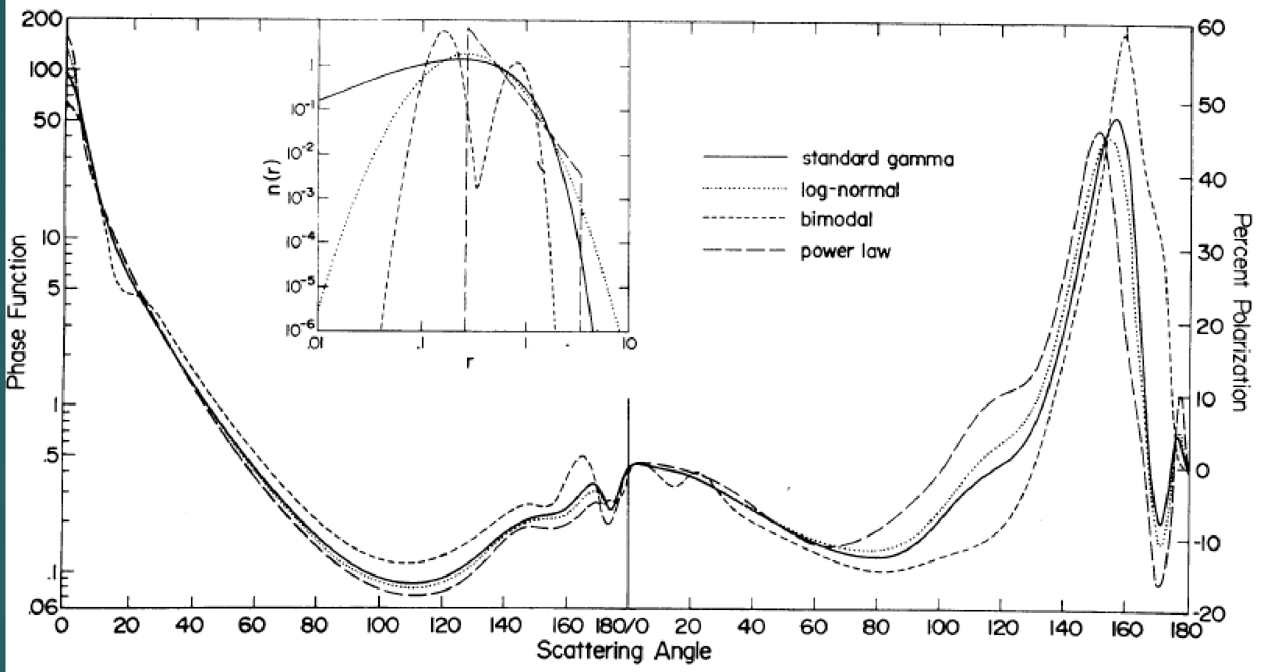


Fig. 15. Phase function, P^{11}, and percent polarization, $-100P^{21}/P^{11}$, for single scattering of unpolarized incident light. Results are shown for the four size distributions illustrated in the inset. The standard gamma distribution is the same as in Figure 14. All four distributions have $\bar{r} = 0.5\ \mu$ and $\sigma^2 = 0.125\ \mu^2$, where $\bar{r}$ is the mean radius and σ^2 the variance. The calculations are for the real refractive index $n_r = 1.33$ and wavelength $\lambda = 0.55\ \mu$.

Scattering by particles (4)

