The Nature of Light

Interaction of Light and Matter

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- 1978. MS in Oceanography, University of Gdansk, Poland
- 1978 - 1986. Research Scientist, Institute of Oceanology, Polish Academy of Sciences, Sopot, Poland
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- 1996. “Poste Rouge” Visiting Scientist, Villefranche-sur-Mer, France
- 1997 – present. Professor, Scripps Institution of Oceanography, University of California San Diego, USA

UNIWERSYTET GDAŃSKI

PAN

OBSERVATOIRE OCEANOLOGIQUE VILLEFRANCHE/MER

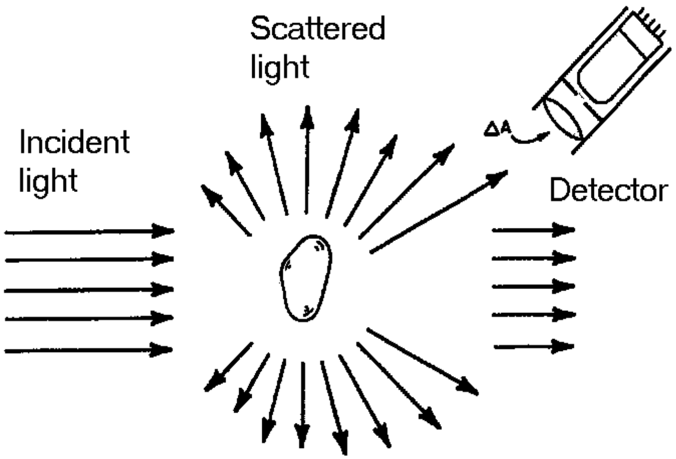
UNIVERSITÉ LAVAL

UNIVERSITY OF SOUTHERN CALIFORNIA 1880 PALMAM QUI MERUIT FERAT

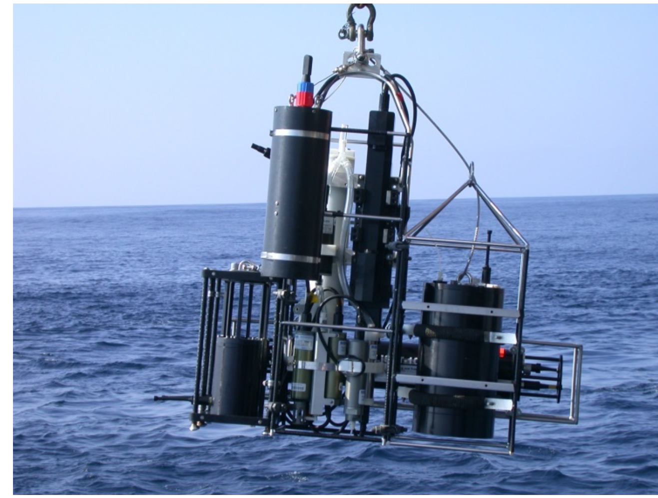
SCRIPPS INSTITUTION OF OCEANOGRAPHY UCSD

OCEAN OPTICS RESEARCH LAB AT SIO

PARTICLE OPTICS



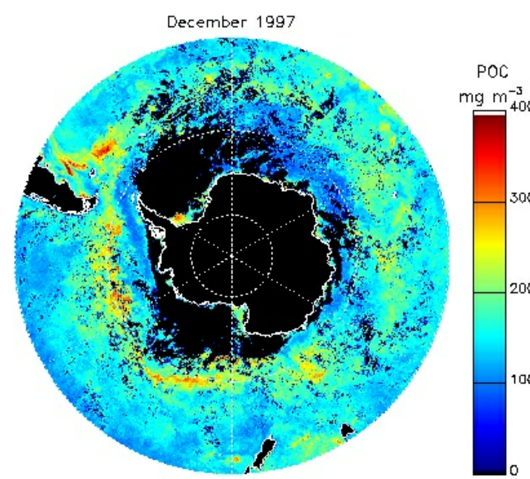
FIELD OBSERVATIONS



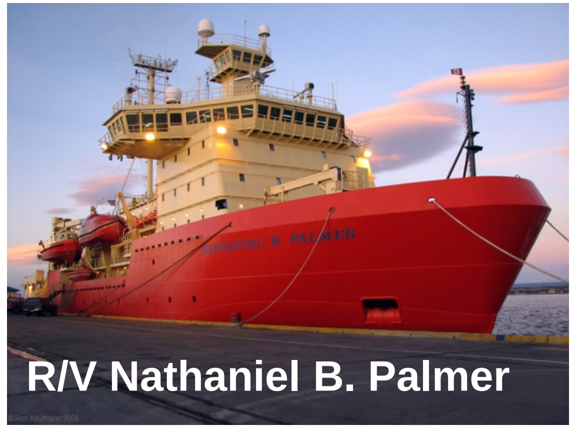
MODELING

$$\cos\theta \frac{dL(z,\xi,\lambda)}{dz} = -c(z,\lambda)L(z,\xi,\lambda) + \int_{\Xi} L(z,\xi',\lambda)\beta(z,\xi'\rightarrow\xi,\lambda)\,d\Omega(\xi') + S(z,\xi,\lambda)$$

REMOTE SENSING




USCGC Healy


R/V Nathaniel B. Palmer


R/V Kilo Moana


CCGS Amundsen

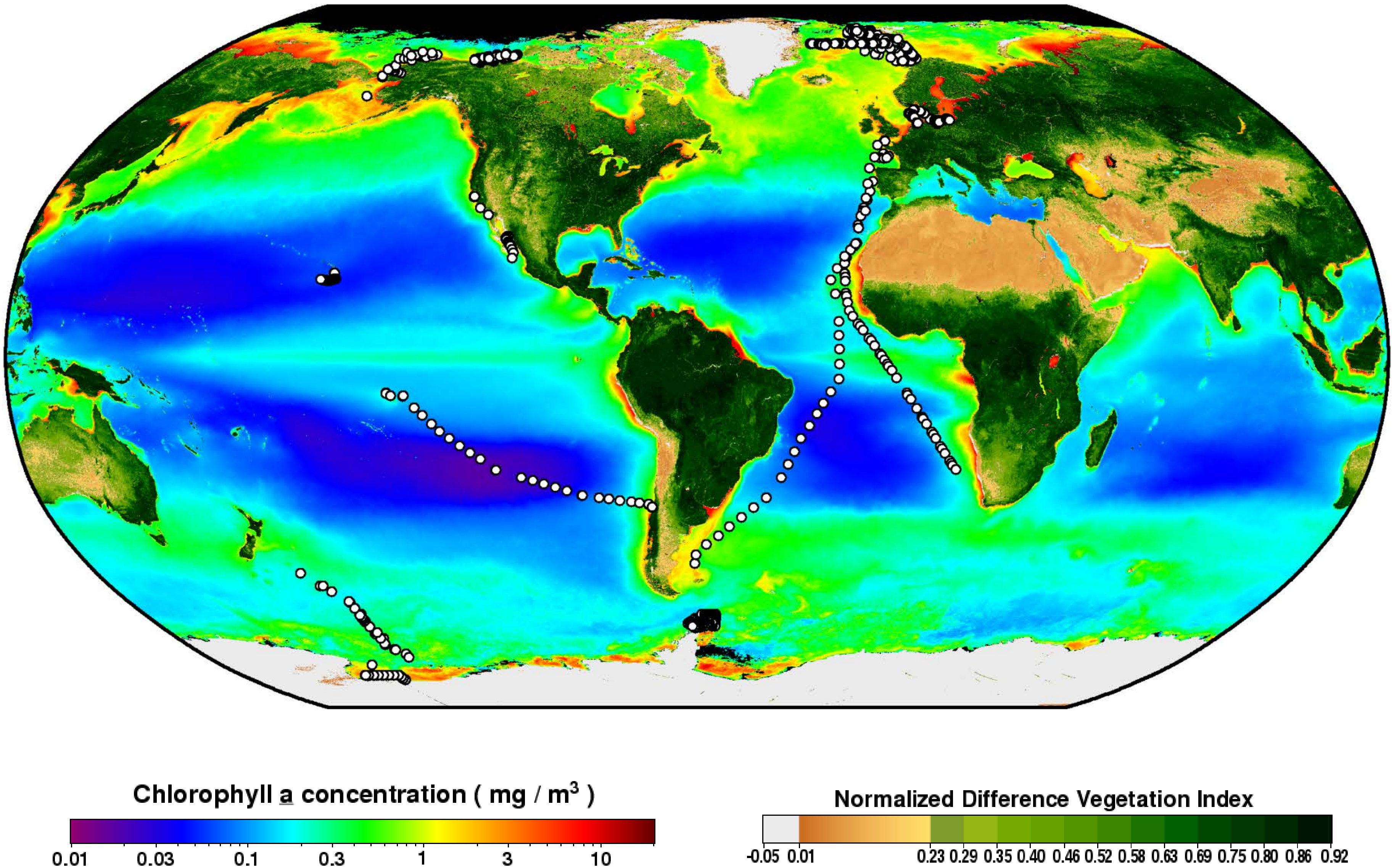

R/V L'Atalante


R/P FLIP


R/V Mirai


R/V Oceania


R/V Polarstern


Chlorophyll a concentration (mg / m3)
0.01 0.03 0.1 0.3 1 3 10
Normalized Difference Vegetation Index
-0.05 0.01 0.23 0.29 0.35 0.40 0.46 0.52 0.58 0.63 0.69 0.75 0.80 0.86 0.92

What is light?

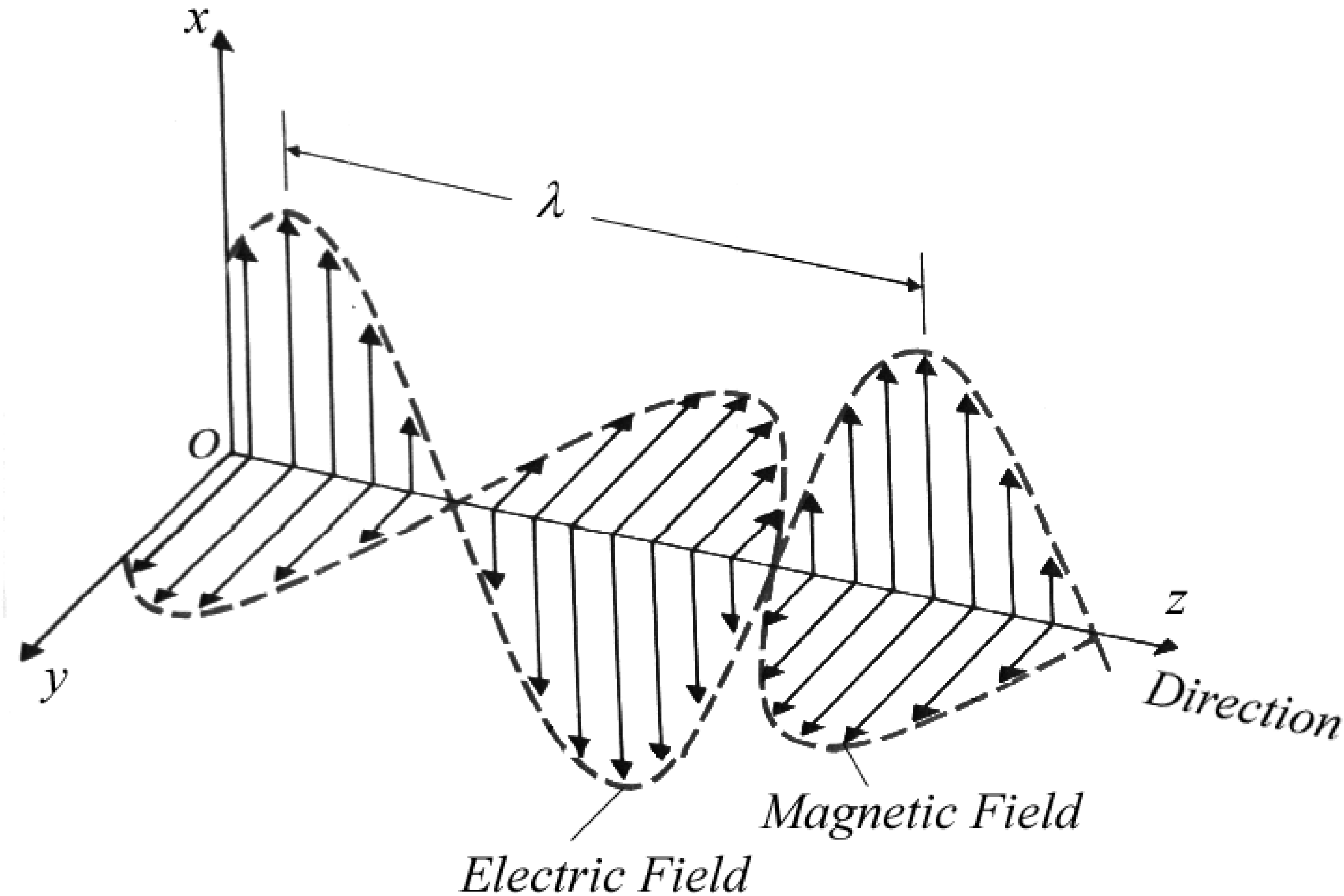
“Every physicist thinks he knows what a photon is. I spent my life to find out what a photon is and I still don’t know it”

“Physics should be made as simple as possible, but no simpler”

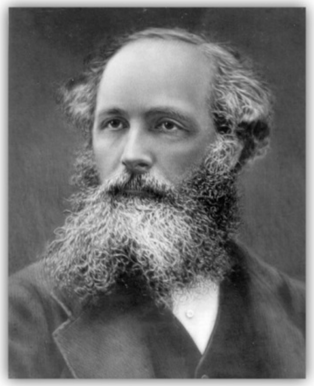
- Albert Einstein

Electromagnetic wave

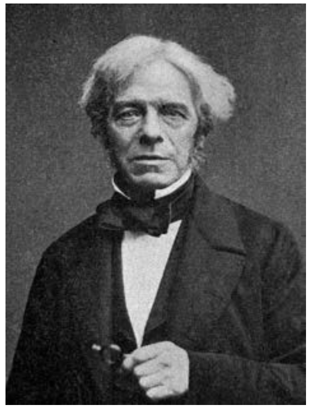
Time-varying electric and magnetic fields are coupled in an electromagnetic field radiating from the source



Maxwell equations:
How is an electromagnetic field produced?



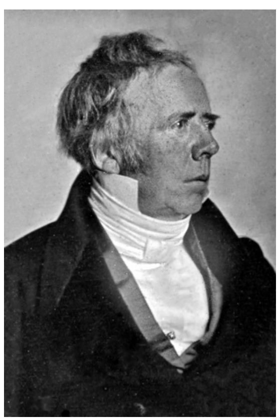
James Clerk Maxwell
(1831 - 1879)



Michael Faraday
(1791 - 1867)

Electric fields are generated by:

- Electric charges
- Time-varying magnetic fields



Hans Christian Ørsted
(1777 - 1851)

André-Marie Ampère
(1775 - 1836)

Magnetic fields are generated by:

- Charges in motion (electric currents)
- Time-varying electric fields

Force equations: How fields affect charges?

- If a point charge experiences a force $\vec{F}_E$, the electric field at the position of charge is: $\vec{F}_E = q\,\vec{E}$

- A moving charge may experience another force that is proportional to its velocity $\vec{v}$: $\vec{F}_M = q\,\vec{v} \times \vec{B}$

- If forces $\vec{F}_E$ and $\vec{F}_M$ occur concurrently then the charge experiences electric and magnetic fields: $\vec{F} = q\vec{E} + q\,\vec{v} \times \vec{B}$

• From Maxwell's equations in differential form we obtain in free space

$$\nabla^2 \vec{E} = \mu_0 \epsilon_0 \frac{\partial^2 \vec{E}}{\partial t^2}$$

$$\nabla^2 \vec{B} = \mu_0 \epsilon_0 \frac{\partial^2 \vec{B}}{\partial t^2}$$

where $\nabla^2 \equiv \nabla \cdot \nabla$ is the scalar operator known as Laplacian

$$\nabla^2 = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2}$$

• Example of one of six scalar equations

$$\frac{\partial^2 E_x}{\partial x^2} + \frac{\partial^2 E_x}{\partial y^2} + \frac{\partial^2 E_x}{\partial z^2} = \epsilon_0 \mu_0 \frac{\partial^2 E_x}{\partial t^2}$$

• Wave equation if

$$\epsilon_0 \mu_0 = \frac{1}{c^2}$$

Poynting Vector

Energy transported by electromagnetic wave per unit time per unit area

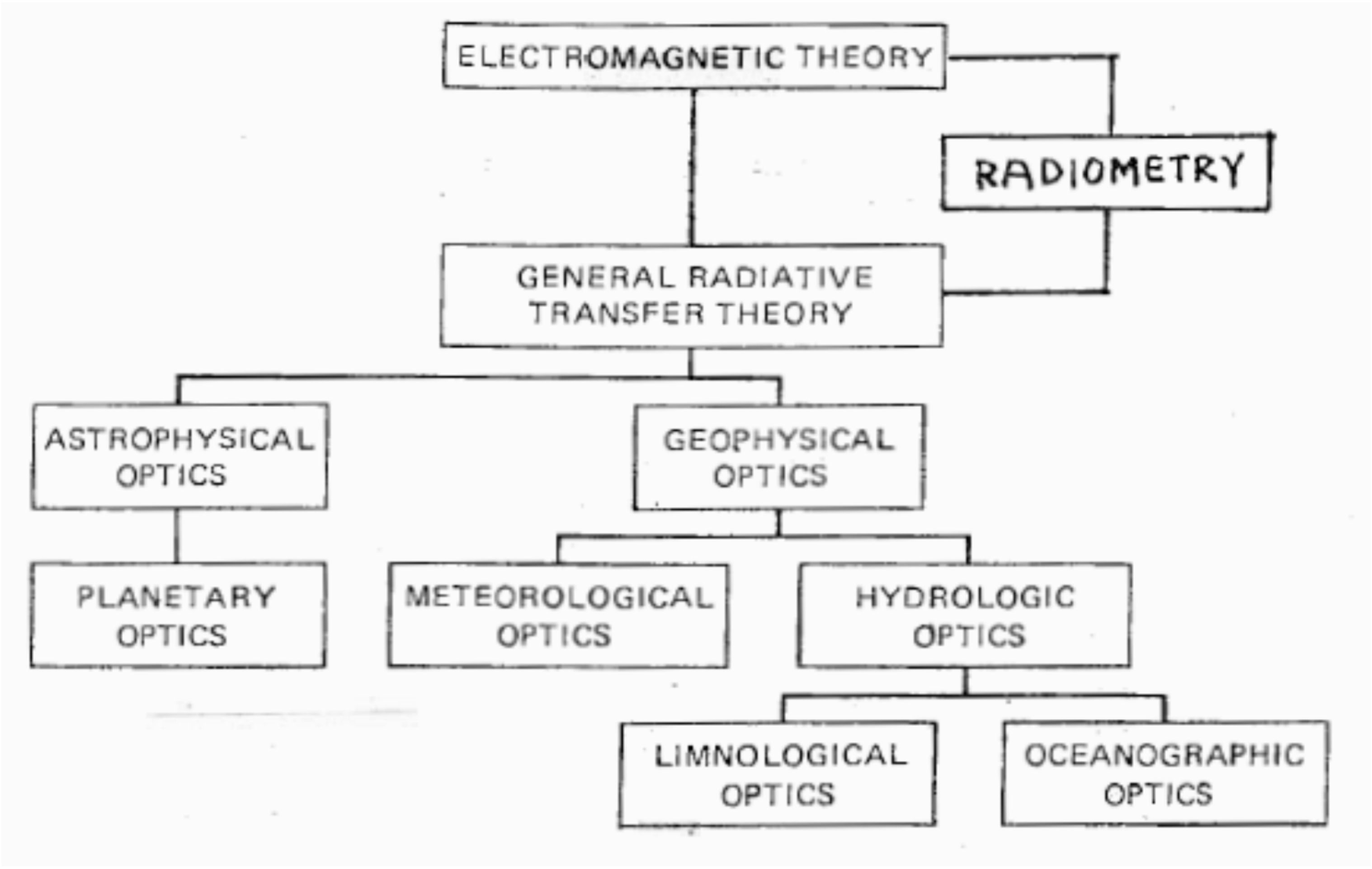
- Poynting vector at time instant t

$$\vec{S}(t) = \frac{1}{\mu_0}\vec{E}(t) \times \vec{B}(t) = c^2 \epsilon_0 \vec{E}(t) \times \vec{B}(t)$$

- Time-average magnitude of $\vec{S}(t)$ is

$$\langle S \rangle_T = \frac{c^2 \epsilon_0}{2} \left| \vec{E}_0 \times \vec{B}_0 \right| = \frac{c\,\epsilon_0}{2} E_0^2$$

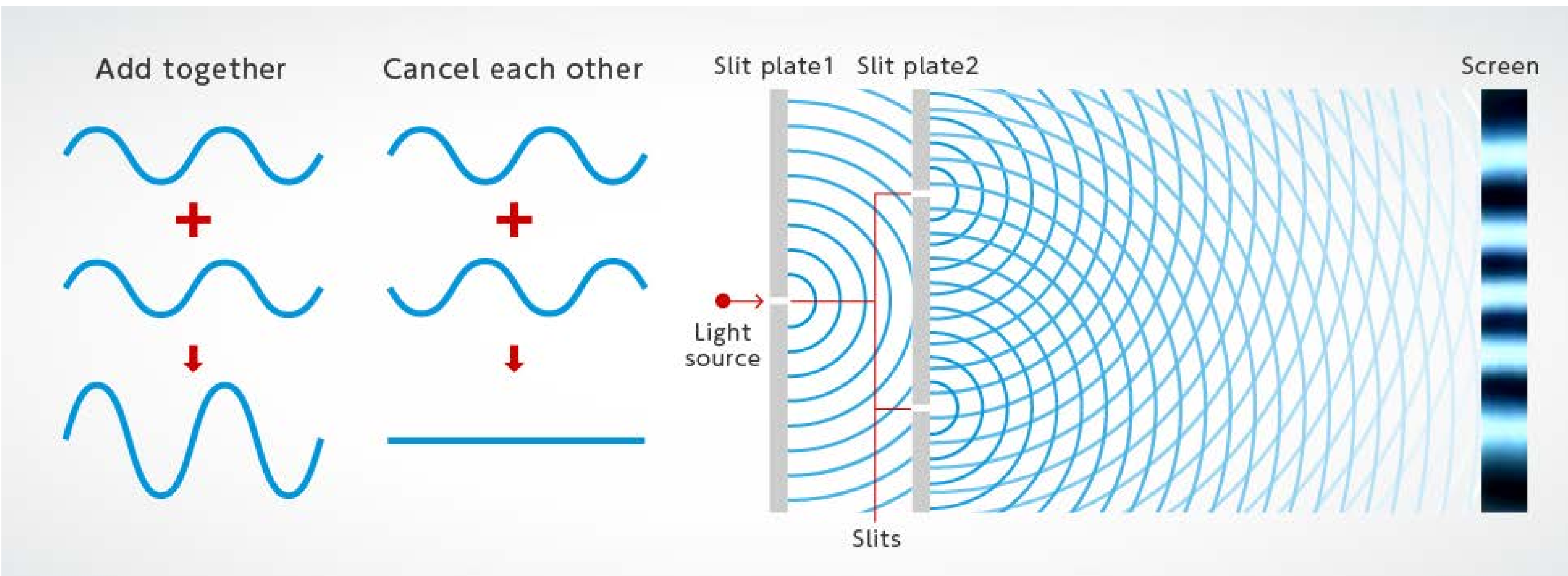
The relation between ocean optics and fundamental electromagnetic theory in physics

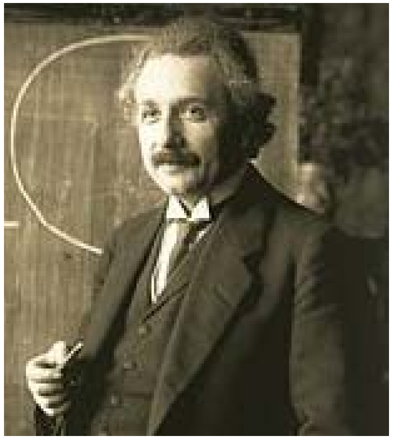


Preisendorfer 1976

Thomas Young
(1773 - 1829)

In 1807, an English physicist Thomas Young asserted that light has the properties of a wave in an experiment called Young's Interference Experiment. This Young's interference experiment showed that light beams (waves) passing through two slits (double-slit) add together or cancel each other and then interference fringes appear on the screen. This phenomenon can be explained if light is considered as a wave.



