Patrick Gray
Zuckerman Postdoctoral Fellow
U of Maine / U of Haifa
Thanks James and Gustav!

Caltech Mechanical Universe and Beyond
Maxwell’s Equations https://www.youtube.com/watch?v=SS4tcajTsW8

X = (π*diam*n)/ λ
Scattering Brain Teasers
Why is the sky blue?
Why is the sky blue?
Why isn’t the sky violet?

MOMMY, WHY IS THE SKY BLUE?
RAYLEIGH SCATTERING! SHORT WAVELENGTHS GET SCATTERED WAY MORE (PROPORTIONAL TO $\frac{1}{\lambda^4}$). BLUE LIGHT DOMINATES BECAUSE IT’S SO SHORT.

OH.

SO WHY ISN’T THE SKY VIOLET?
WELL, BECAUSE, UH...
...HMM.

MY HOBBY: TEACHING TRICKY QUESTIONS TO THE CHILDREN OF MY SCIENTIST FRIENDS.
Why isn’t the sky violet?

The graph shows the spectral irradiance of different sources of light. The black body radiation (temperature 5900 K) peaks in the visible range, but due to the scattering effect of the atmosphere, the sky appears blue. Terrestrial sunlight, which includes scattered light from the sky, appears white. Extraterrestrial sunlight, which is the unscattered sunlight from space, peaks in the ultraviolet region.
So why are sunsets red?
So why are sunsets red?
How can we get a red sky with particles $r << \lambda$?

Intuition check
How can we get a red sky with particles $r << \lambda$?

**Fig. 5** Spectrum of overhead skylight for the present molecular atmosphere (solid curve), as well as for hypothetical atmospheres 10 (dashes) and 40 (dots) times thicker.
On to polarization of light

“As with radiometry, polarization can be a confusing topic. Unfortunately, unlike radiometry, its complexity is not primarily due to confusing units.”

- Johnsen
Why else do we care?

- Size, shape, and refractive index can influence polarization
  - Maybe we can gain new insight!
Fundamentals

• What is a dielectric?

• Polarizability?

• What is permittivity?
Resonance

- Natural frequency of an object
  - Swings
  - Tides
  - Bathtub
  - Guitar strings
  - Dipoles!
- Much of what we see from Mie is actually the impact of resonances between the dipole (swing) and wavelength of light (push)

**Figure 19.16:** Each push of a swing at the right time increases the amplitude (height) of the swing. Each push is a periodic force.
Harmonic input (EM wave) getting faster
Permittivity determines the refractive index

- The applied electric field tends to align the polar molecules, but random thermal motions tend to randomize the directions.
- It takes time for the molecules to rotate into alignment, so if the applied field is not constant, P depends on the frequency of the applied field.
  - This is the origin of the frequency wavelength dependence of the index of refraction!
Permittivity determines the refractive index

Dipole structure $\rightarrow$ polarizability $\rightarrow$ permittivity $\rightarrow$ refractive index

ref index + $\rightarrow$ dipole resonances $\rightarrow$ interaction w/ $\rightarrow$ scattering efficiency
size/lambda + light field

Morphology

*Fundamentally refractive index is about how electrons interact with the EM wave*
Permittivity determines the refractive index

Dipole structure $\rightarrow$ polarizability $\rightarrow$ permittivity $\rightarrow$ refractive index

ref index $+ \rightarrow$ dipole resonances $\rightarrow$ interaction w/ $\rightarrow$ scattering efficiency

size/lambda $+ \rightarrow$ light field

Morphology

Fundamentally refractive index is about how electrons interact with the EM wave
To first order:

- EM waves make dipoles oscillate (wiggle)
  - direction they wiggle and radiate depends on polarization
- high refractive index $\rightarrow$ more mineral
- low refractive index $\rightarrow$ more organic
So what even is polarization?
So why is scattered light often polarized?

Polarized scattering: https://www.youtube.com/watch?v=QrOOwT2JWgo
Let’s make some polarized rope
Multiple scattering impacts?
When $r \ll \lambda$ isn’t true?

“All the simple rules about polarization upon scattering are broken when we turn from molecules and small particles to particles comparable to the wavelength.

... the degree of polarization of light scattered by small particles is a simple function of scattering angle. But simplicity gives way to complexity as particles grow”

- Bohren, *Atmospheric Optics*
Rayleigh Scattering

From overhead, the Rayleigh scattering is dominant, the Mie scattered intensity being projected forward. Since Rayleigh scattering strongly favors short wavelengths, we see a blue sky.

Mie Scattering

When there is large particulate matter in the air, the forward lobe of Mie scattering is dominant. Since it is not very wavelength dependent, we see a white glare around the sun.
So what is in the size range to polarize predictably?