The variable space is enormous

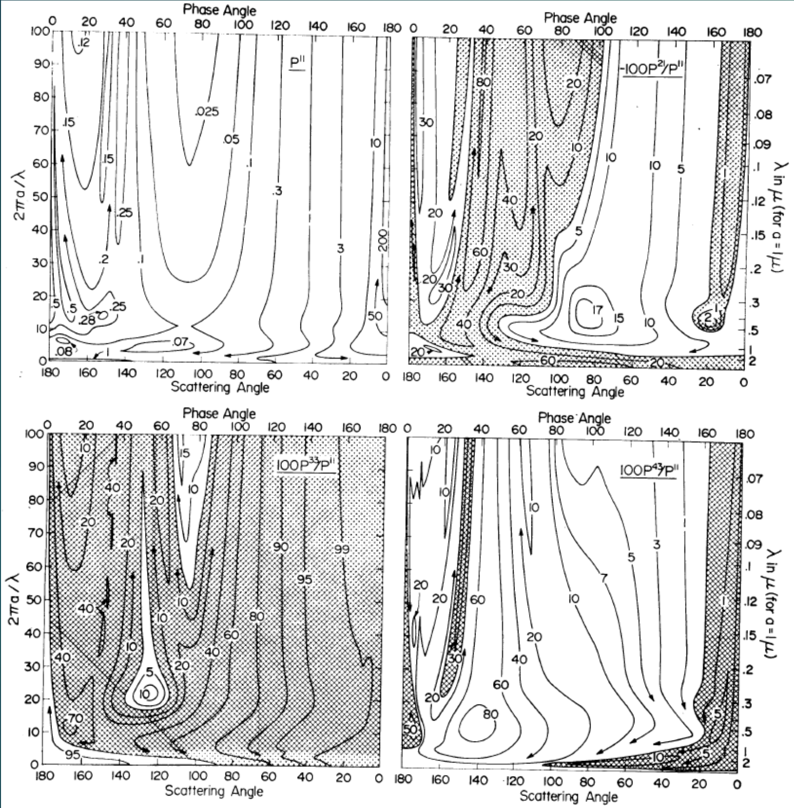


Fig. 16. Phase matrix for a size distribution of spheres with the real refractive index $n_r = 1.33$. The size distribution is given by (2.56) with $b = 0.07$. P^{11} is positive everywhere; for the other matrix elements positive regions are crosshatched.

Just for incoming unpolarized light, and single scattering on spheres: $(I, Q, 0{,}0)_{out}$ depends on

- Wavelength
- Scattering angle
- Real refractive index (scattering)
- Imaginary refractive index(absorption)
- Number density of particles
- 'average' size
- Distribution width

→ A 7-D table of (I, Q) values.

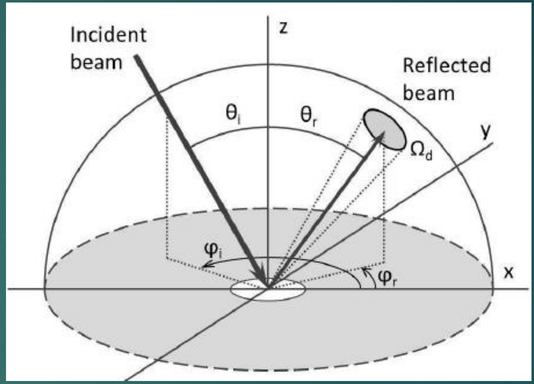
Don't get me started on multiple scattering, irregular particles, mixtures of different compositions, multiple distribution modes, coated particles, …

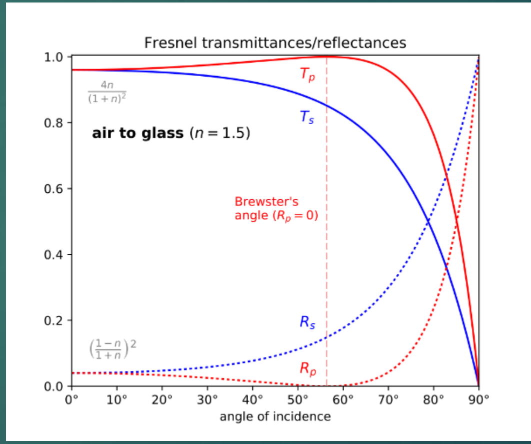
Reflection

E.g. the Martian surface

- Bidirectional Reflectance Distribution Function (BRDF)
- $\frac{R_{out}(\theta_r,\phi_r)}{I_{in}(\theta_i,\phi_i)} = A\rho(\theta_r,\phi_r,\theta_i,\phi_i)$
- Ok, but what about Malus, Brewster, Fresnel?
- Solution: Mueller matrix! (for all directions!)
- $\boldsymbol{R}_{out}(\theta_r,\phi_r) = \boldsymbol{M}\,\boldsymbol{I}_{in}(\theta_{in},\phi_{in})$
- Example: VLIDORT (Rob Spurr) RT code:

Index	*Name*	*Size* $\mathbf{b}_k$	*Reference*	*Scalar/Vector*
1	Lambertian	0		Scalar
2	Ross thin	0	*Wanner et al.*, 1995	Scalar
3	Ross thick	0	*Wanner et al.*, 1995	Scalar
4	Li sparse	2	*Wanner et al.*, 1995	Scalar
5	Li dense	2	*Wanner et al.*, 1995	Scalar
6	Hapke	3	*Hapke*, 1993	Scalar
7	Roujean	0	*Wanner et al.*, 1995	Scalar
8	Rahman	3	*Rahman et al.*, 1993	Scalar
9	Cox-Munk	2	*Cox/Munk*, 1954	Scalar
10	Giss Cox-Munk	2	*Mishchenko/Travis* 1997	Vector
11	Giss Cox-Munk Cri	2	*V. Natraj*, 2010 [personal communication]	Vector
12	BPDF Soil	1	*Maignan et al.*, 2009	Vector
13	BPDF Vegetation	1	*Maignan et al.*, 2009	Vector
14	BPDF NDVI	3	*Maignan et al.*, 2009	Vector
15	New Cox-Munk	3	*A. Sayer*, 2015 [personal communication]	Scalar
16	New Giss Cox-Munk	3	*A. Sayer*, 2016 [personal communication]	Scalar
17	Ross-Thick Hotspot	0	*Lucht et al.*, 2002;	Scalar
18	Modified Fresnel	4	*P. Litvinov et al.*, 2011	Vector





A word on circular polarization
(and then we assume: $V = 0$)

- For usual atmospheric research, V is negligible (although not zero)
- Biological organisms: homochirality!

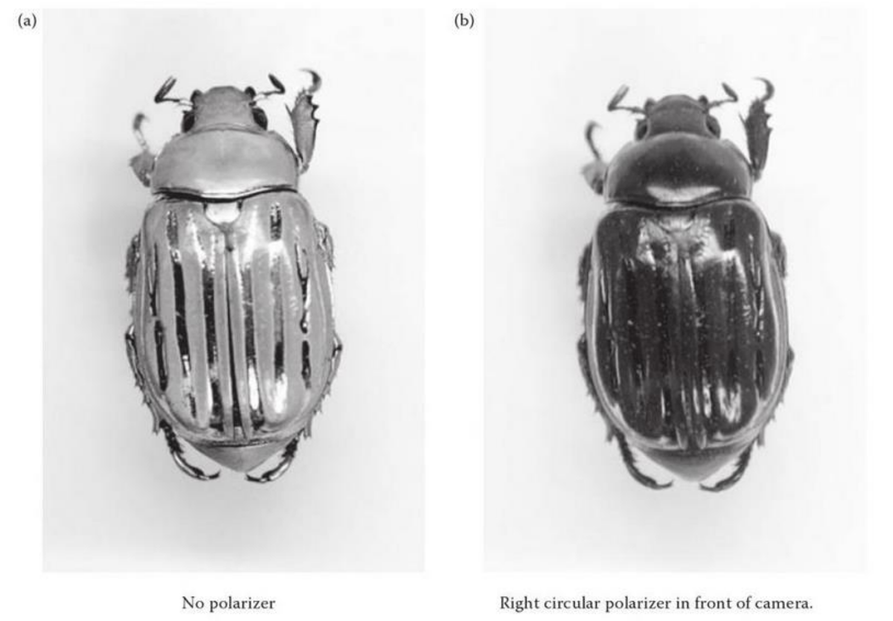


FIGURE 2.10 **(See color insert following page 394.)** Photographs of *Plusiotis gloriosa* (b) with and (a) without a polarizer. A photograph of the scarab with a left circular polarizer in front of the camera would appear as in (a). (Photos courtesy of D. H. Goldstein.)