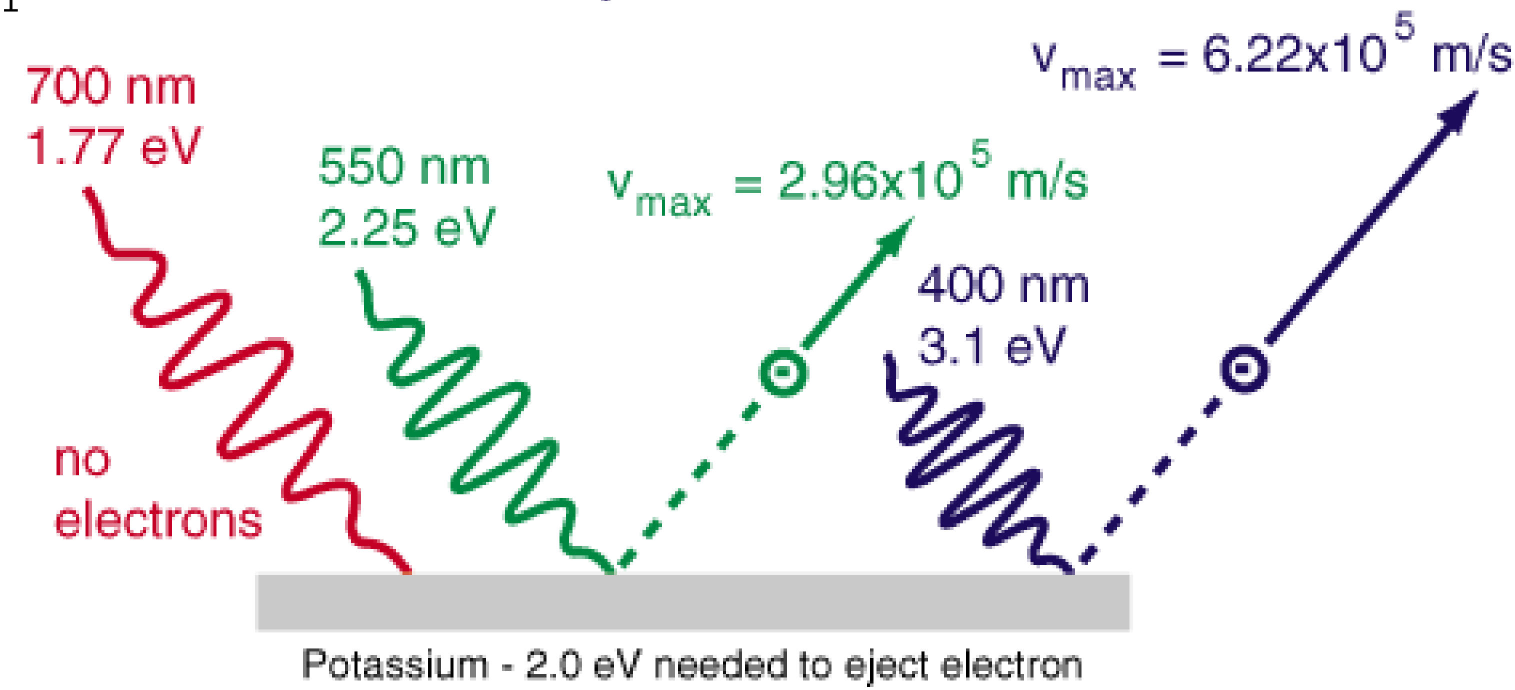


Albert Einstein (1879 - 1955)
Nobel Prize 1921

On a Heuristic Viewpoint Concerning the Production and Transformation of Light, *Annalen der Physik*, ***17*** *(6), 132–148 (1905).*

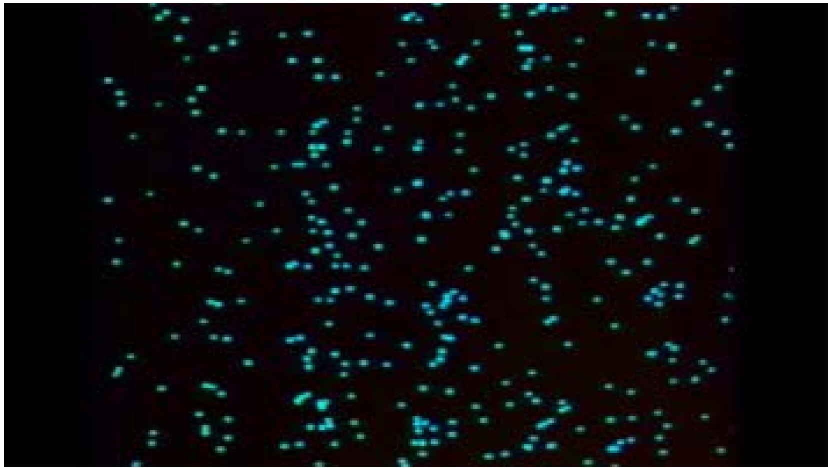
One of four Einstein’s Annus Mirabilis (Miracle Year) papers published in 1905.

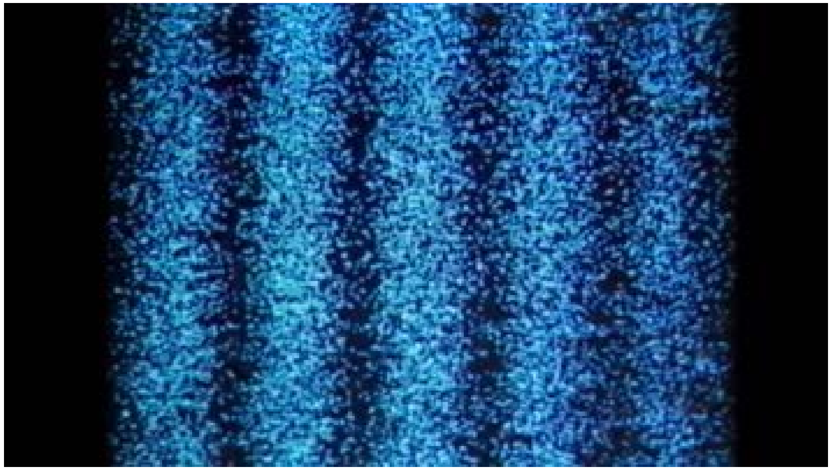
$$E_{photon} = h\nu$$



Photoelectric effect

Young's Interference Experiment or Double-slit Interference Experiment carried out using technology to detect individual light particles to investigate whether interference fringes appear even if the light is drastically weakened to the level having only one particle. Results from the experiment confirmed that one photon exhibited an interference fringe (Hamamatsu Photonics, 1981).

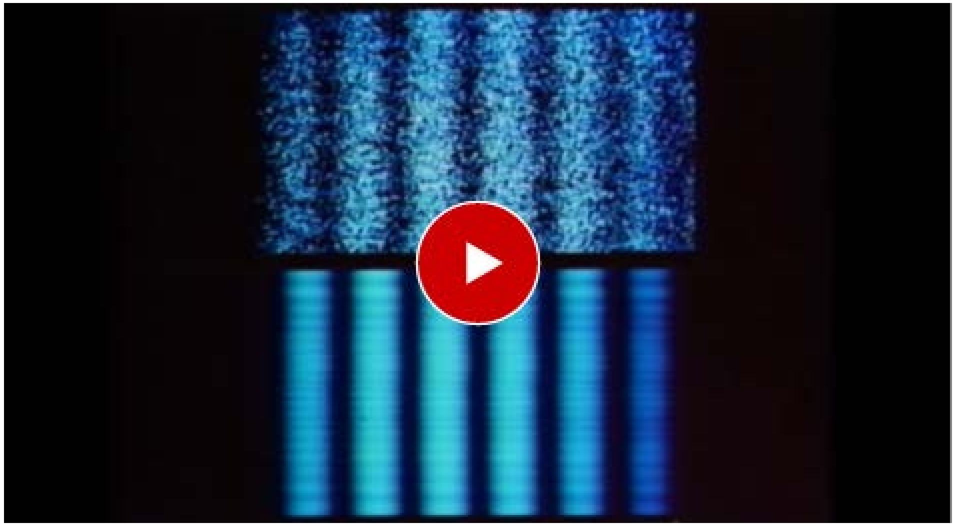




Young's Interference Experiment with a single photon (top)

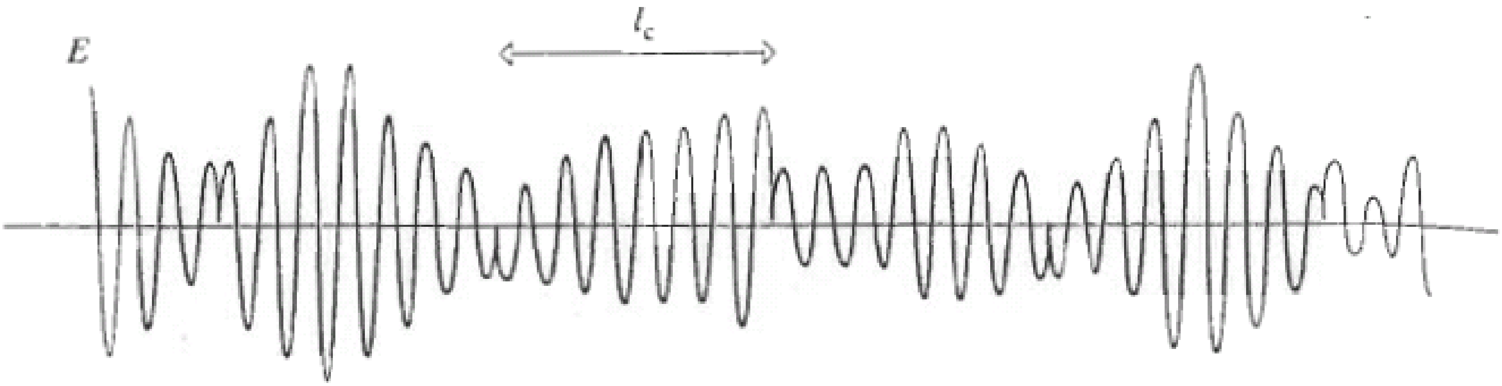
Young's Interference Experiment with a very large number of photons (bottom)

http://photonterrace.net/en/photon/duality/



This experiment captured the dual nature of the photon by a special camera for the first time ever

Electromagnetic radiation: A mix of photon wavetrains



The energy q of photon is related to its frequency f and corresponding wavelength λ :

$$q = h\, f = h\, c / \lambda$$

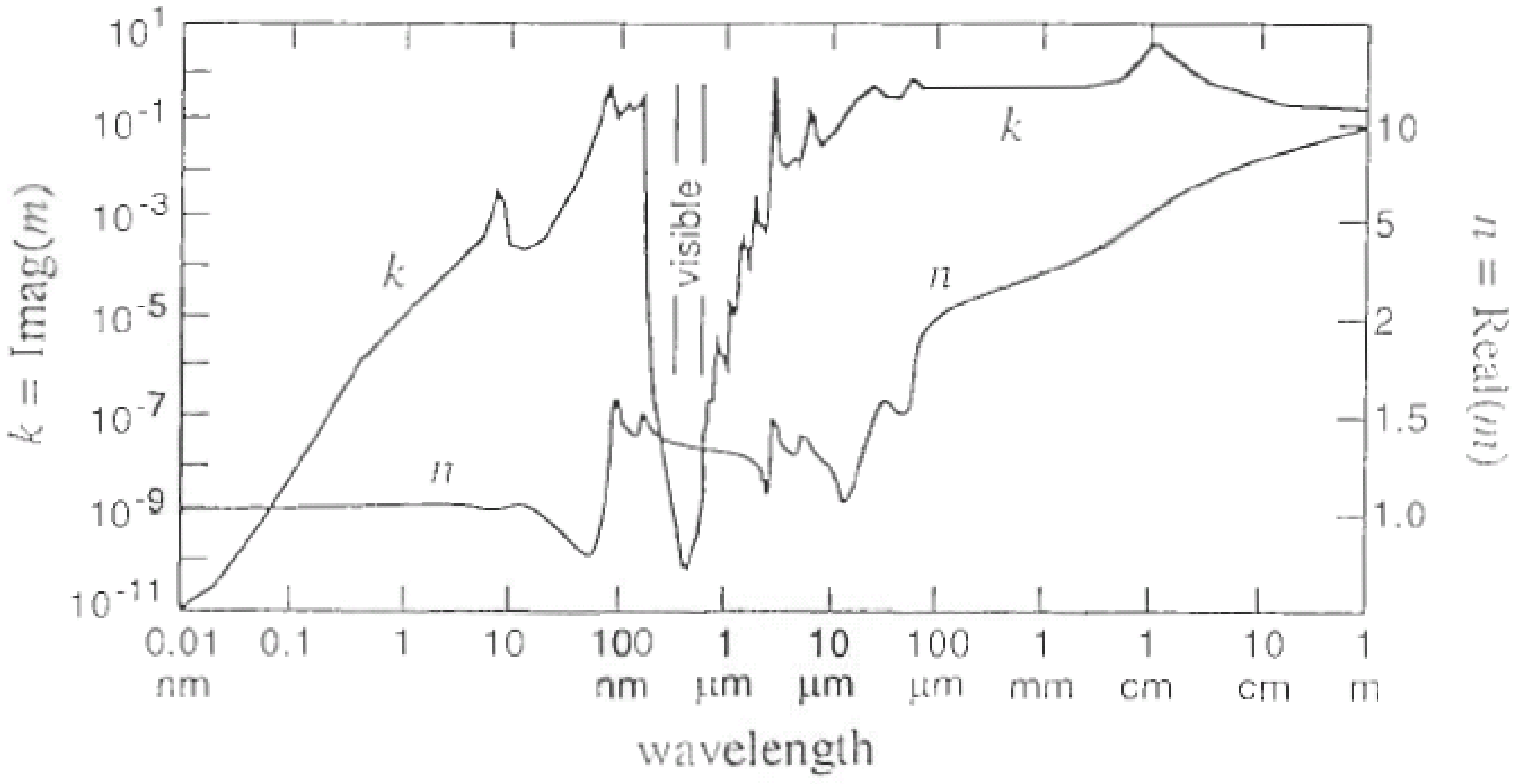
where h = 6.626 x 10^{-34} J s is Planck's constant and c = 2.998 x 10^{8} m s^{-1} is the speed of photons (phase velocity) in free space.

The speed of photons (phase velocity) in water is $v_w = c / n_w$
where n_w is refractive index of water $n_w = c / v_w$

The energy q_w of photon in water is:

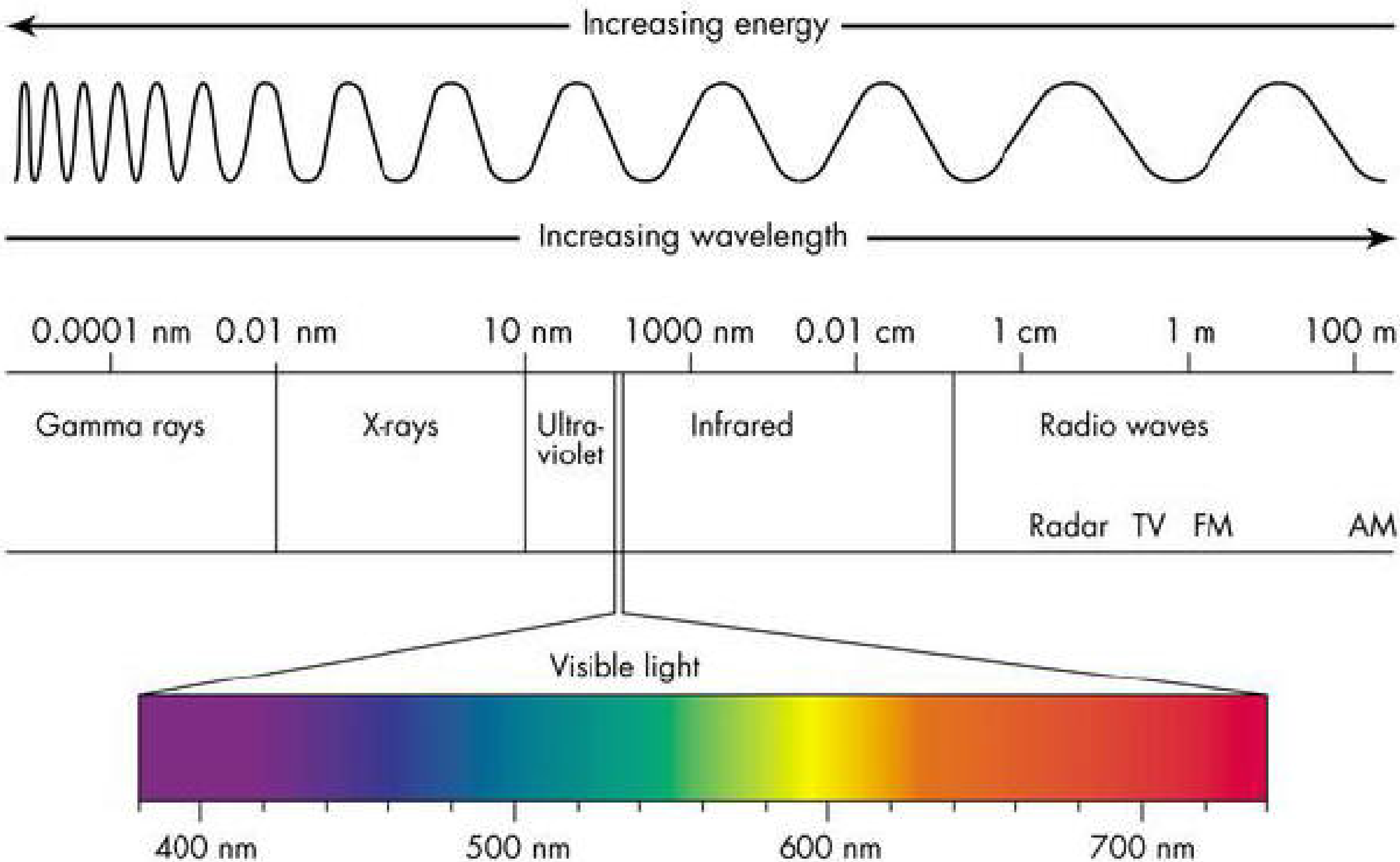
$$q_w = q = h\, f = h\, v_w / \lambda_w \quad \text{where } \lambda_w = \lambda / n_w$$