*Figure 2* Representative sizes of different constituents in sea-water, after Stramski et al (2004). Optical regions referred to in the text are denoted at the top axis (shading represents approximate boundaries between these regions). These boundaries vary with refractive index for a given particle size.
Can absorption create polarized light?
Can absorption create polarized light?
Measuring Polarization
Brewster’s Angle
\[
\begin{pmatrix}
I_s \\
Q_s \\
U_s \\
V_s
\end{pmatrix} = \frac{1}{k^2 r^2}
\begin{pmatrix}
S_{11} & S_{12} & S_{13} & S_{14} \\
S_{21} & S_{22} & S_{23} & S_{24} \\
S_{31} & S_{32} & S_{33} & S_{34} \\
S_{41} & S_{42} & S_{43} & S_{44}
\end{pmatrix}
\begin{pmatrix}
I_i \\
Q_i \\
U_i \\
V_i
\end{pmatrix}
\]

Stokes vector describing intensity and polarization of incident beam

Mueller matrix (for a "scattering event")

Every element has wavelength and angular dependencies
Measuring Polarization
Measuring Polarization

Polarsens image sensor (images from Sony web page)
PACE Polarimeters
Microcystis without gas vacuoles

Microcystis with gas vacuoles

Silt (3um to 5um)

Silt (5um to 12 um)

Coastal Pacific and Atlantic

Voss and Fry and Volten et al

scattering angle (in degrees)

DOP

Voss and Fry and Volten et al
Koestner et al. 2018

Offshore San Diego

Scripps Pier

San Diego River Estuary

Koestner et al. 2018
Degree of Polarization at 90°

Particle Size Distribution Parameter

Refractive Index

Loisel et al 2008
Intuition Test

• Is light from the sun polarized?
• Is light from the sky polarized?
• Is light from the ocean polarized?
Dispersion and Birefringence

![Rainbow](image1)

![Light Dispersion Diagram](image2)

Nat Geo
Dispersion and Birefringence

Incident polarized beam

Birefringent Crystal

Optical Axis

Horizontal polarized beam

Vertical polarized beam

Johnsen 2011
Reading List

• Papers
  • Volten et al., l&o, 1998 Laboratory measurements of angular distributions of light scattered by phytoplankton and silt

• Books
  • Optics of Life, Johnsen – very reader friendly and fun
  • Absorption and Scattering, Bohren & Huffman – comprehensive
  • Fundamentals of Atmospheric Radiation, Clothiaux & Bohren 2006
  • Oceanic Optics, Mobley – excellent and highly relevant
  • QED, Feynman – very fun
Stokes vectors to describe light polarization

Polarization is defined in terms of the direction of the plane wave E-field

\[
S_{LHP} = I_0 \begin{pmatrix} 1 \\ 1 \\ 0 \\ 0 \end{pmatrix}, \quad S_{LVP} = I_0 \begin{pmatrix} 1 \\ -1 \\ 0 \\ 0 \end{pmatrix}, \quad S_{L+45P} = I_0 \begin{pmatrix} 1 \\ 0 \\ 1 \\ 1 \end{pmatrix},
\]

\[
S_{L-45P} = I_0 \begin{pmatrix} 1 \\ 0 \\ -1 \\ 0 \end{pmatrix}, \quad S_{RCP} = I_0 \begin{pmatrix} 1 \\ 0 \\ 0 \\ 1 \end{pmatrix}, \quad S_{LCP} = I_0 \begin{pmatrix} 1 \\ 0 \\ 0 \\ -1 \end{pmatrix},
\]
Mueller matrix describes polarized scattering

incident beam \( \mathbf{s}_{\text{inc}} = \begin{bmatrix} I_i \\ Q_i \\ U_i \\ V_i \end{bmatrix} \)

scattered light \( \mathbf{s}_{\text{sca}} = \begin{bmatrix} I_s \\ Q_s \\ U_s \\ V_s \end{bmatrix} \)

Add polarizers in the incident and scattered paths

\[
\begin{pmatrix}
I_s \\
Q_s \\
U_s \\
V_s
\end{pmatrix} =
\begin{pmatrix}
M_{11} & M_{12} & 0 & 0 \\
M_{21} & M_{22} & 0 & 0 \\
0 & 0 & M_{33} & M_{34} \\
0 & 0 & M_{43} & M_{44}
\end{pmatrix}
\begin{pmatrix}
I_i \\
Q_i \\
U_i \\
V_i
\end{pmatrix}
\]

Simplified Mueller matrix for randomly oriented particles with symmetry

\[
M_{11}(\psi) = \beta_p(\psi)
\]

\[
\text{DoLP} = \frac{M_{12}(\psi)}{M_{11}(\psi)}
\]