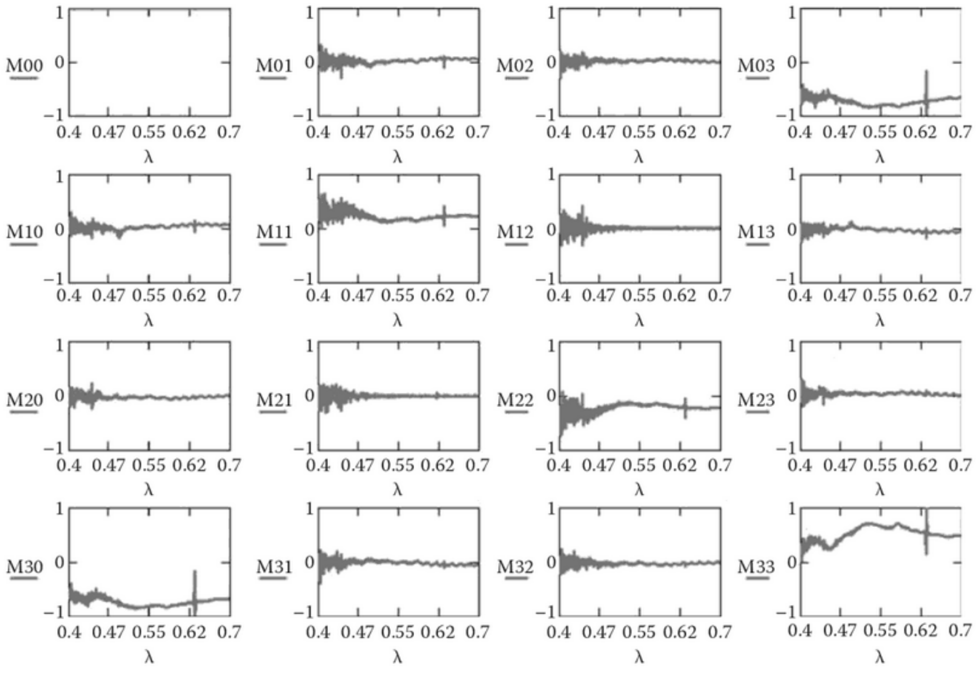


FIGURE 2.15 Mueller matrix for *Plusiotis gloriosa*. Wavelength λ is in micrometers.

Interested in beetles on Mars or exoplanets? Measure V!

Measurement bias (1)

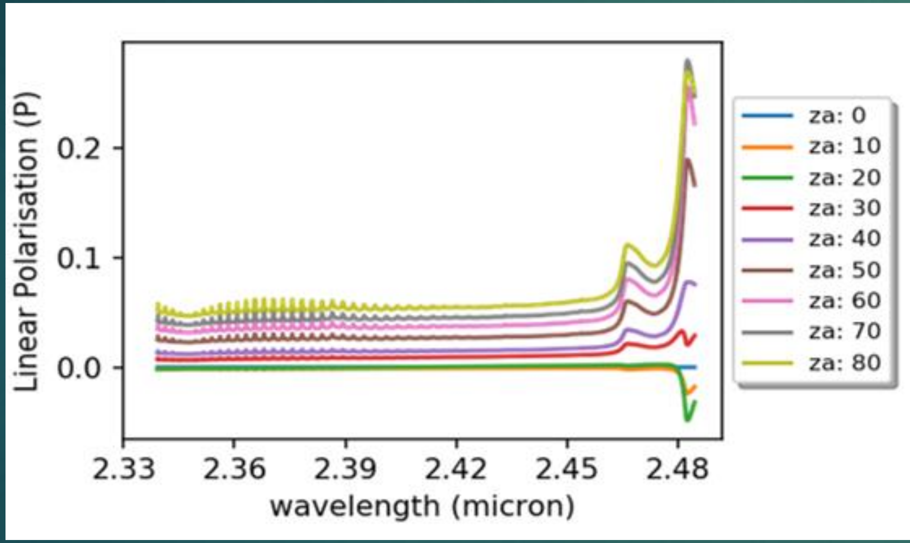
Being unaware is being biased (the annoying part)

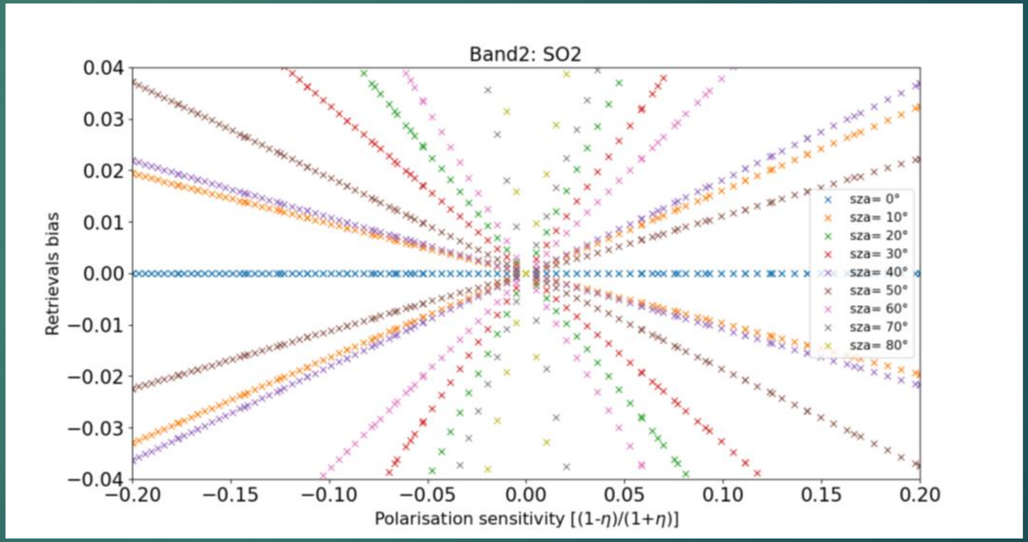
- Instrument with Mueller matrix $\mathbf{M} = (m_{ij})$ measures incoming light:
  - $I_{det} = m_{11}I_{in} + m_{12}Q_{in} + m_{13}U_{in} = m_{11}I_{in}(1 + P_m P_{in}\cos[2(\psi_m - \psi_{in})])$
- The unaware you thinks that the instrument is polarization insensitive ($P_m = 0$), **or** that the incoming light is unpolarized ($P_{in} = 0$).
  - $I_{det} = m_{11}I_{in} \rightarrow I_{in,est} = \frac{I_{det}}{m_{11}}$
- Unknowingly, you calculate:
  - $I_{in,est} = I_{in}(1 + P_m P_{in}\cos[2(\psi_m - \psi_{in})])$
- Rel. radiometric bias: $\frac{I_{in,est} - I_{in}}{I_{in}} = P_m P_{in}\cos[2(\psi_m - \psi_{in})]$