Refractive Index of Water

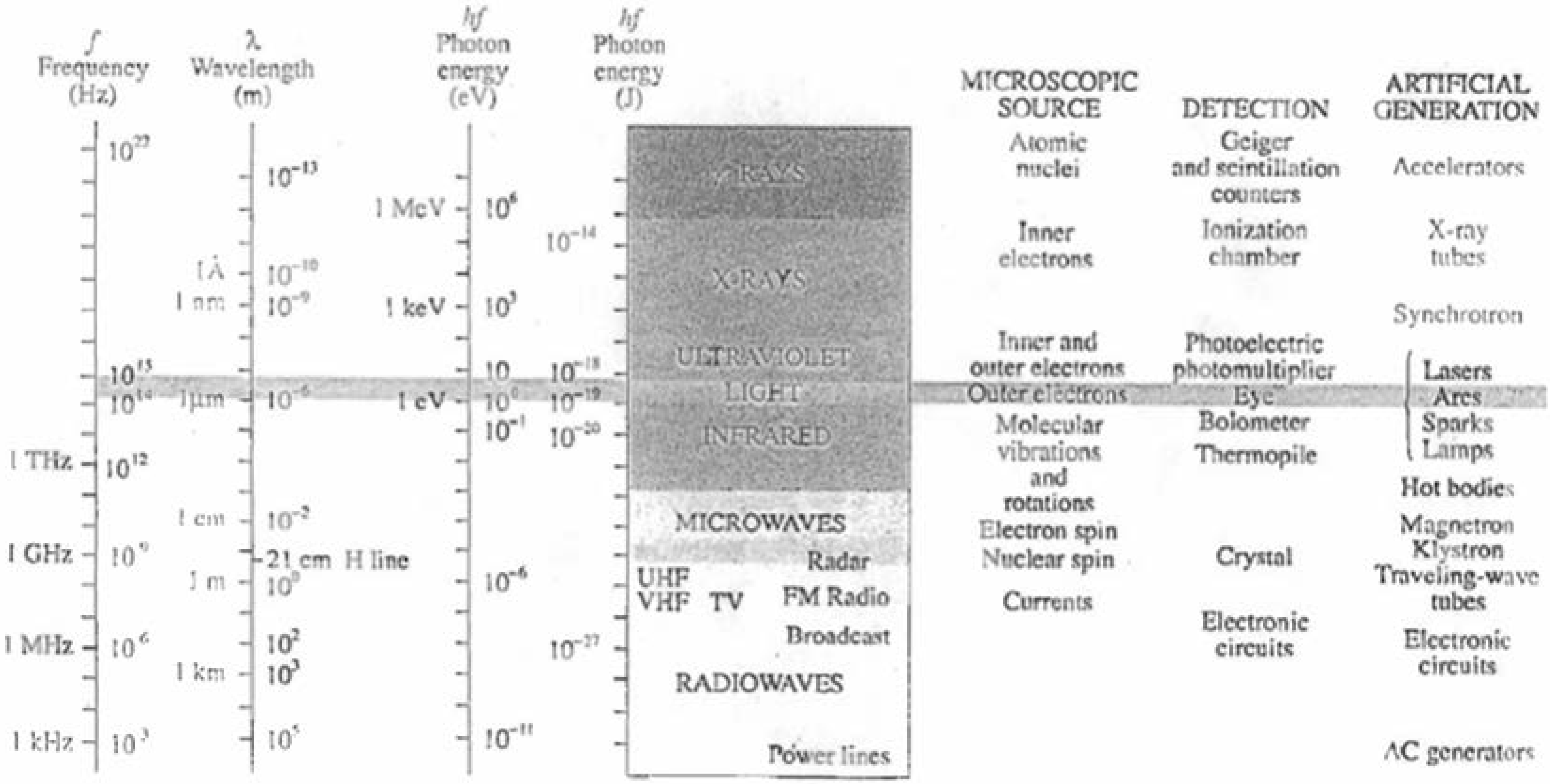


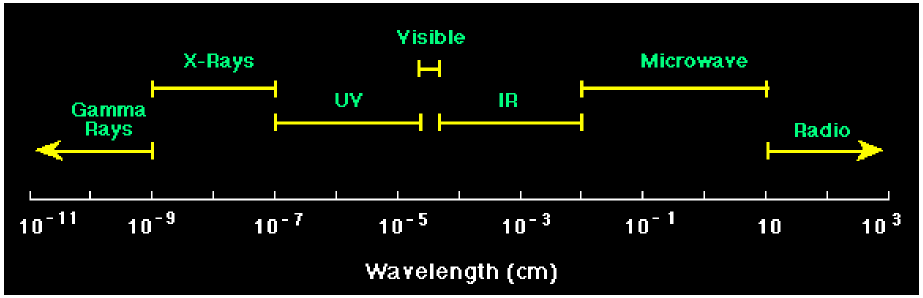
(Mobley 1994)

The Electromagnetic-Photon Spectrum



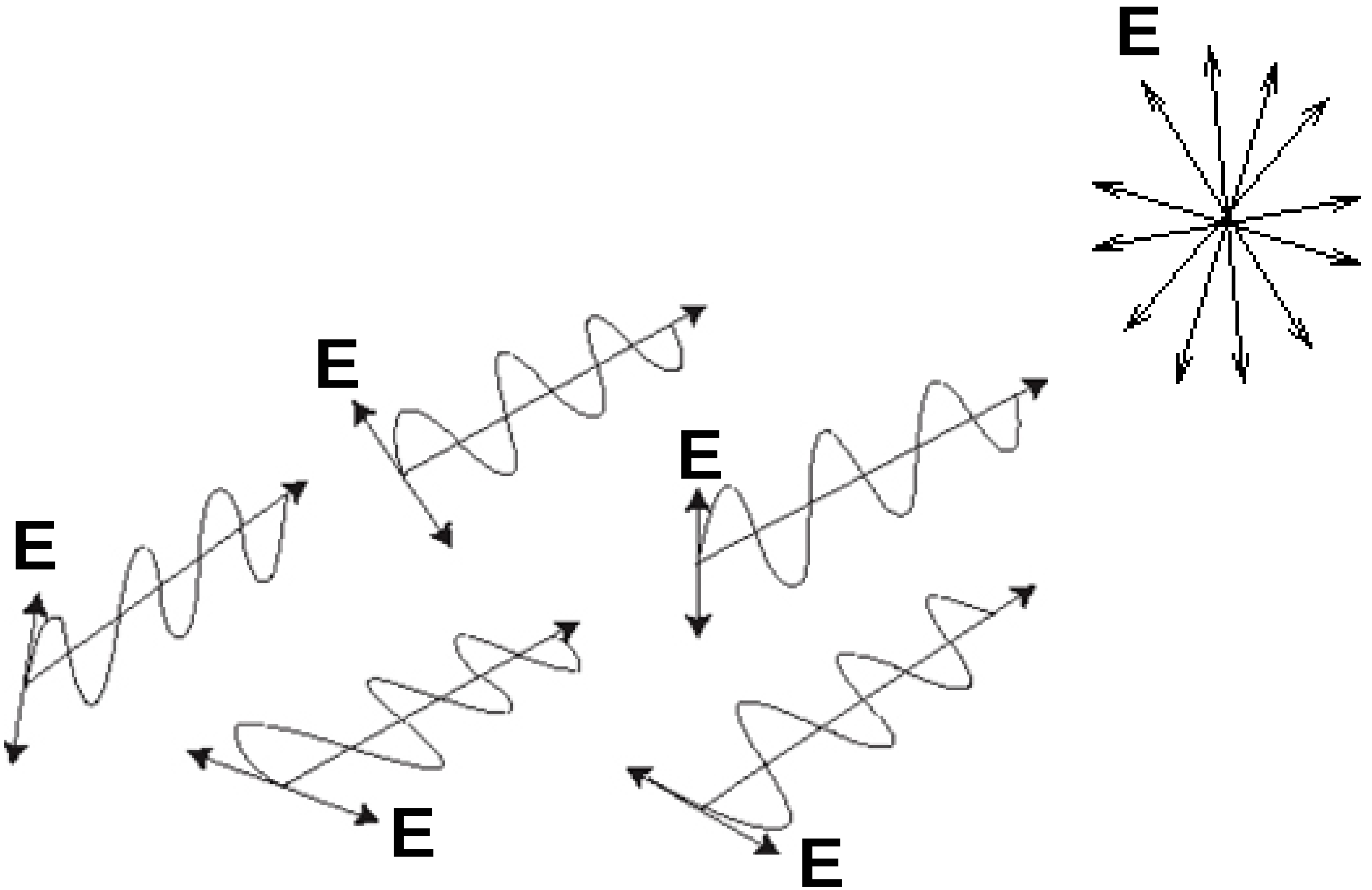
The electromagnetic-photon spectrum





(Hecht 1994)

Randomly polarized (unpolarized) light is a jumble of random, rapidly changing **E**-fields



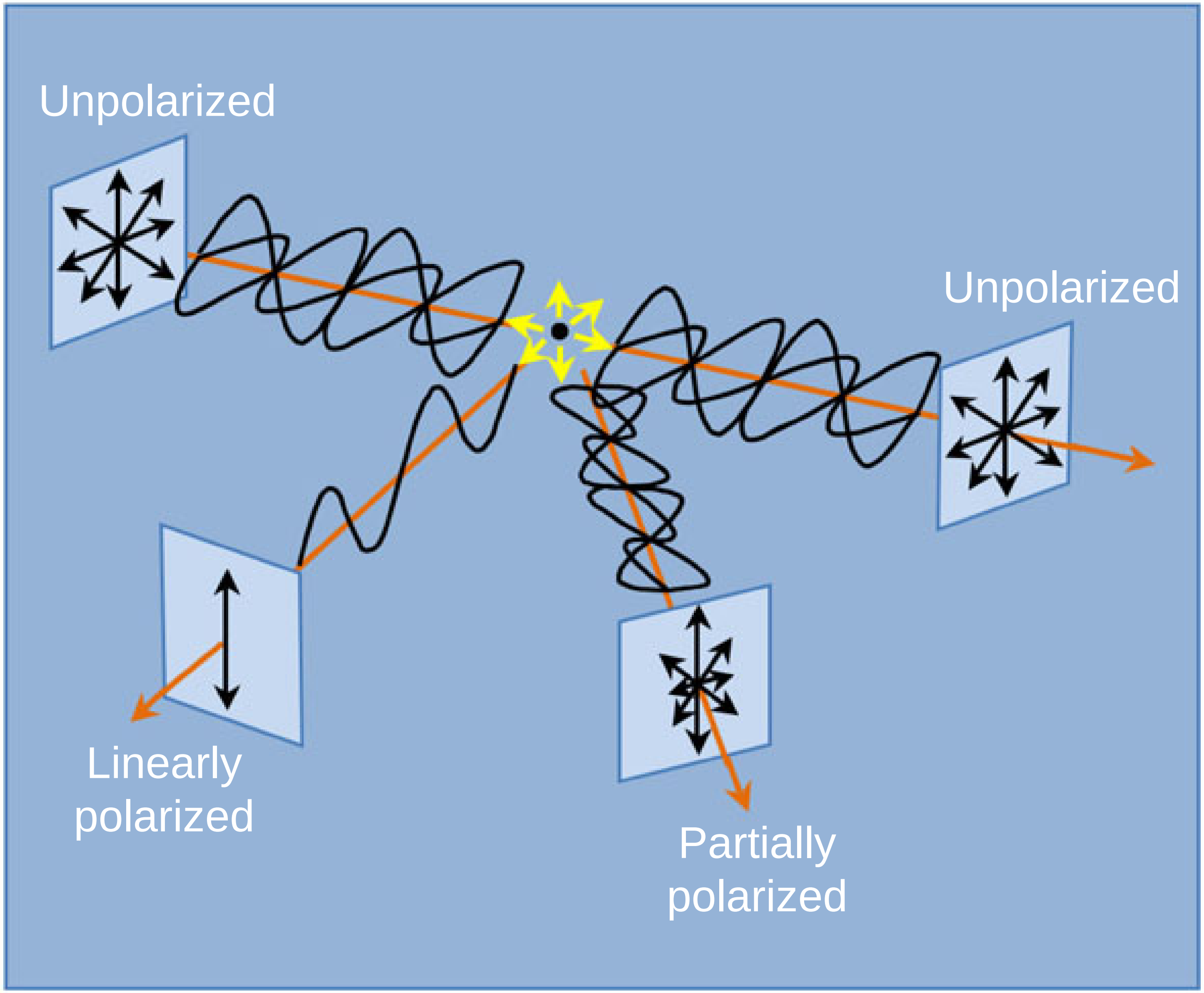
Polarization by transmission (polarizing filters)

Relationship Between Long-Chain Molecule Orientation and the Orientation of the Polarization Axis

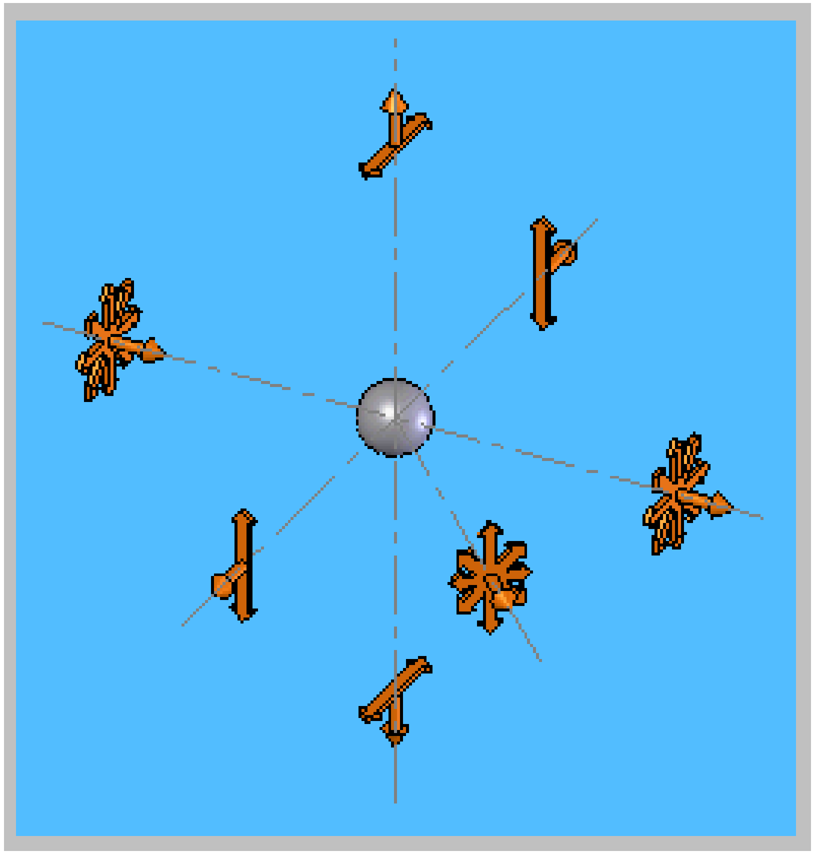
When molecules in the filter are aligned vertically, the polarization axis is horizontal.

When molecules in the filter are aligned horizontally, the polarization axis is vertical.

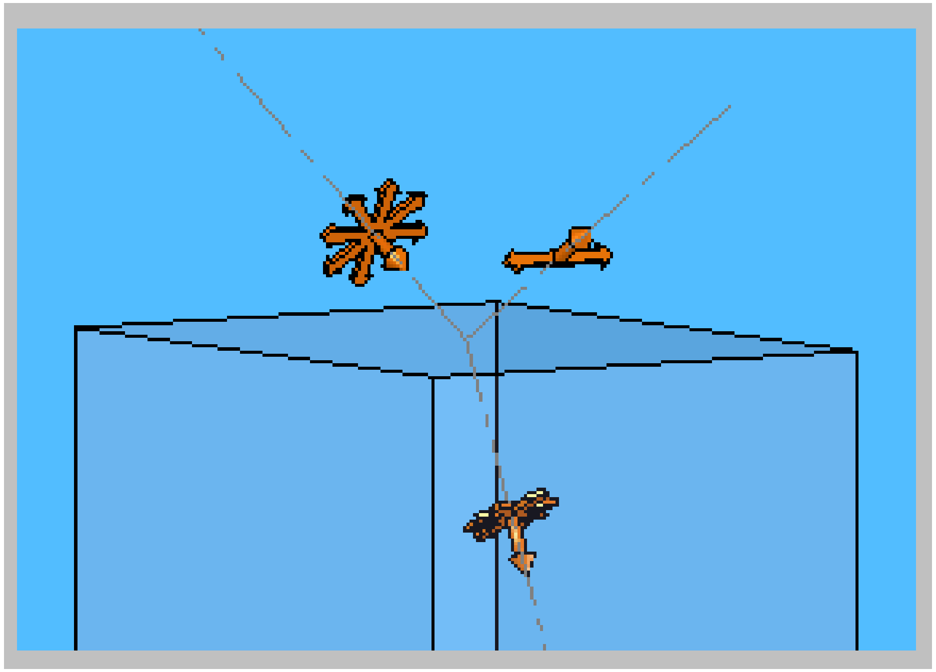
Polarization by scattering



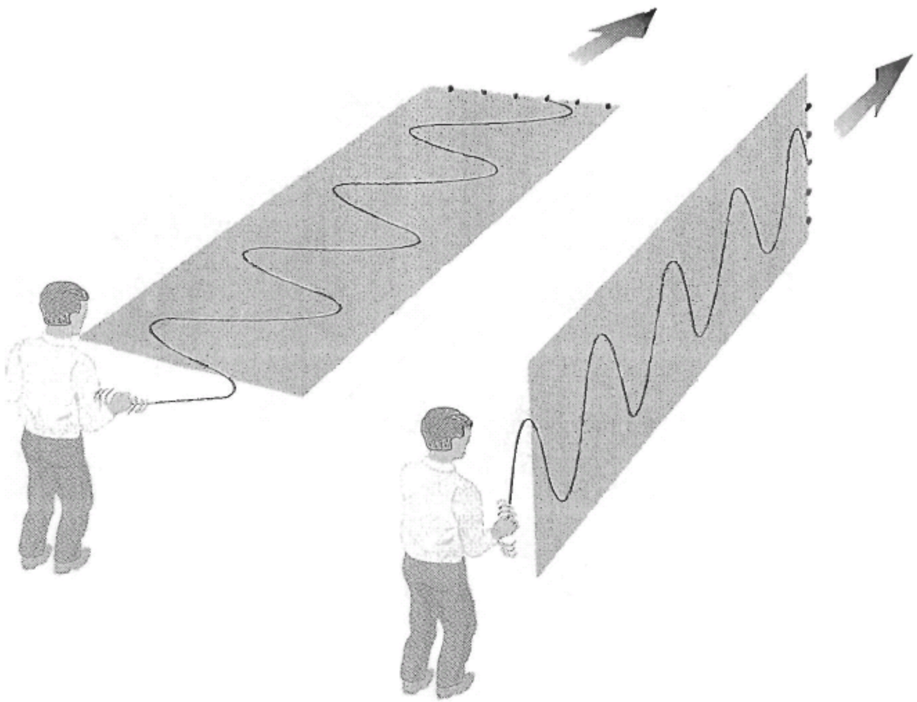
Polarization by scattering

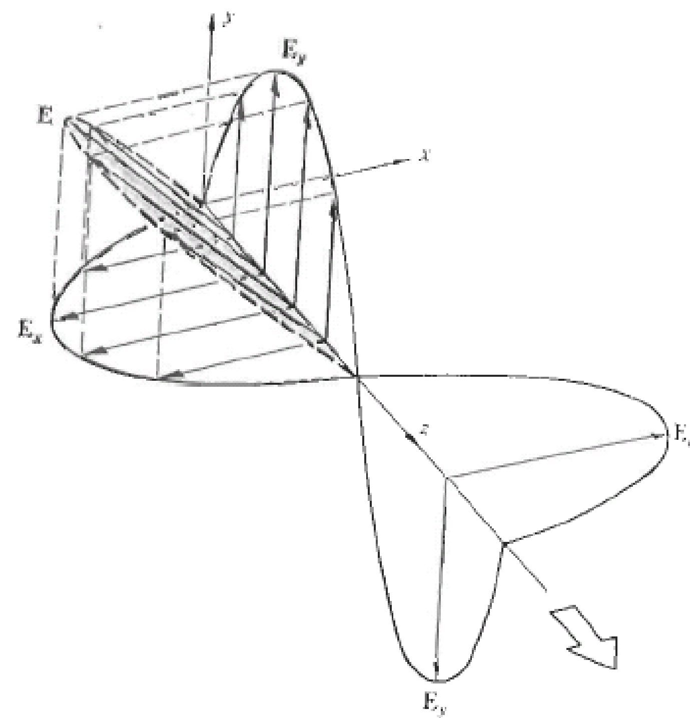


Polarization by reflection



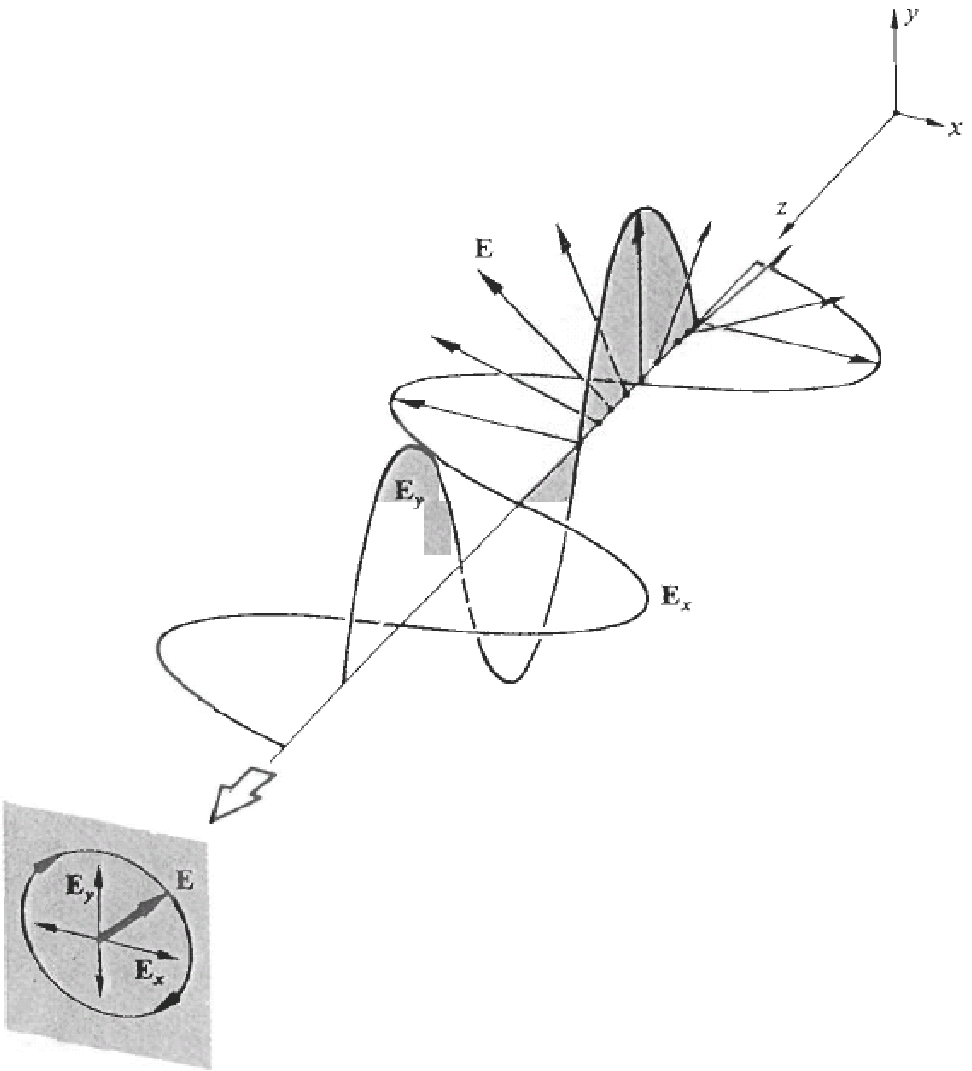
Plane-Polarized or Linearly-Polarized Light





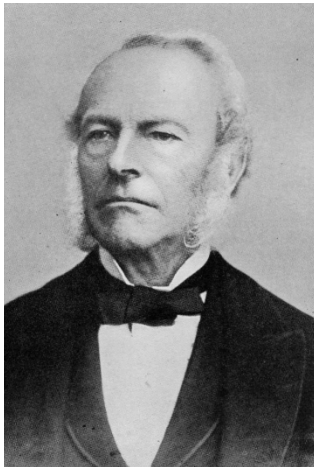
(Hecht 1998)