Measurement bias (2)

Example: Venspec-H/Envision

- Nadir IR instrument (BIRA-IASB), Venus, focus on possible volcanic activity.
- Rel. bias on total column of species (approx.): $\frac{\Delta n}{n} \sim \frac{P_m P_{in}}{\tau} \cos[2(\theta_m - \theta_{in})]$



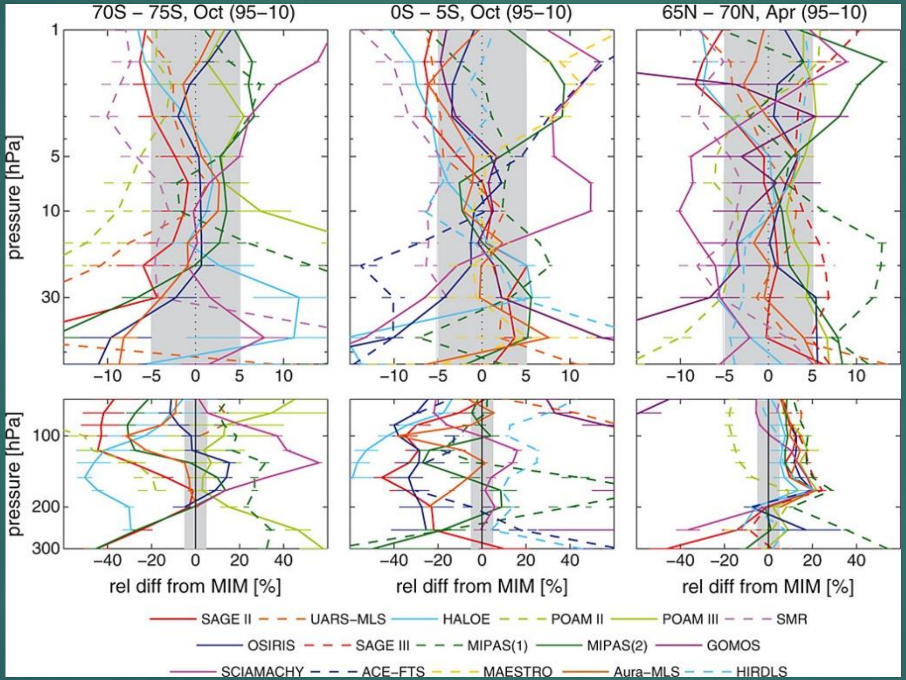


- Simulations: Séverine Robert, Justin Erwin (BIRA-IASB, fluxes from ASIMUT-ALVL RT code) and Daphne Stam (TUDelft, degree of polarization from DAP RT code)

Measurement bias (3)

Polarization bias is possibly widespread

- Earth observation: Monthly zonal mean ozone differences (1995 -2010) for 16 instruments (solar/stellar occultation, limb scatter, emission)



- Tegtmeier et al., J. Geophys. Res., 2013
- Liebing et al., Atm. Meas. Tech. Discuss., 2013: SCIAMACHY has up to 15% radiometric error due to polarization.