Right-circular light



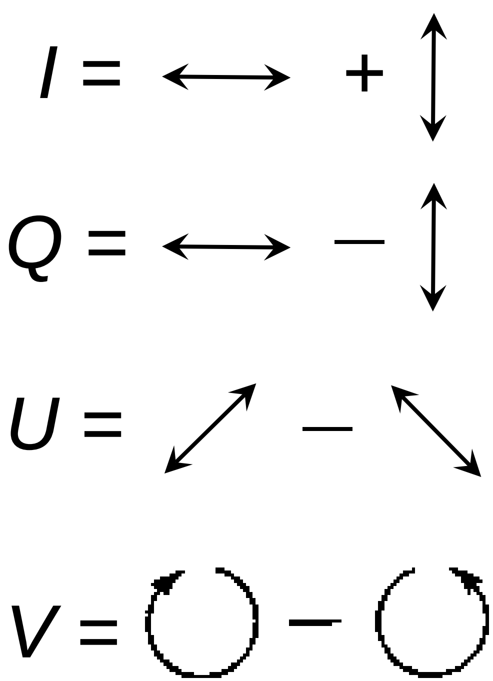
(Hecht 1998)

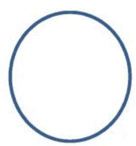
Stokes vector



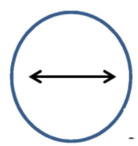
George Gabriel Stokes
(1819 – 1903)

$$S = \begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix} = \begin{pmatrix} \langle E_x{}^2 \rangle + \langle E_y{}^2 \rangle \\ \langle E_x{}^2 \rangle - \langle E_y{}^2 \rangle \\ 2E_x E_y \cos \xi \\ 2E_x E_y \sin \xi \end{pmatrix}$$

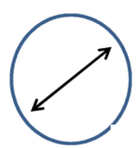




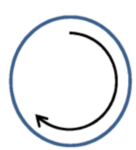
Unpolarized:
transmits intensity
of any incident light



transmits only
horizontal light



transmits only
linear light at 45º



transmits only
R-polarized light

Degree of polarization

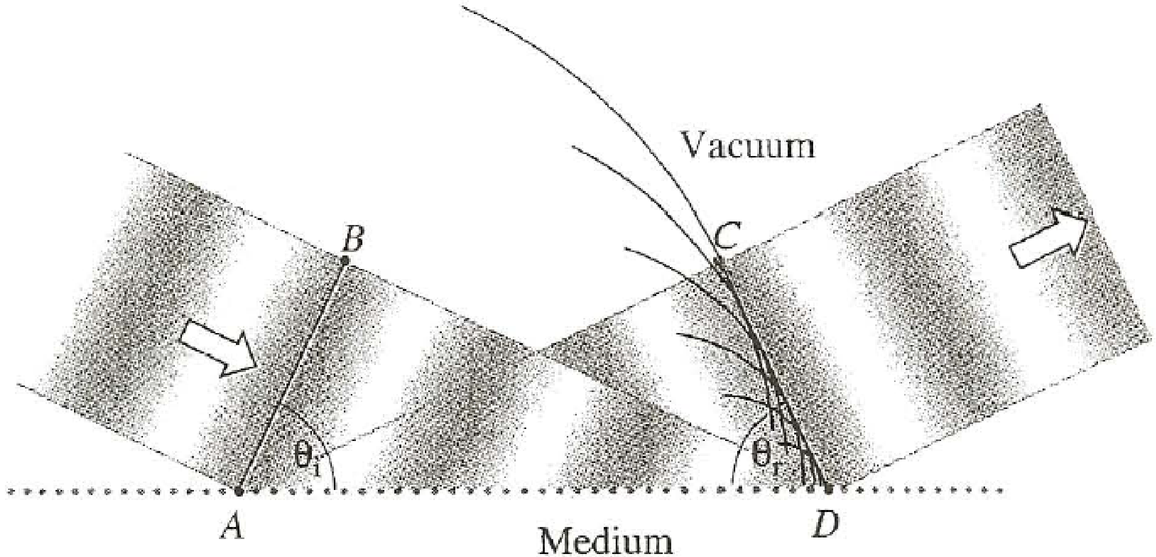
$$p = \frac{\sqrt{Q^2 + U^2 + V^2}}{I},$$

$$p_{\text{lin}} = \frac{\sqrt{Q^2 + U^2}}{I},$$

$$p_{\text{circ}} = \frac{V}{I}$$

Reflection at the boundary between the media of different densities (refractive index)

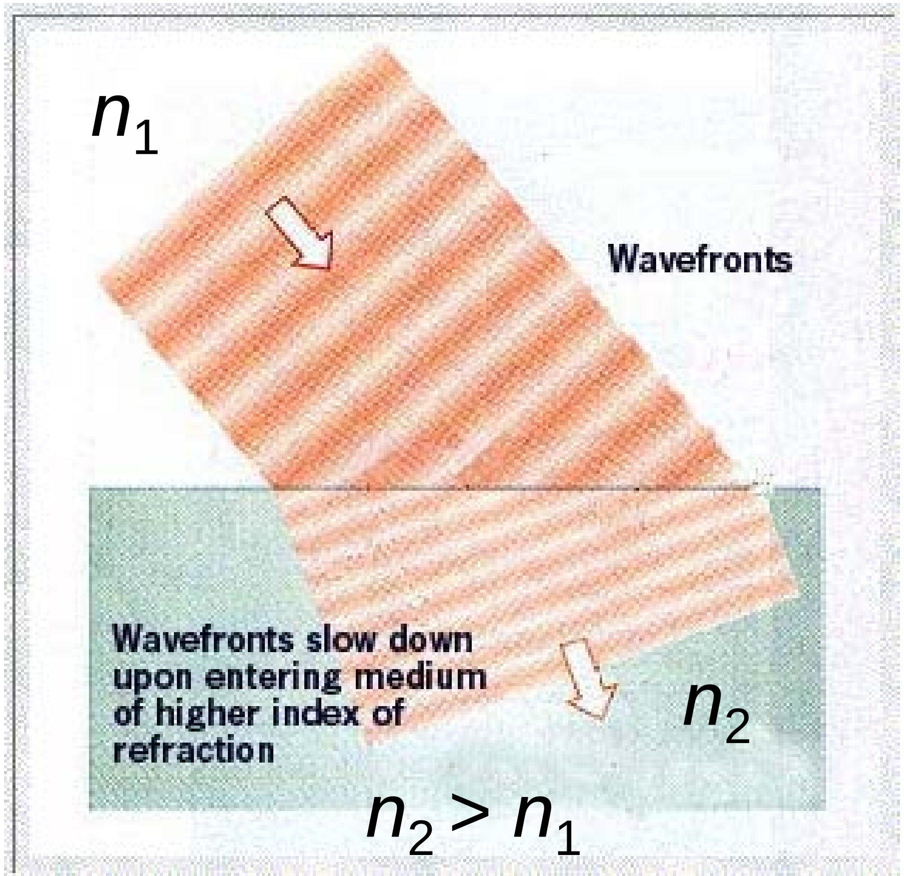
Christian Huygens
(1629 - 1695)

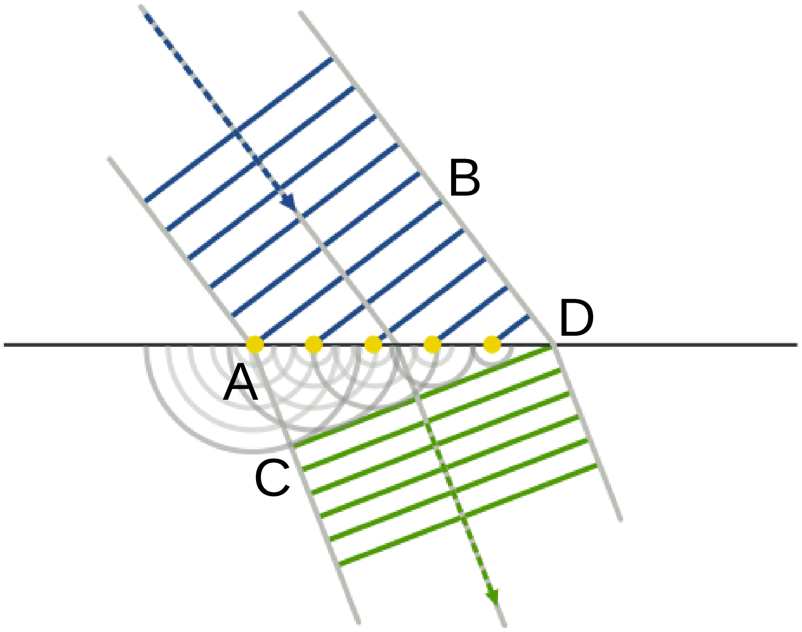


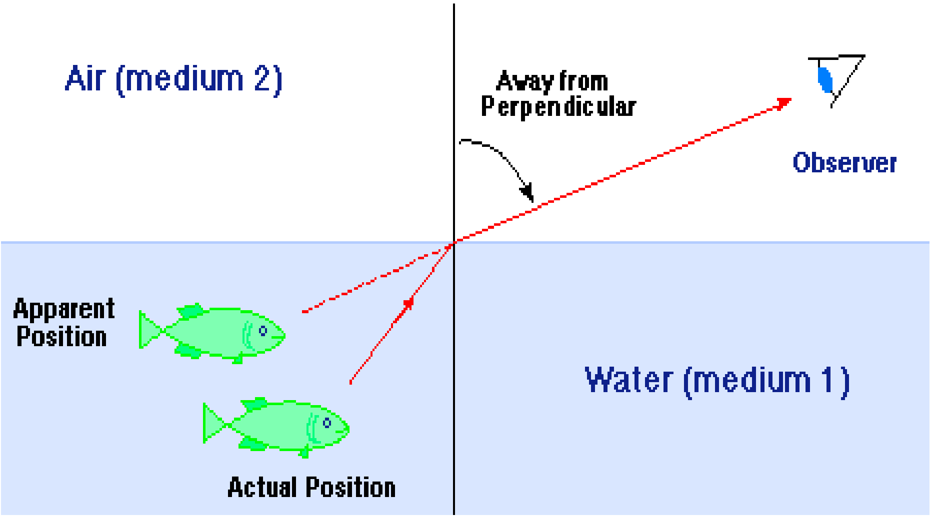
Wavefront geometry for reflection. The reflected wavefront $\overline{CD}$ is formed of waves scattered by the atoms on the surface from *A* to *D*. Just as the first wavelet arrives at C from *A*, the atom at *D* emits, and the wavefront along $\overline{CD}$ is completed.

Angle of incidence = Angle of reflection

Refraction



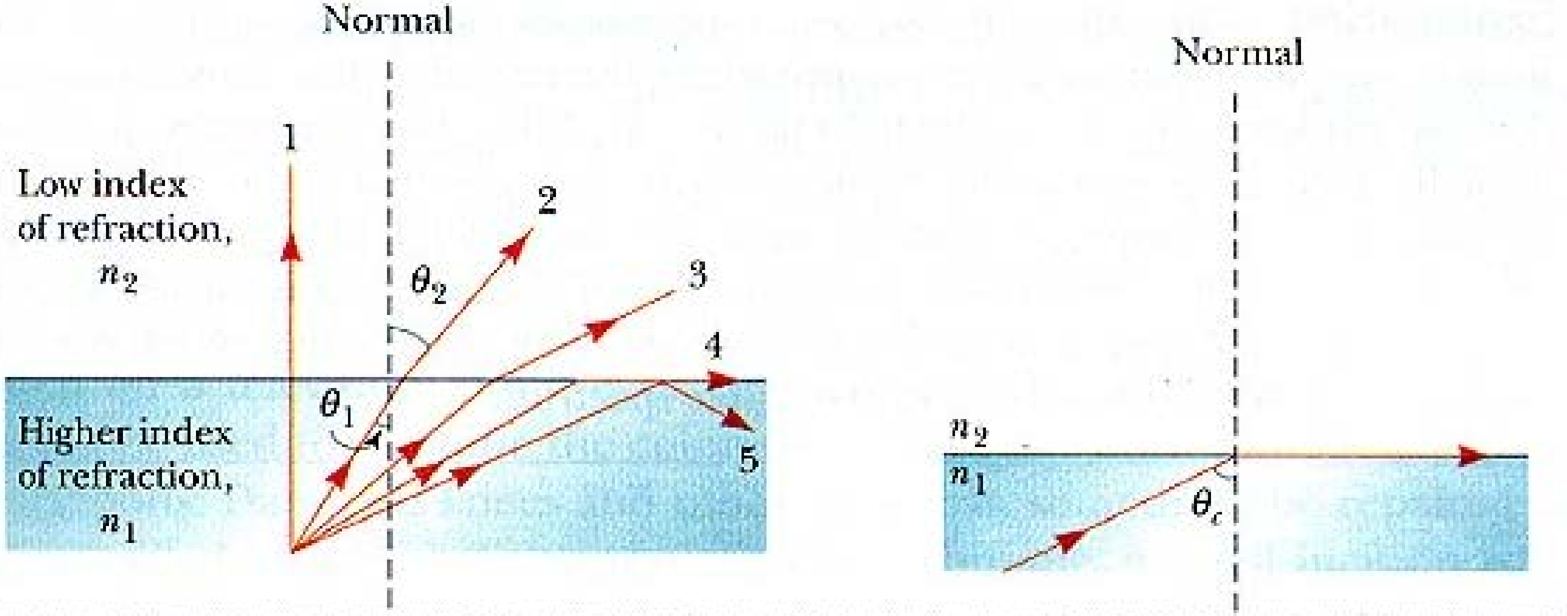




Snell's law

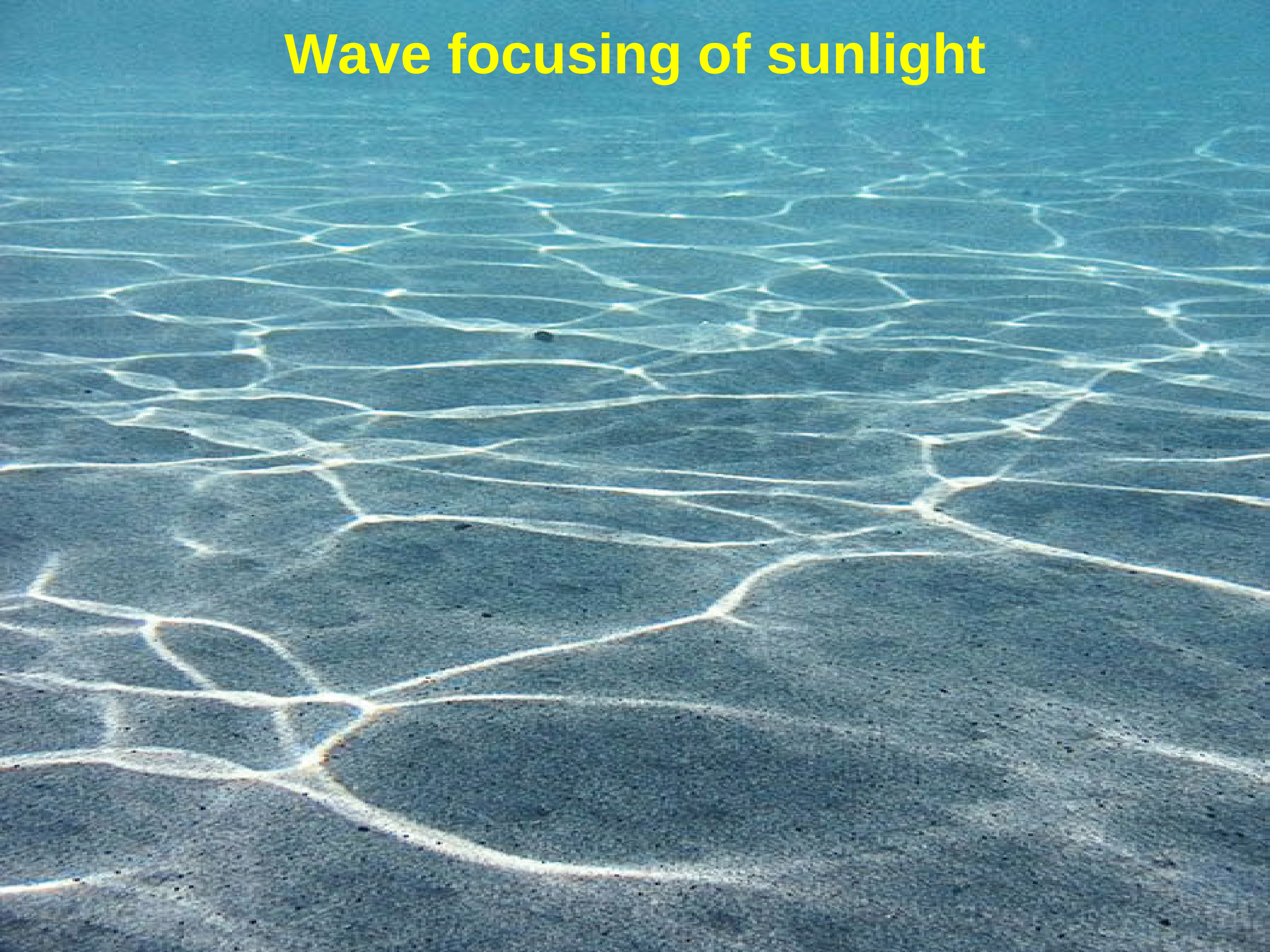
$$n_1 \sin(i) = n_2 \sin(r)$$

Internal Reflection

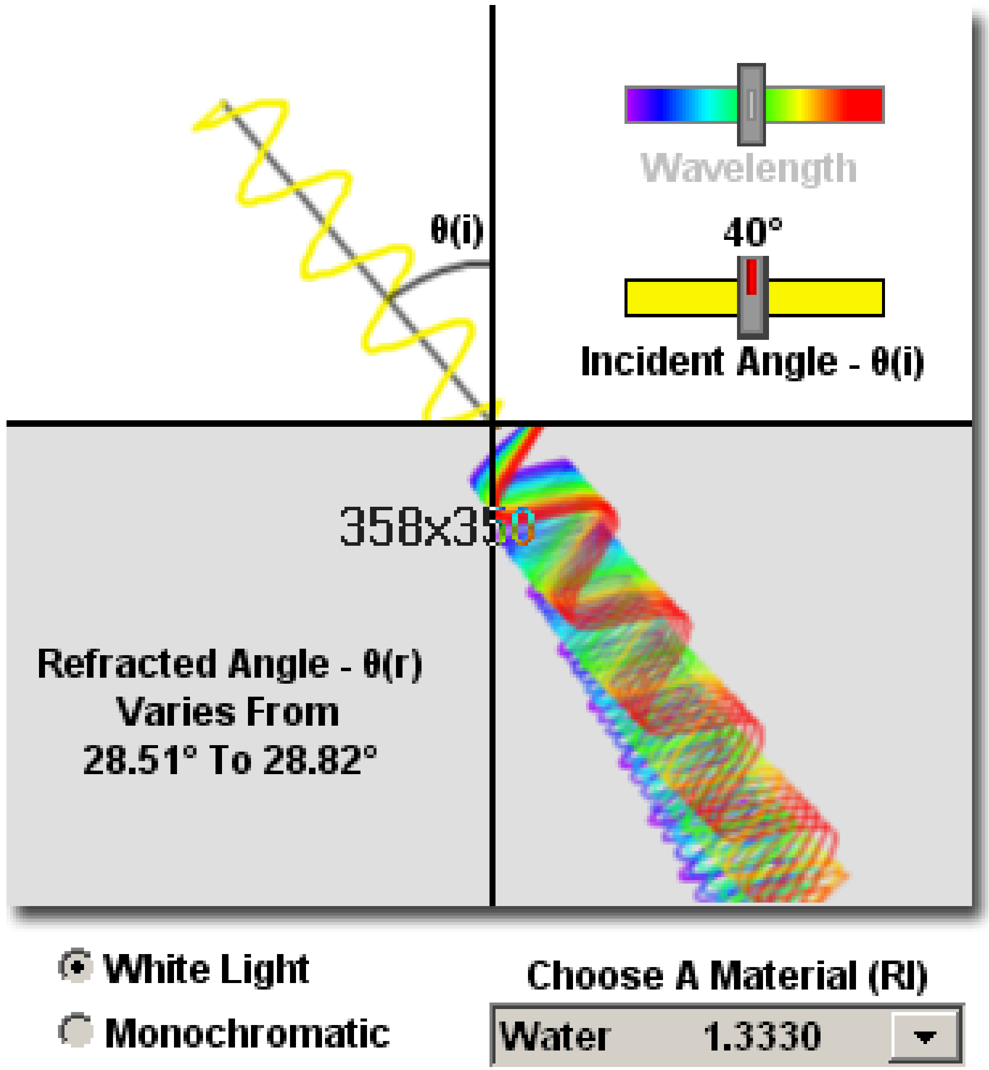


Ray 4 is the first to be 100 % reflected; it's angle of incidence is called the *critical angle*.

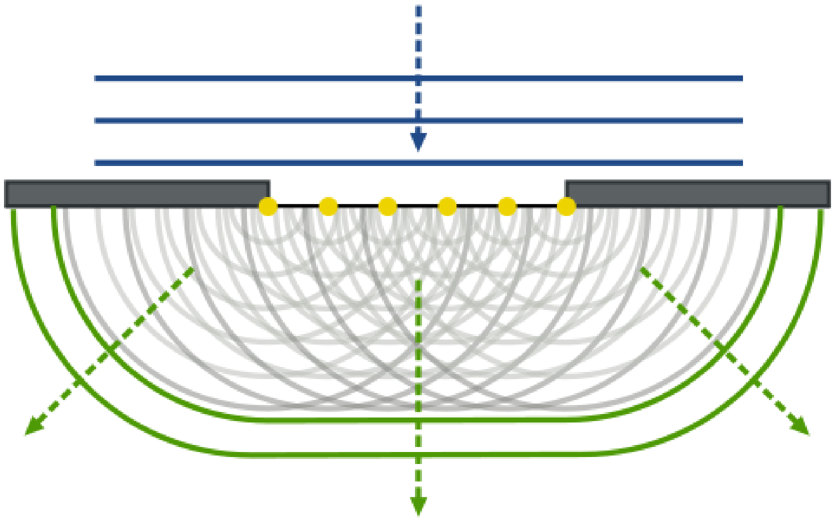
Wave focusing of sunlight



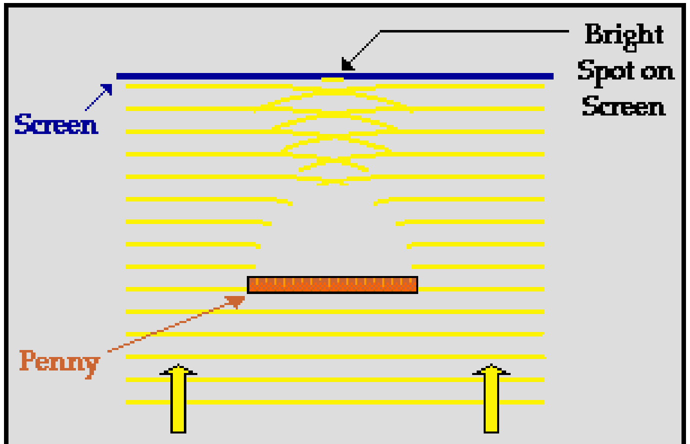
Dispersion


θ(i)
Wavelength
40°
Incident Angle - θ(i)
358x350
Refracted Angle - θ(r)
Varies From
28.51° To 28.82°
White Light
Monochromatic
Choose A Material (RI)
Water 1.3330

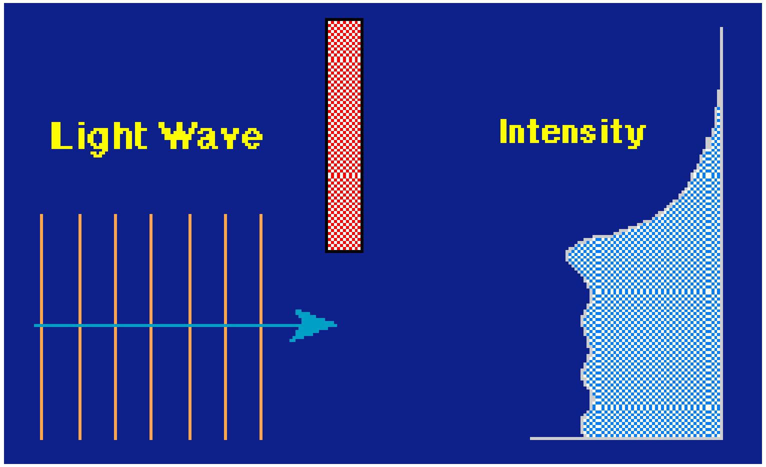
Diffraction



Augustin-Jean Fresnel
(1788 - 1827)



The diffraction of light around a penny and its ultimate interference upon a screen produces a pattern which could only be observed if light is a wave.



The intensity of light behind the barrier is not zero in the shadow region due to diffraction (light wave has a capability to “bend around corners”)

Light and matter

Emission - birth of a photon

Absorption - death of a photon

Scattering - life of a photon

Emission of Light

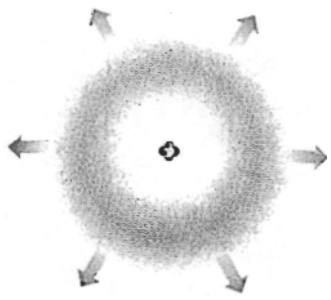
Thermal radiation

light emission is related to the temperature of an object with all molecules, atoms, and subatomic particles involved in thermal motion

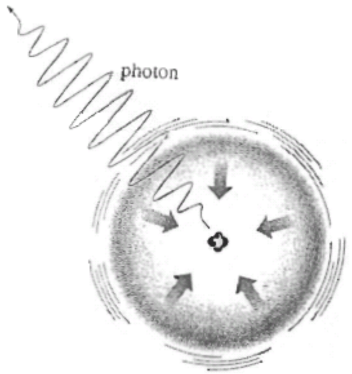
Luminescence

light emission is related to the specific changes in the energy levels of specific molecules

Energy changes within atoms



Excitation of the ground state



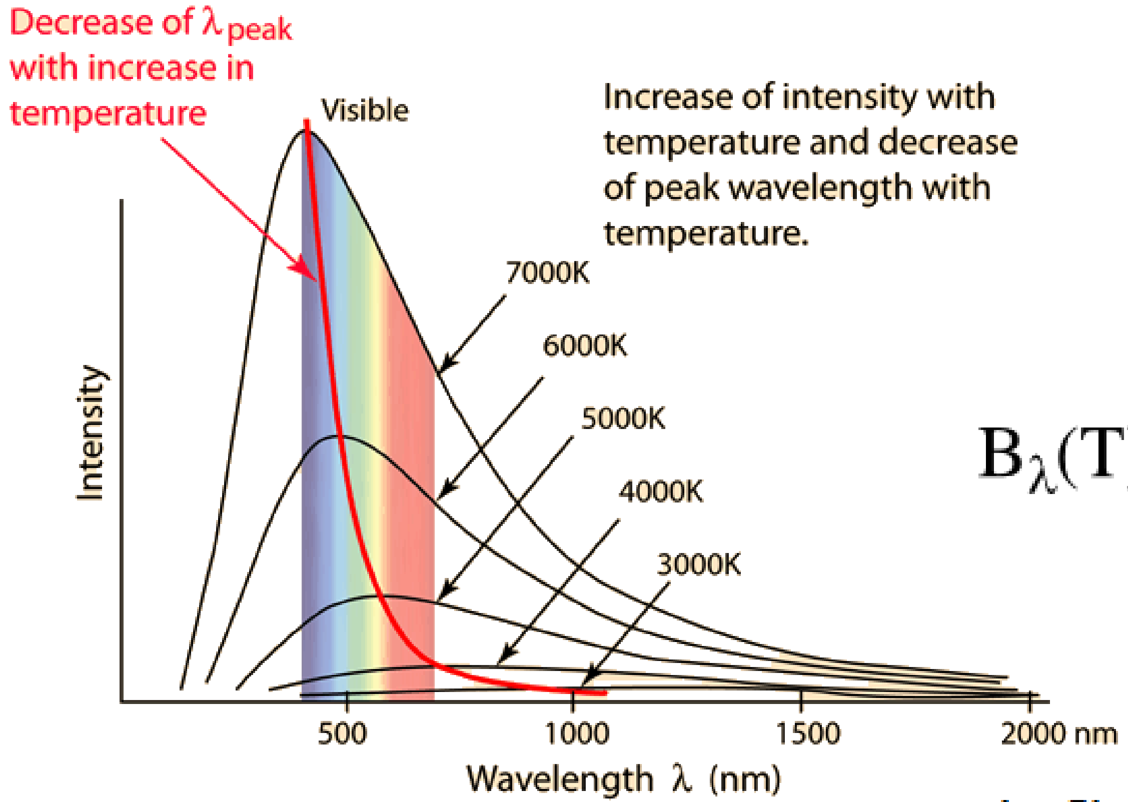
De-excitation with emission of a photon

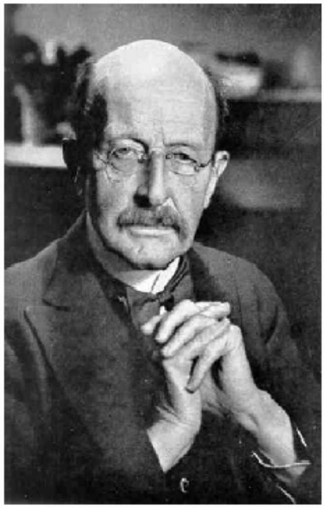
Ground state ~10^{-9} - 10^{-8} sec later

Hecht 1994

Planck Radiation Law

This law governs the intensity of radiation emitted by unit surface area into a fixed direction (solid angle) from the blackbody as a function of wavelength for a fixed temperature.





Max Planck (1858 - 1947)
Nobel Prize 1918

$$B_\lambda(T) = \frac{2hc^2}{\lambda^5} \frac{1}{e^{\frac{hc}{\lambda k_B T}} - 1}$$

h = Planck's constant = $6.626 * 10^{-34}\ J*s$
c = speed of light = $2.997925 * 10^8\ m/sec$
λ = wavelength (m)
k = Boltzmann's constant = $1.381 * 10^{-23}\ J/K$
T = temperature (K)

Stefan-Boltzmann Law

The Stefan-Boltzmann law states that a blackbody emits electromagnetic radiation with a total energy flux *E* proportional to the fourth power of the Kelvin temperature *T* of the object

Joseph Stefan
(1835 - 1893)

$$E = \sigma T^4$$

where σ (sigma) = $5.67 \times 10^{-8}\ \mathrm{Wm^{-2}\ K^{-4}}$

and T is the temperature in Kelvin

Ludvig Boltzmann
(1844 - 1906)

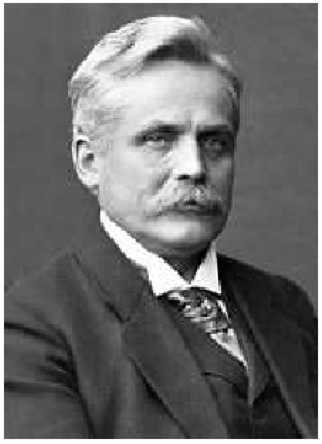
Wien's Displacement Law

Wien's displacement law states that dominant wavelength at which a blackbody emits electromagnetic radiation is inversely proportional to the Kelvin temperature of the object

$$\lambda_{max} = \frac{0.0029 \text{ K m}}{T}$$

λ_{max} = wavelength of maximum emission of the object (in meters)

T = temperature of the object (in kelvins)

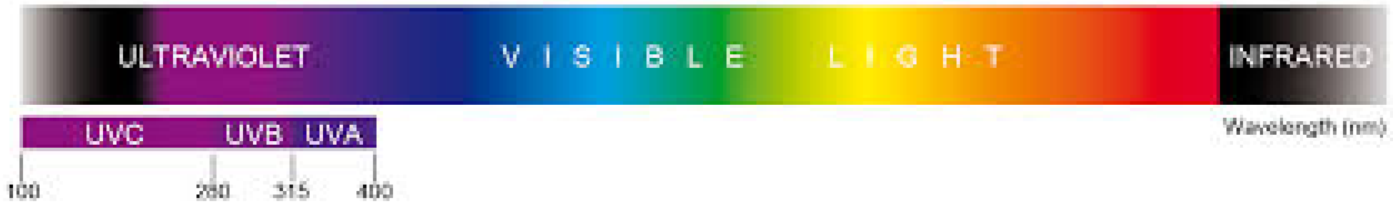


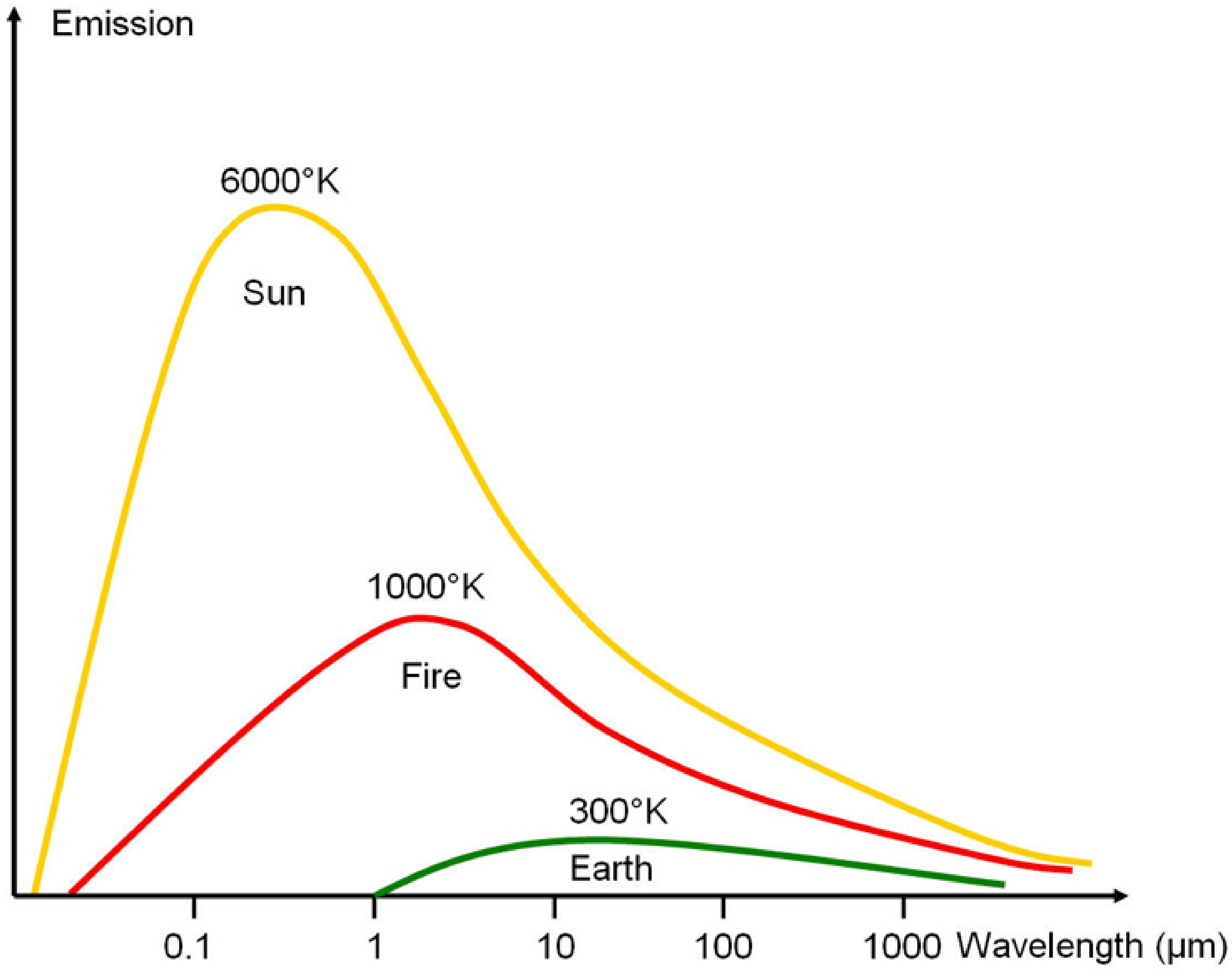
Wilhelm Wien (1864 - 1928)
Nobel Prize 1911

For example

- The Sun, λ_{max} = 500 nm → T = 5800 K
- Human body at 37 degrees Celsius or 310 Kelvin → λ_{max} = 9.35 μm = 9350 nm

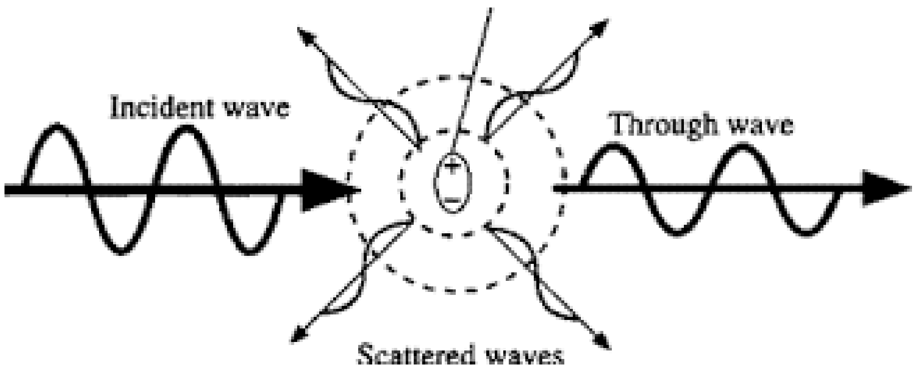
Ocean optics is concerned primarily with the study of visible light, more specifically the relatively narrow range of electromagnetic spectrum from near-UV through visible to near-IR

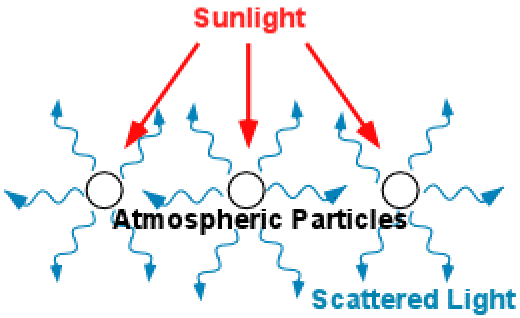



Emission
6000°K
Sun
1000°K
Fire
300°K
Earth
0.1
1
10
100
1000
Wavelength (μm)

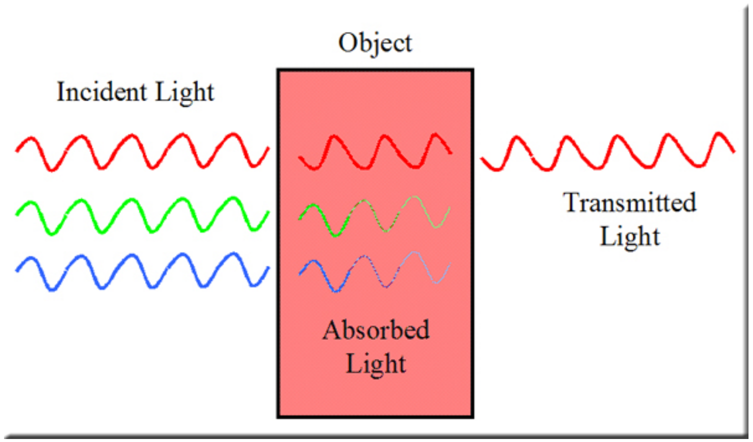
Interaction of Light and Matter

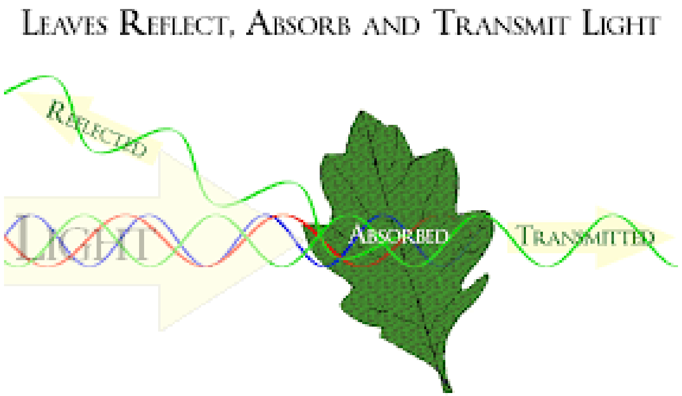
Scattering (life of photon) – change of direction of propagation