Avoiding the bias

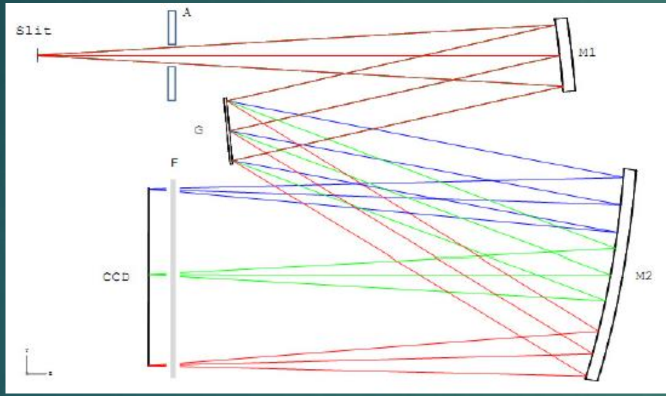
Elementary polarimetry for Venspec-H

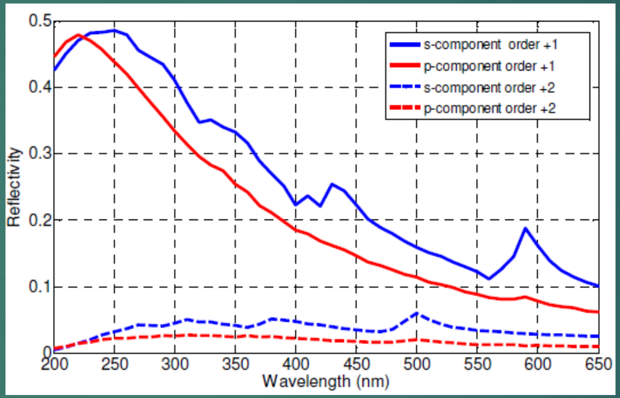
- Stick linear polarizers in front of your instrument!
- For Venspec-H: filter wheel (spectral band selection, a few holes left)
  - $\boldsymbol{S}_{detector} = \boldsymbol{M}_{instr} \, . \boldsymbol{M}_{fw,i} . \boldsymbol{S}_{in}$
  - $\begin{pmatrix} I_{full} \\ I_{pol}(\theta_1) \\ I_{pol}(\theta_2) \end{pmatrix} = \begin{pmatrix} n_{11} & n_{12} & n_{13} \\ n_{21} & n_{22} & n_{23} \\ n_{31} & n_{32} & n_{33} \end{pmatrix} . \begin{pmatrix} I_{in} \\ Q_{in} \\ V_{in} \end{pmatrix}$
  - Invert the matrix, and bingo!

ROADMAP follow-up idea (1)

NOMAD UVIS channel

- Diffraction grating is sensitive to polarization! Mirrors also!





- NOMAD UVIS channel
  - Pessimists: NOMAD UVIS measurements are possibly biased :-/
  - Optimists: NOMAD has polarimetric capabilities!!
- Ideally: we need a way to observe a polarized light source to 'calibrate this'.
- Other possibility: just model the behavior (pre-flight grating, model for the spherical mirrors)
- Possibility: limb measurement of dust-free/ice cloud free atmosphere at scattering angle of 90°

ROADMAP follow-up idea (2) Scalar vs. Vectorial RT models

- Atmospheric process in Vector RT model:
  - $M_{tot,vec} = M_n . M_{n-1} \dots M_2 . M_1$
- Atmospheric process in Scalar RT model (without polarization):
  - $M_{tot,scal} = M_{n,}(1,1). M_{n-1}(1,1) \dots M_2(1,1). M_1(1,1)$
- Well:
  - $[\prod_i M_i](1,1) \neq \prod_i [M_i(1,1)]$
- Send in unpolarized sun light, and you get different results.
- Yet, people doing regular spectroscopy (no polarimetry) think that that only need a scalar code!

Concluding remarks
My opinion

- This is 2023. Every instrument for planetary atmospheric observation should have basic polarimetric capabilities, to avoid radiometric bias, for inflight calibration and aerosol/cloud retrievals. (exception: solar/stellar occultation)
- This stuff may seem difficult. It isn't. It's just a 'vectorization' or 'matrixification' of everything that we are familiar with (the spectroscopic $I(\lambda)$ or $I(\sigma)$; the scattering phase function $p(\theta)$; the instrument response $G(\lambda)$; the surface reflectance ρ, …).
- The payback (information gain) is huge.

THANK YOU!