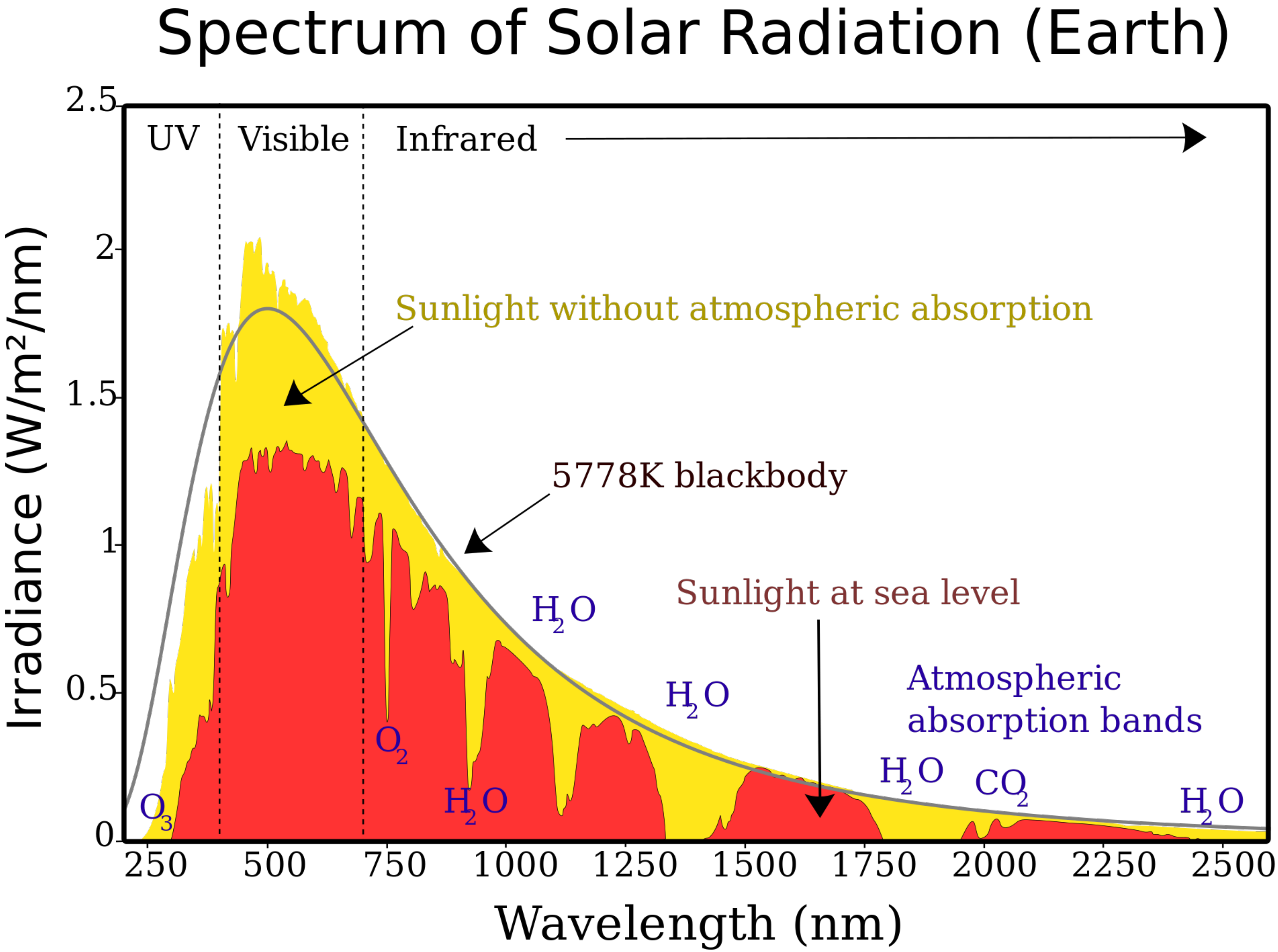




Absorption (death of photon) – transfer of energy to matter

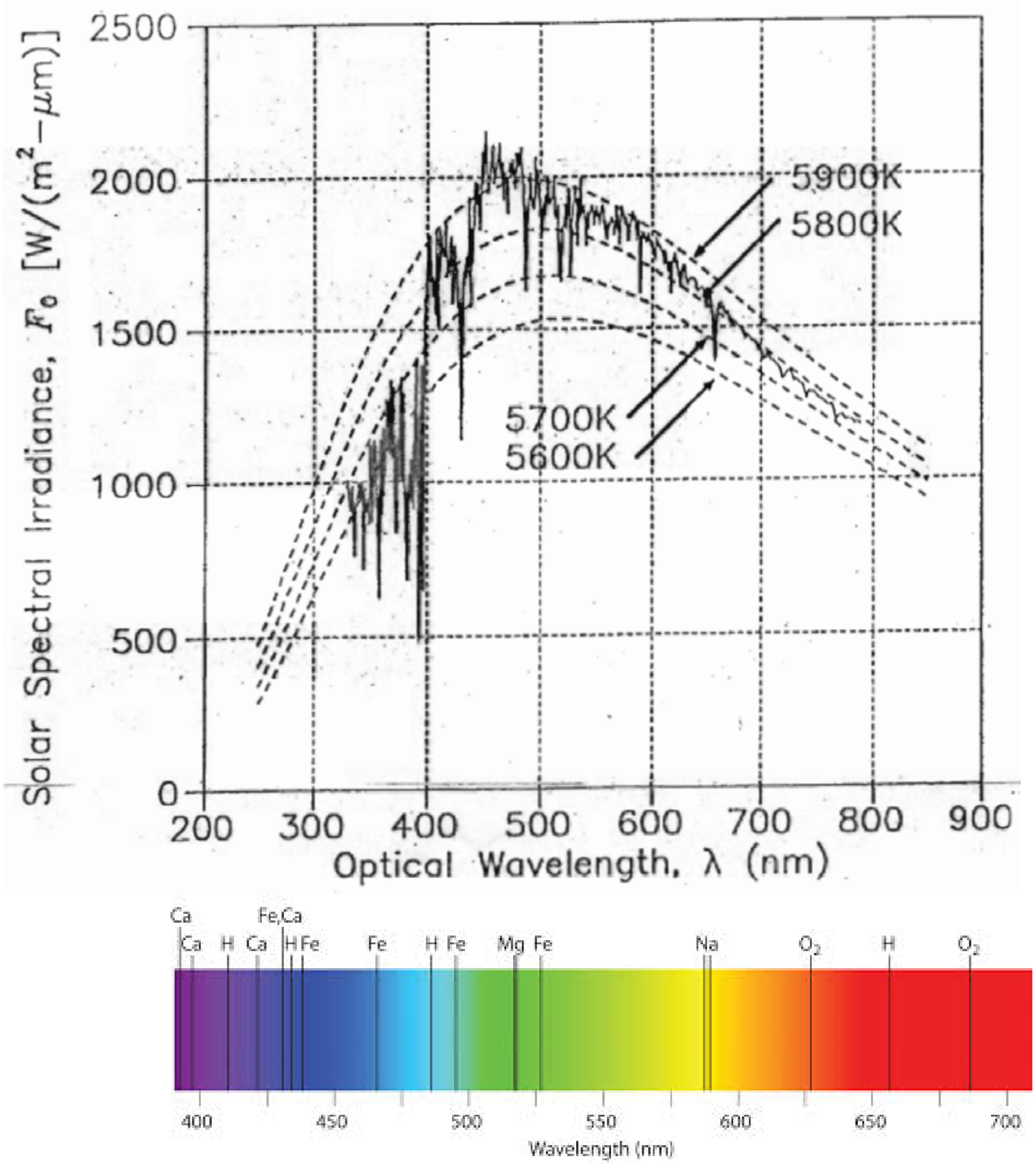






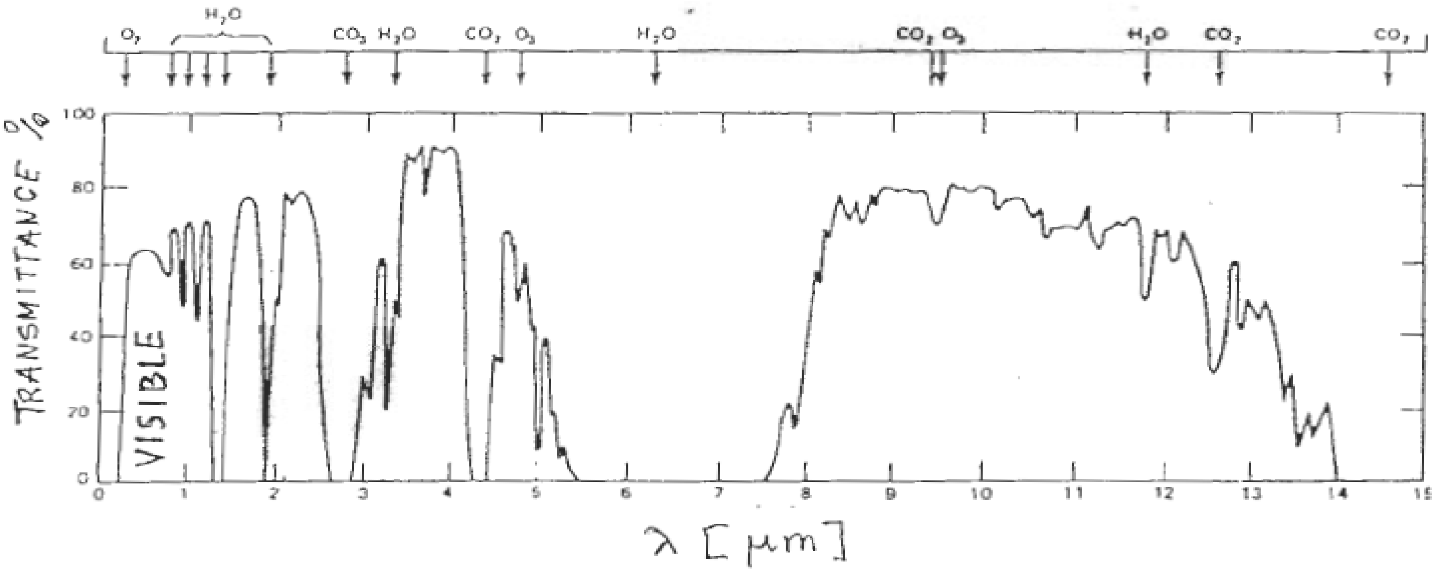
Spectrum of Solar Radiation (Earth)
UV
Visible
Infrared
Sunlight without atmospheric absorption
5778K blackbody
Sunlight at sea level
Atmospheric absorption bands
O_3
O_2
H_2O
H_2O
H_2O
H_2O
H_2O
CO_2
H_2O
Irradiance ($W/m^2/nm$)
2.5
2
1.5
1
0.5
0
250
500
750
1000
1250
1500
1750
2000
2250
2500
Wavelength (nm)

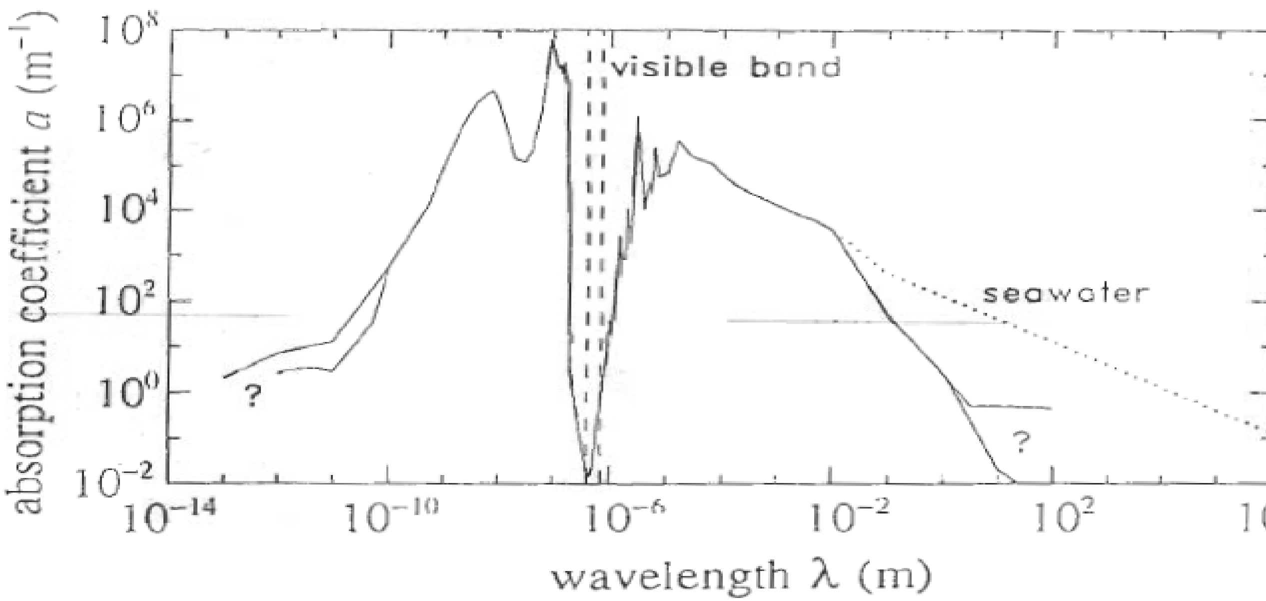
Solar spectral irradiance outside the Earths's atmosphere



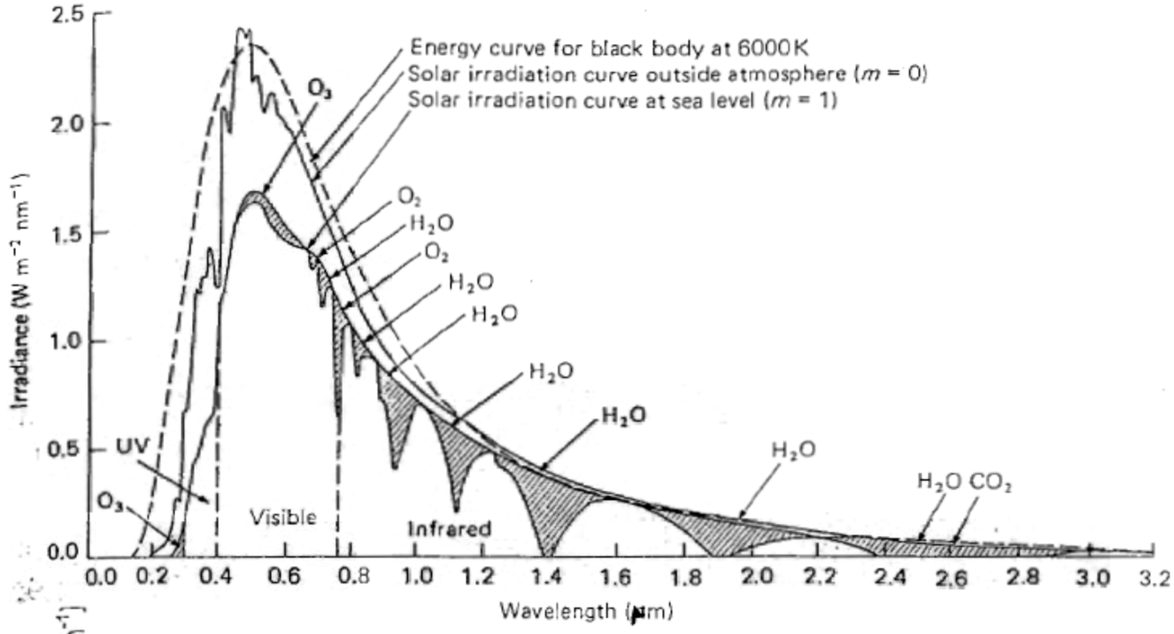
Walker 1994

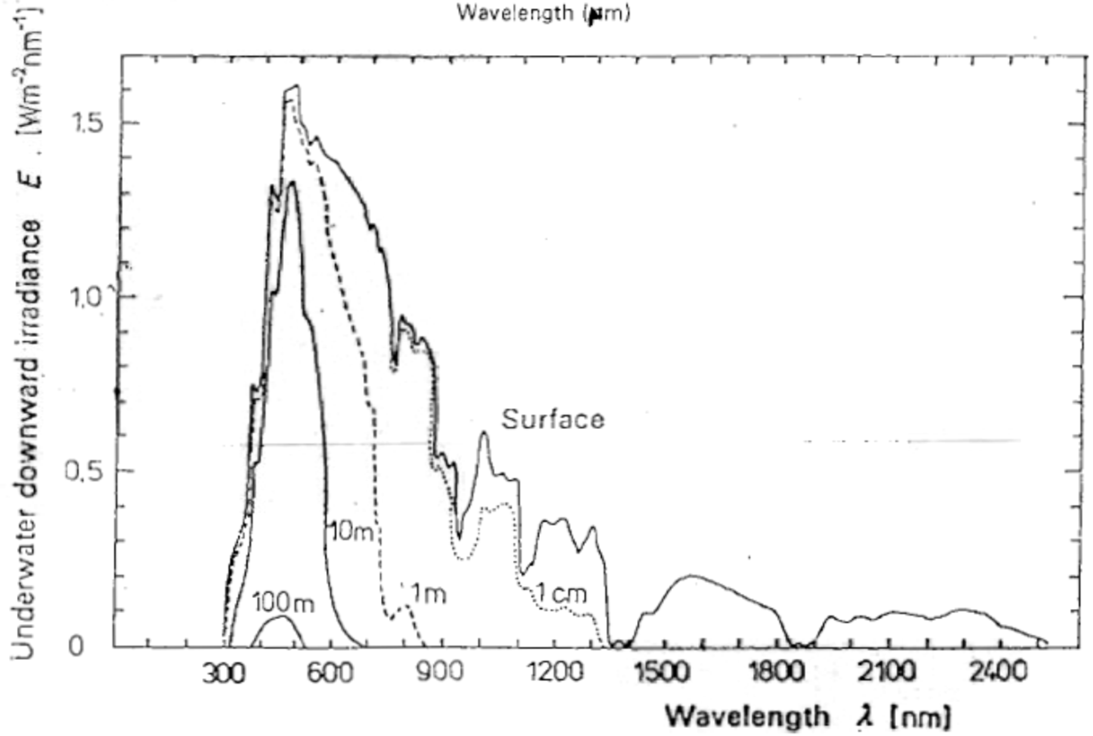
Overlap of "window" in atmospheric transmittance with minimum of water absorption in the visible band.





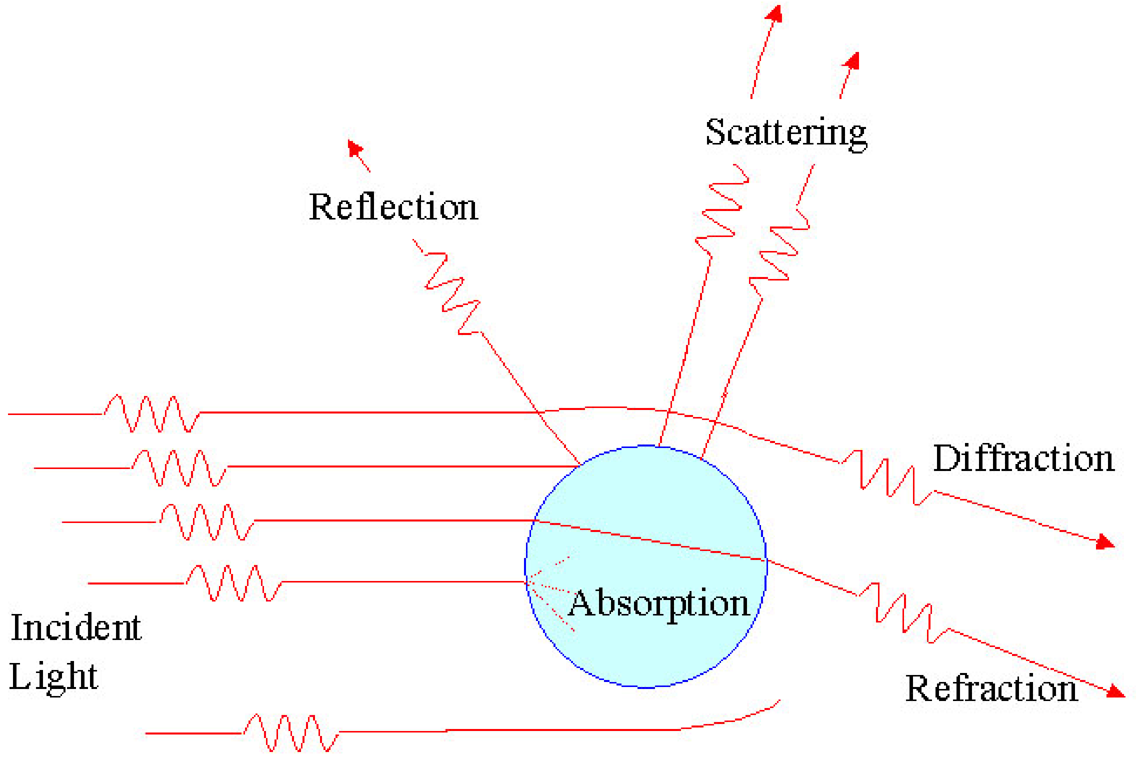
Spectra of Solar Irradiance





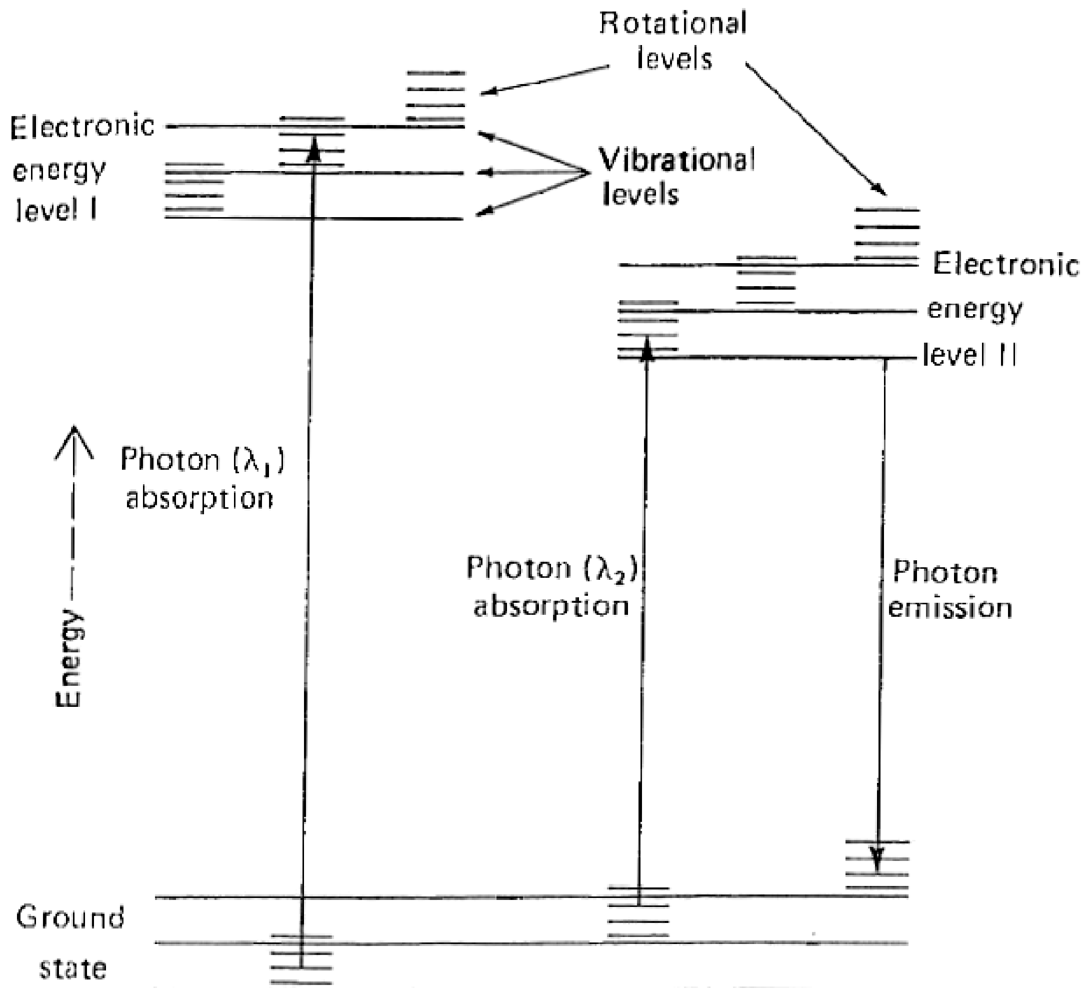
Interaction of light and matter

Scattering - life of photon



Absorption - death of photon

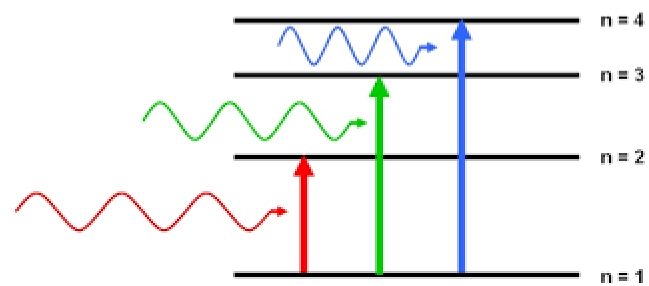
Energy levels of molecule: Mechanism of light absorption



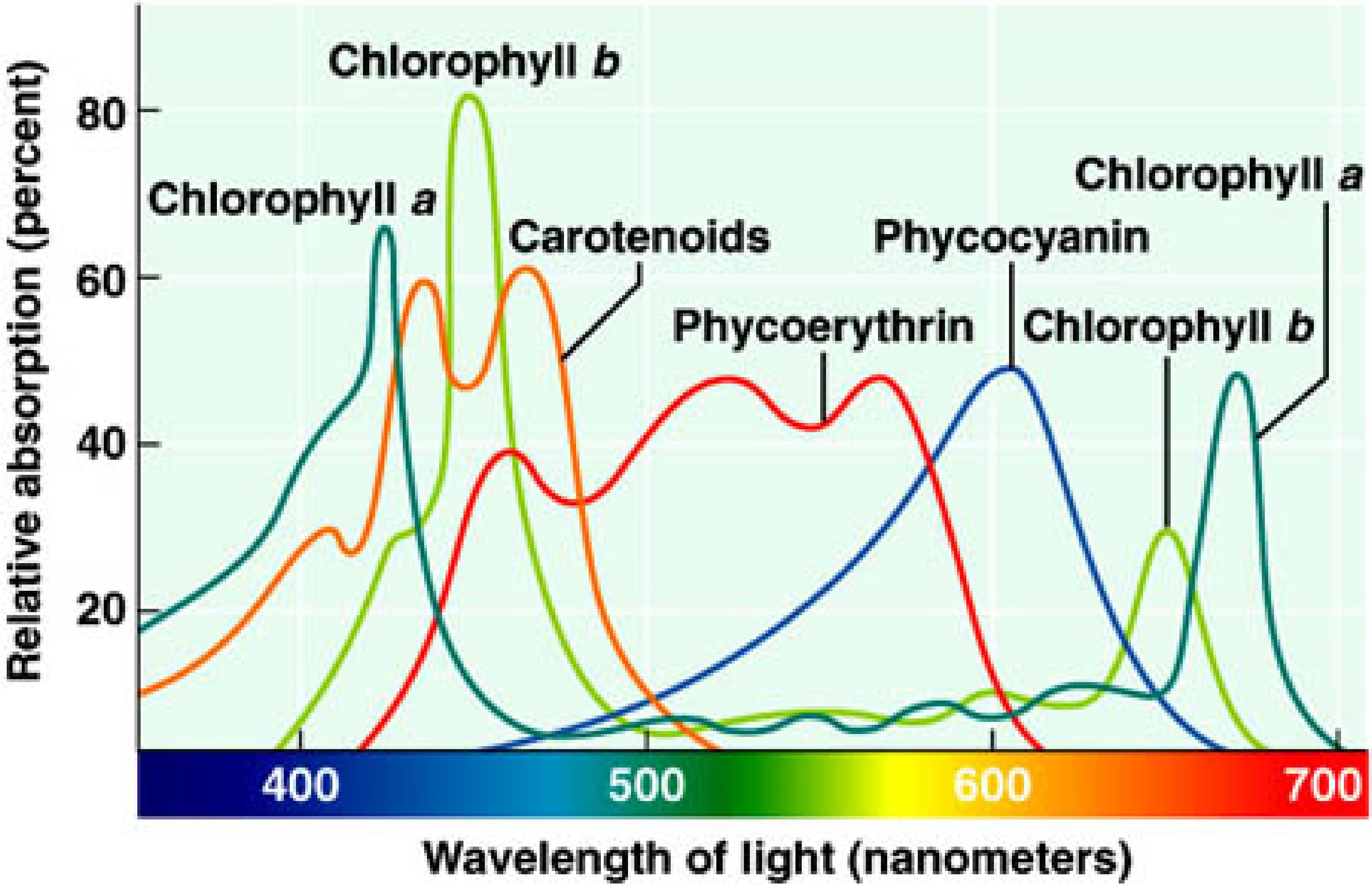
Electronic:
energy ~400 kJ/mol
λ ~100 – 1000 nm

Vibrational:
energy ~4 – 40 kJ/mol
λ ~1 – 20 μm

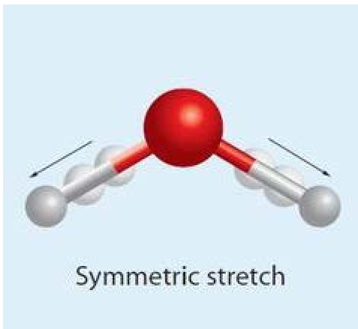
Rotational:
energy ~10^{-2} – 10^{-3} kJ/mol
λ > 20 μm

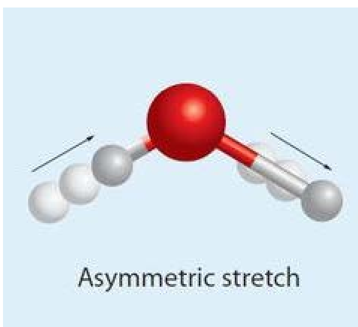


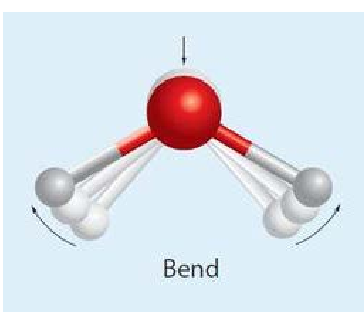
Absorption spectra of plant pigments

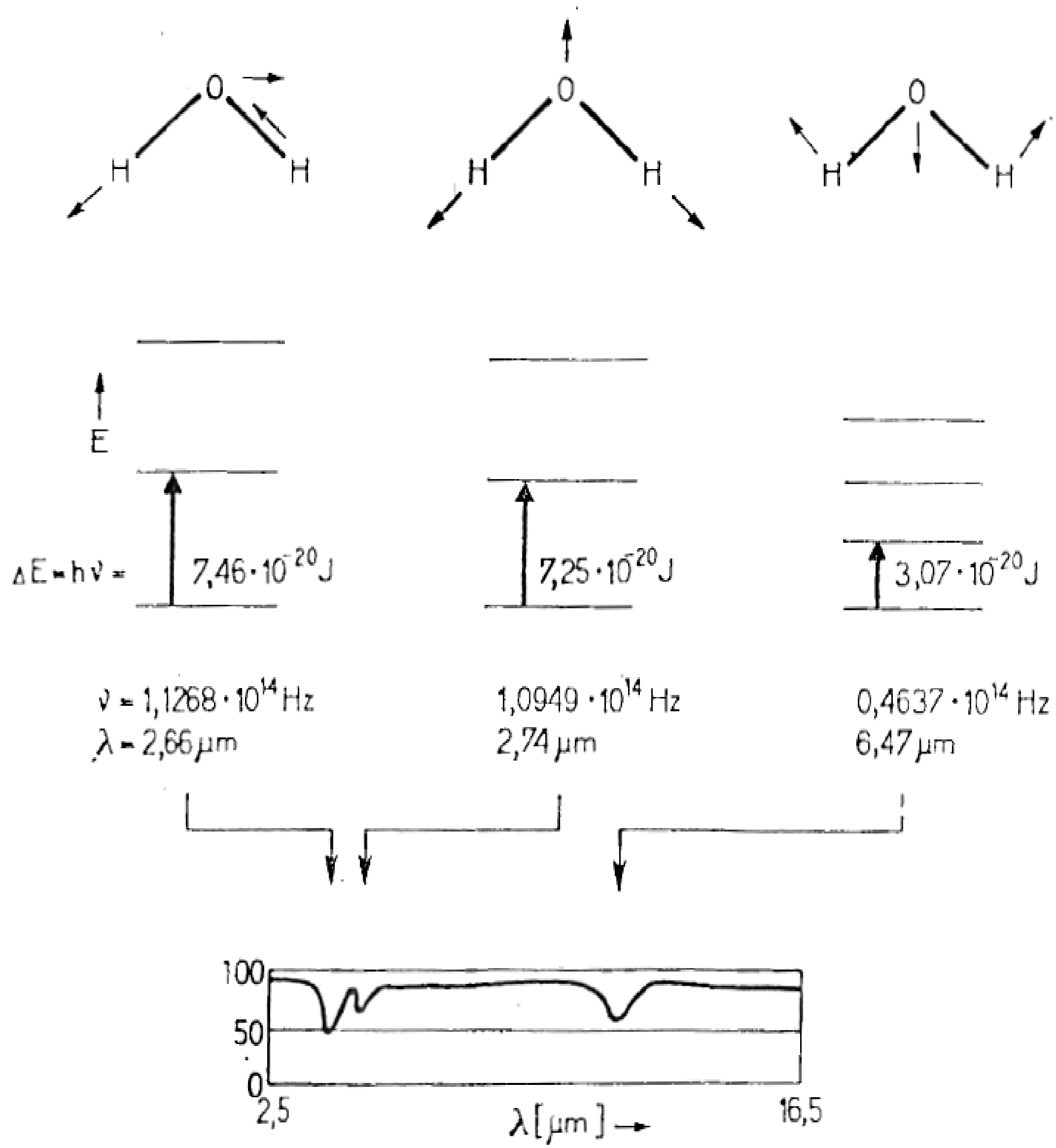


Absorption mechanism associated with water molecule vibrations

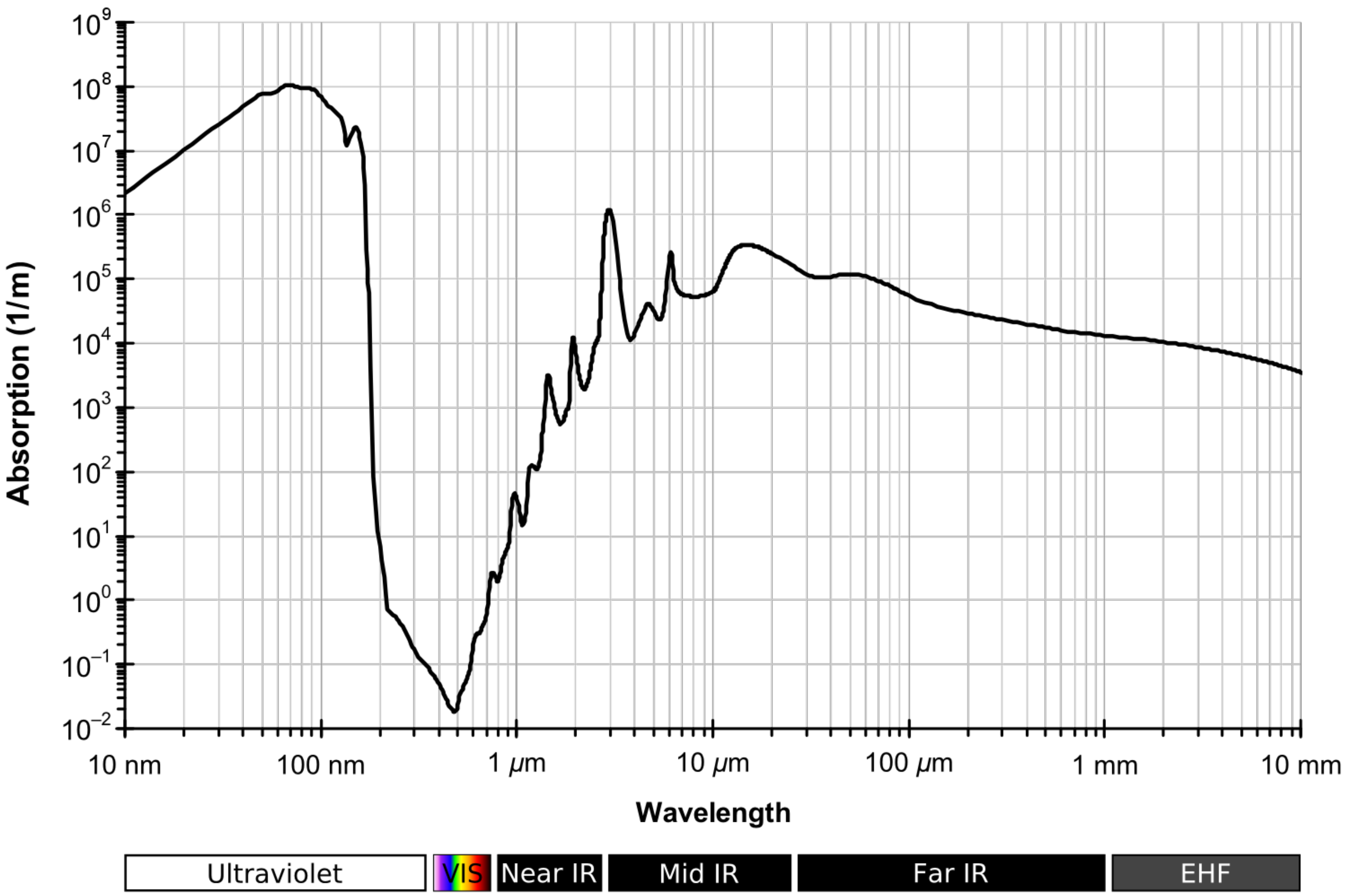




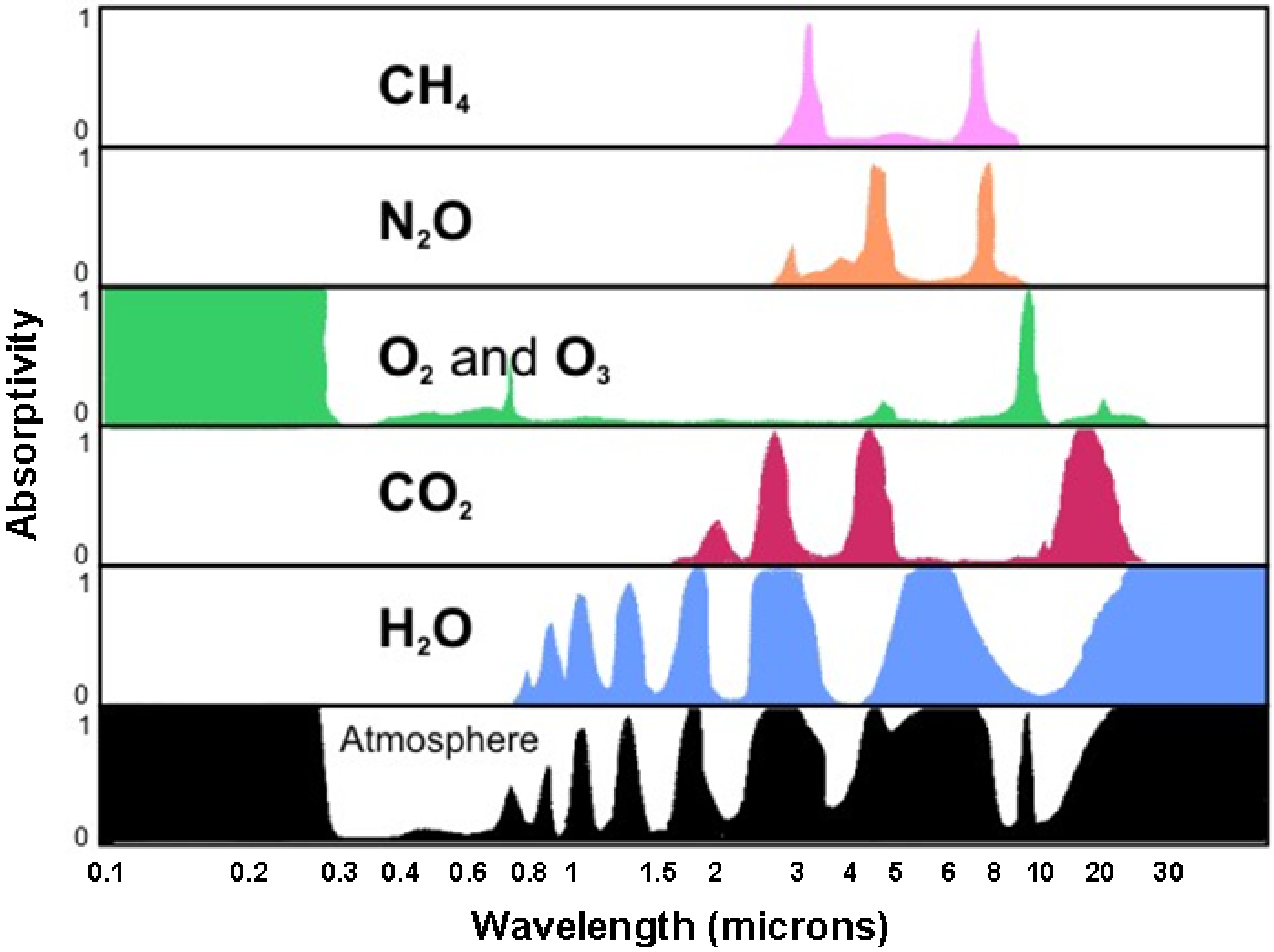




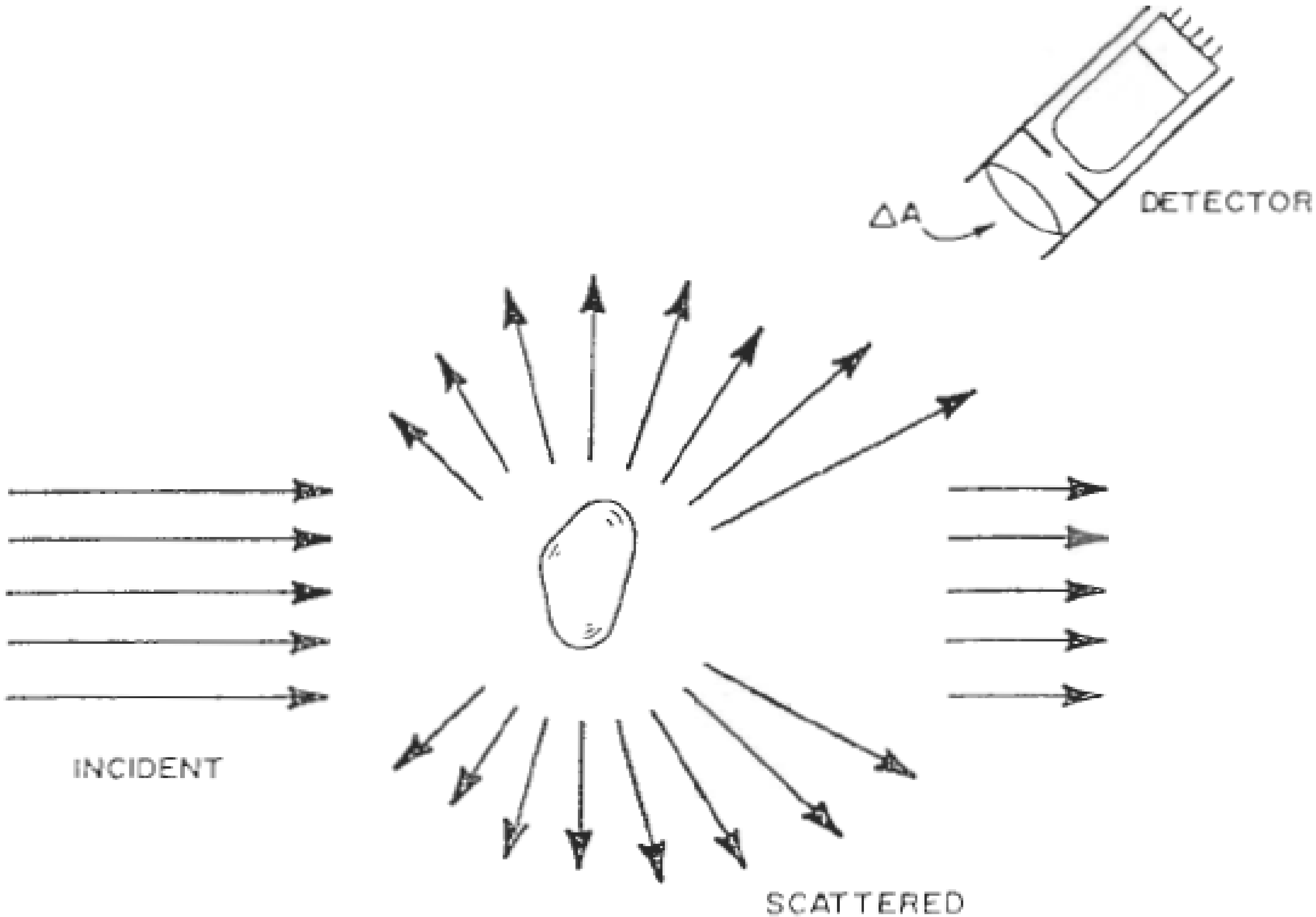
Absorption spectrum of water molecules



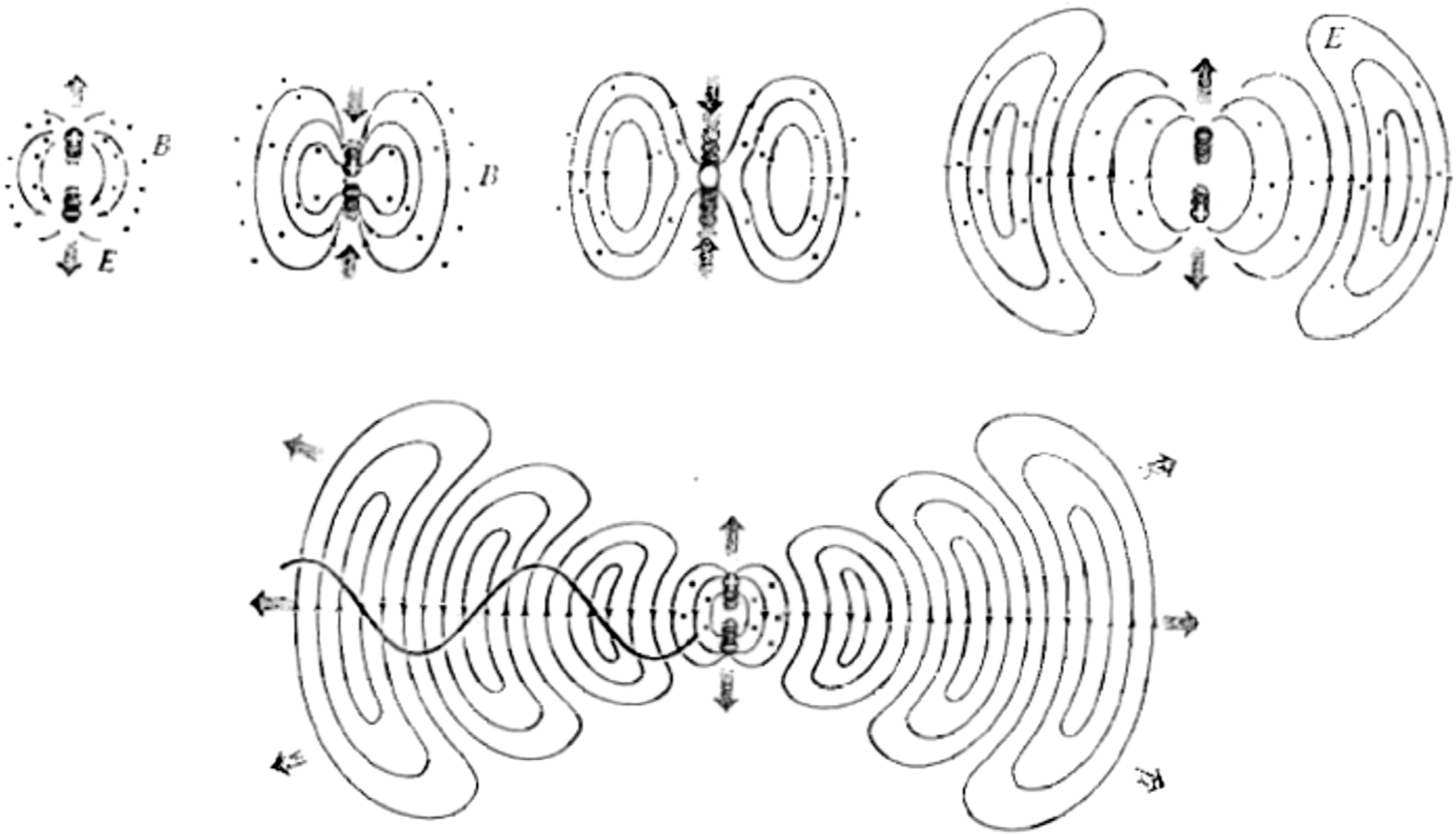
Absorption spectra of atmospheric molecules



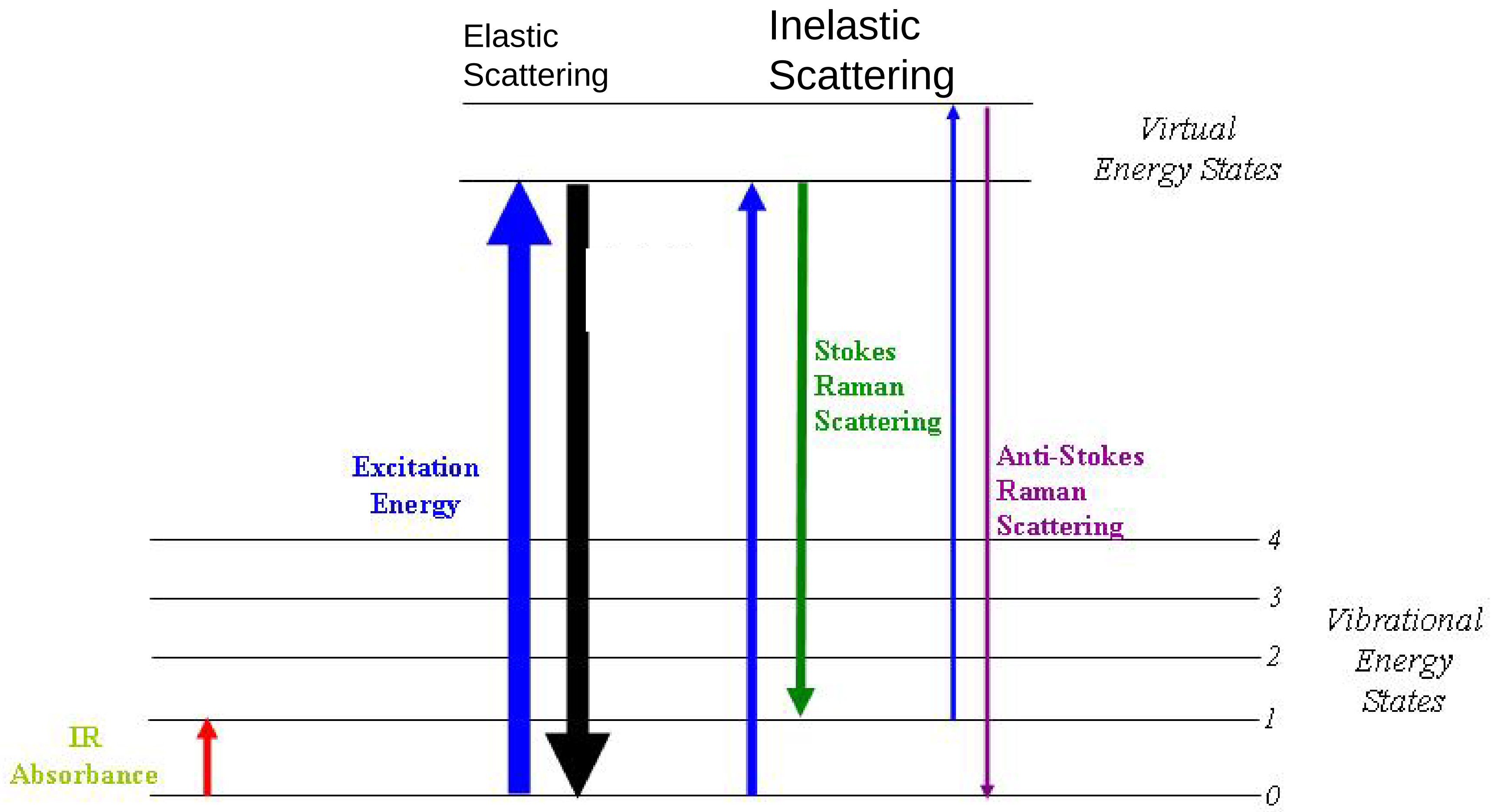
Scattering of light by inhomogeneity of the medium



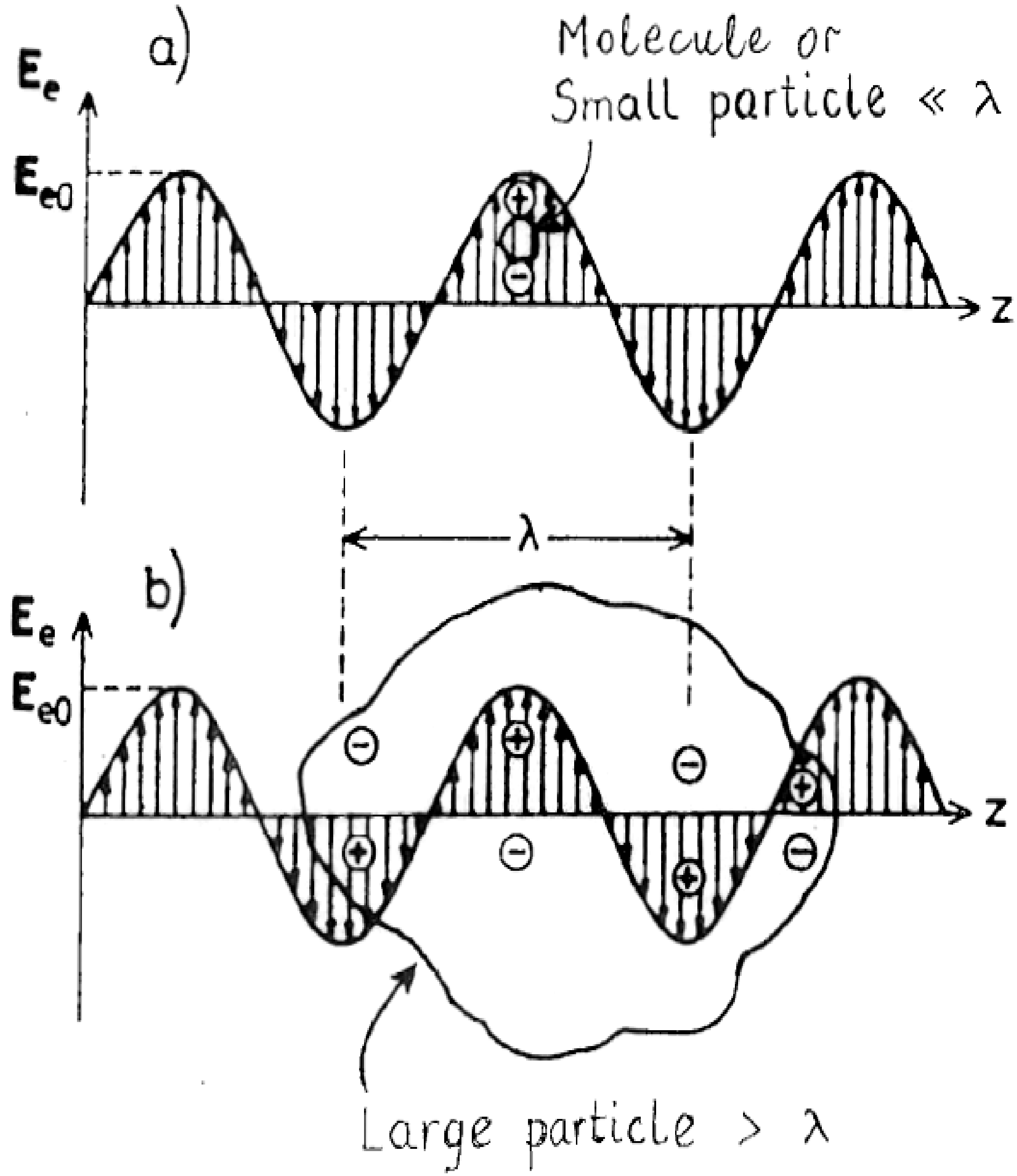
Electromagnetic radiation of an oscillating dipole:
Mechanism of light scattering



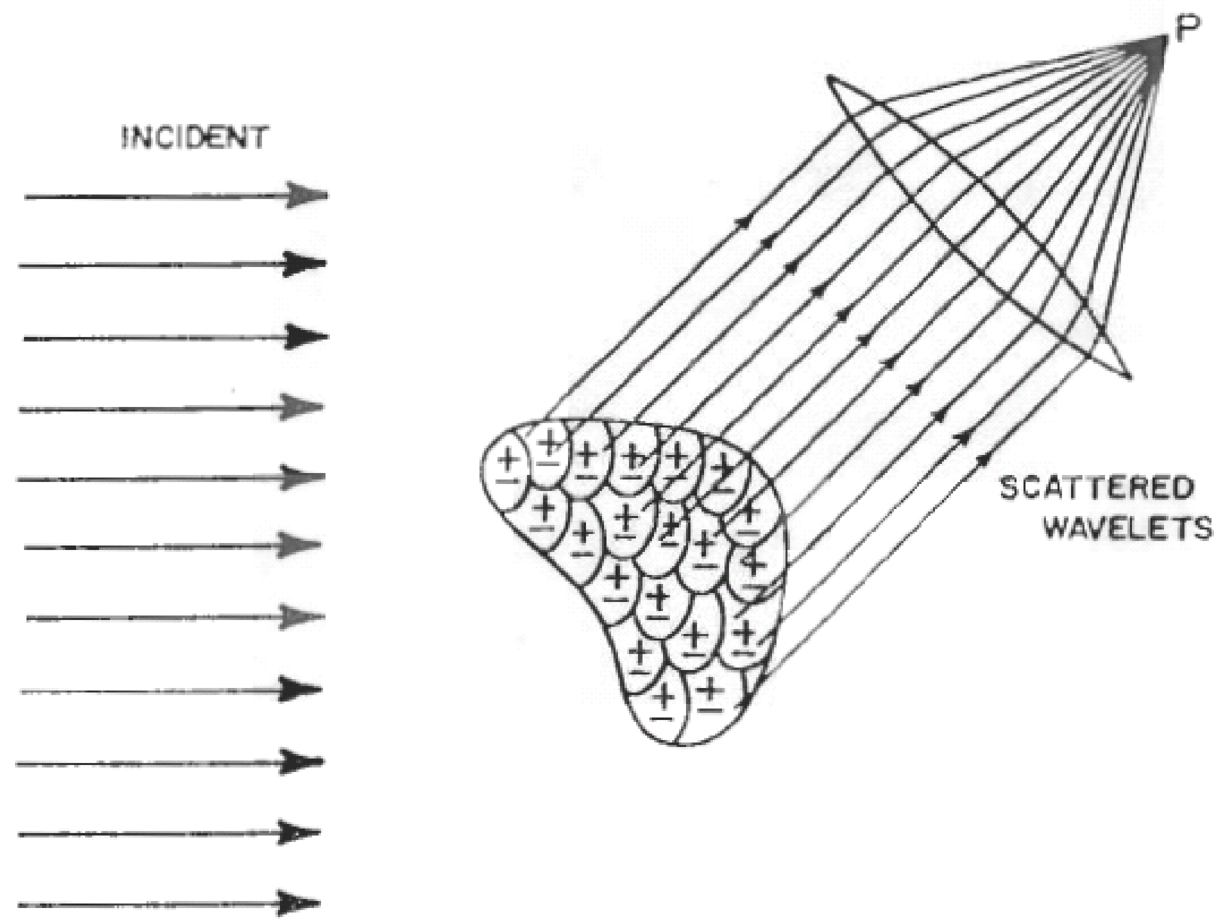
Elastic and inelastic scattering



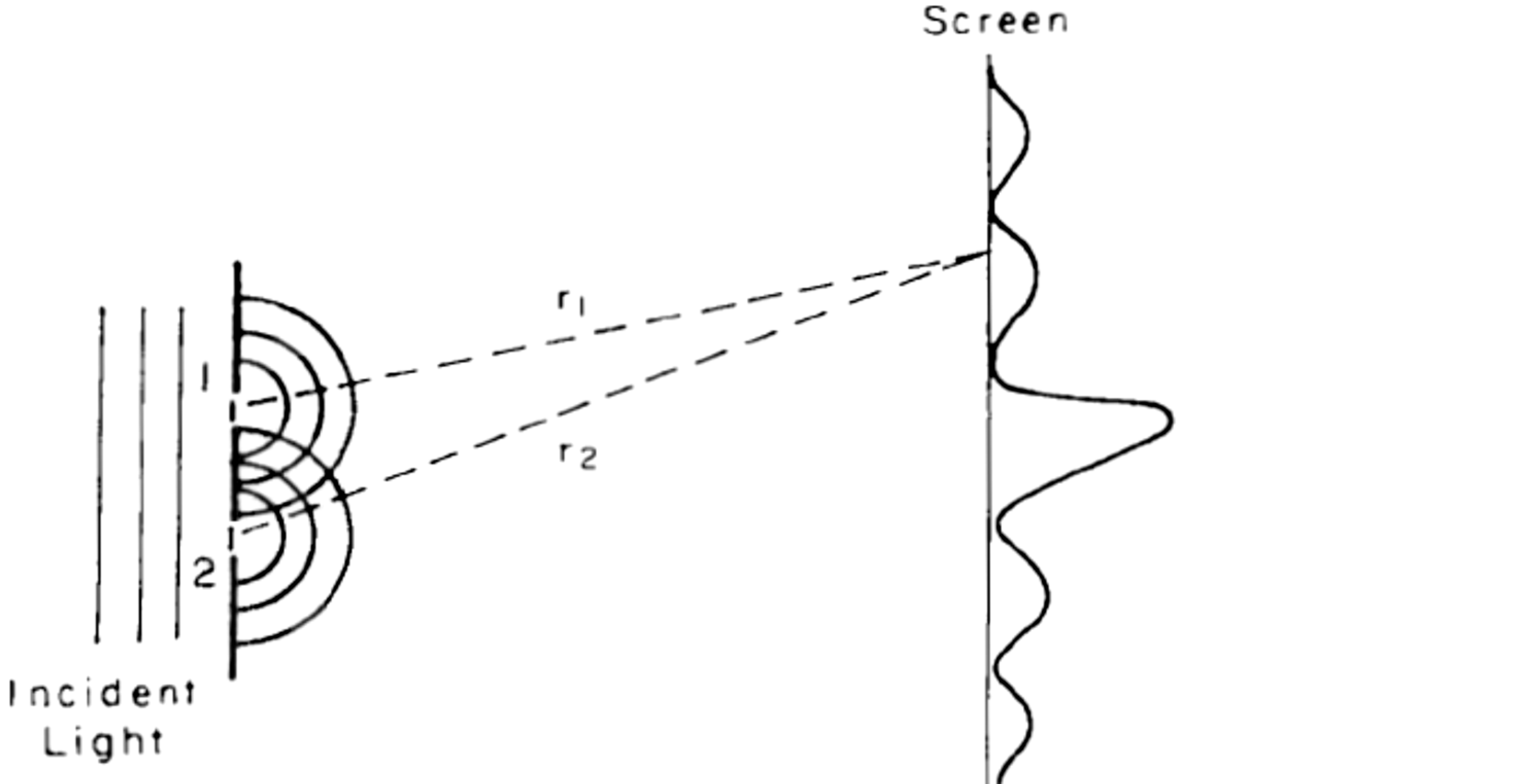
Small and large particle in the electric field of the electromagnetic wave



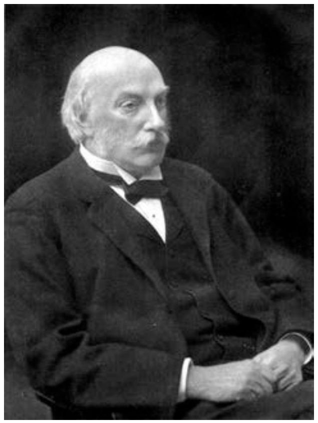
A single particle subdivided into oscillating dipoles



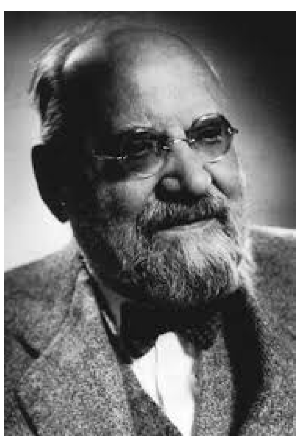
The interference pattern produced by two slits



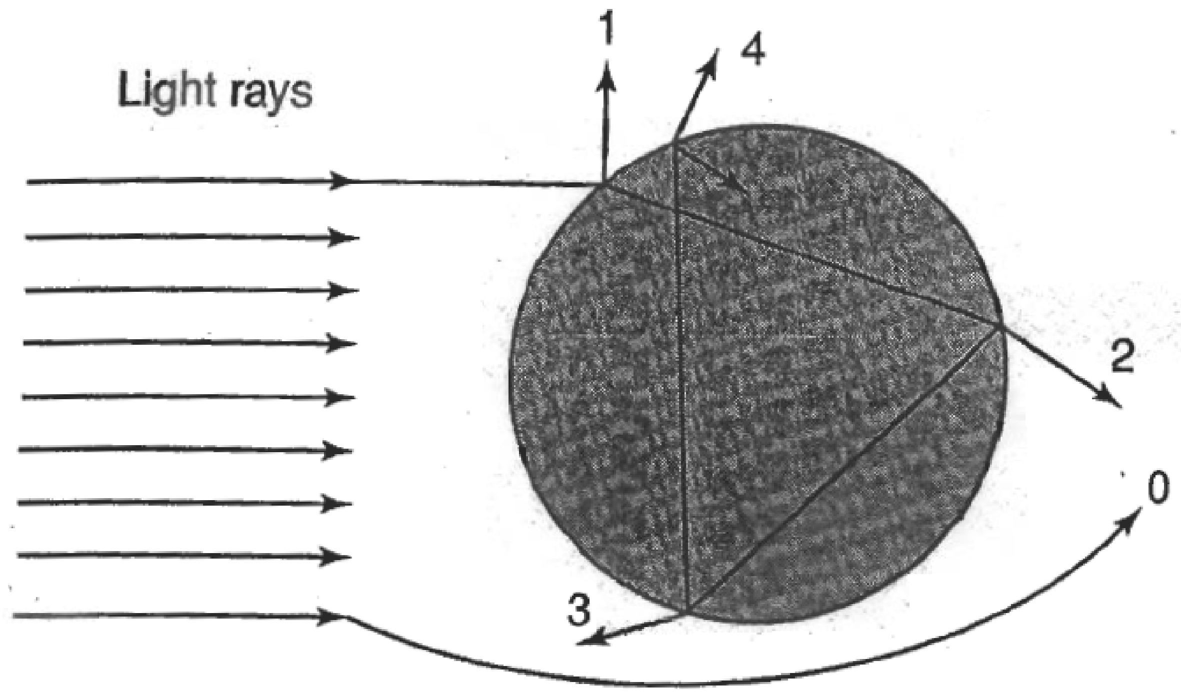
Computations of light scattering: From Rayleigh and Mie theory to geometric ray tracing



John William Strutt
Lord Rayleigh (1842 - 1919)
Nobel Prize 1904



Gustav Mie (1868 - 1957)



0 Exterior Diffraction

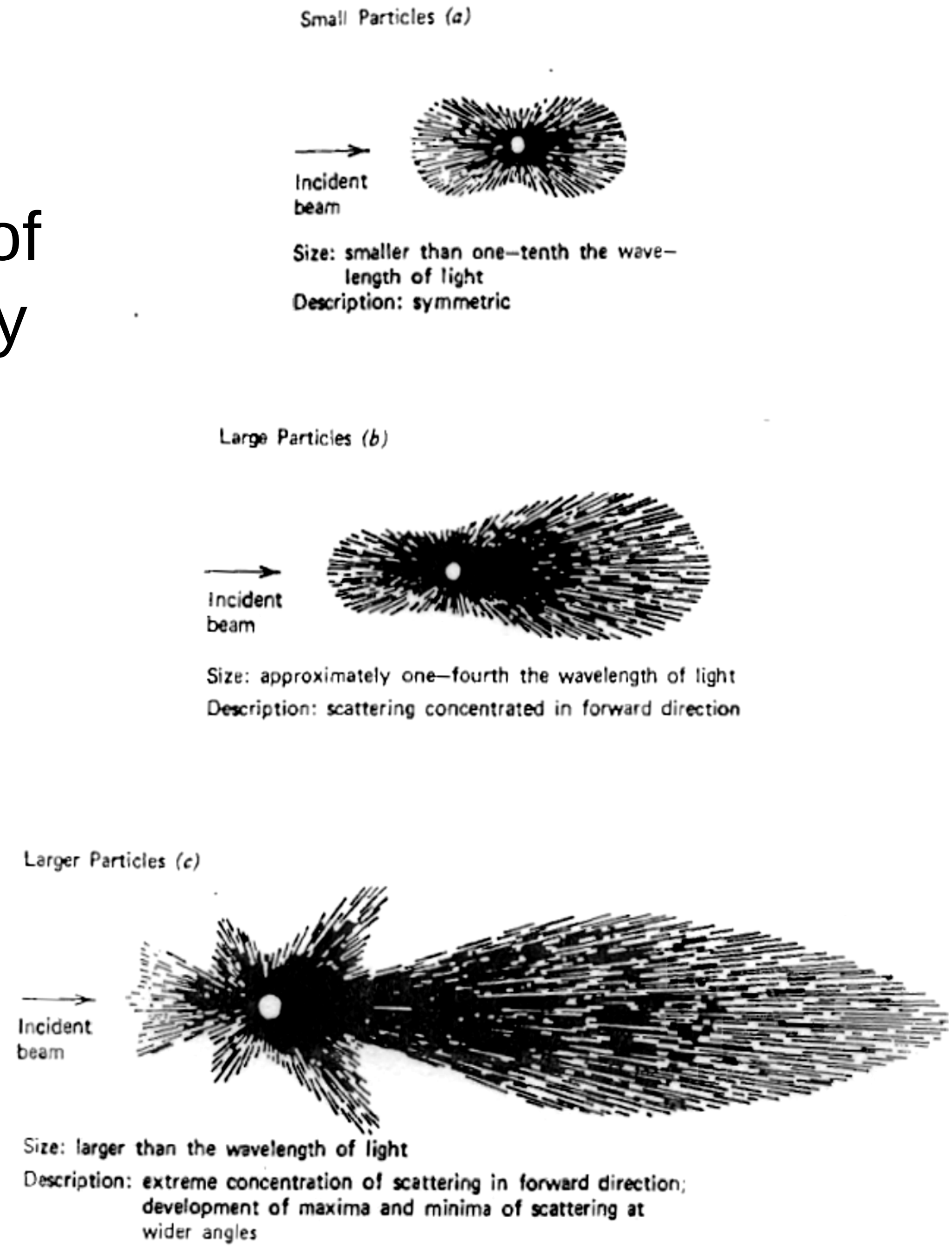
1 External Reflection

2 Two Refractions

3 One Internal Reflection

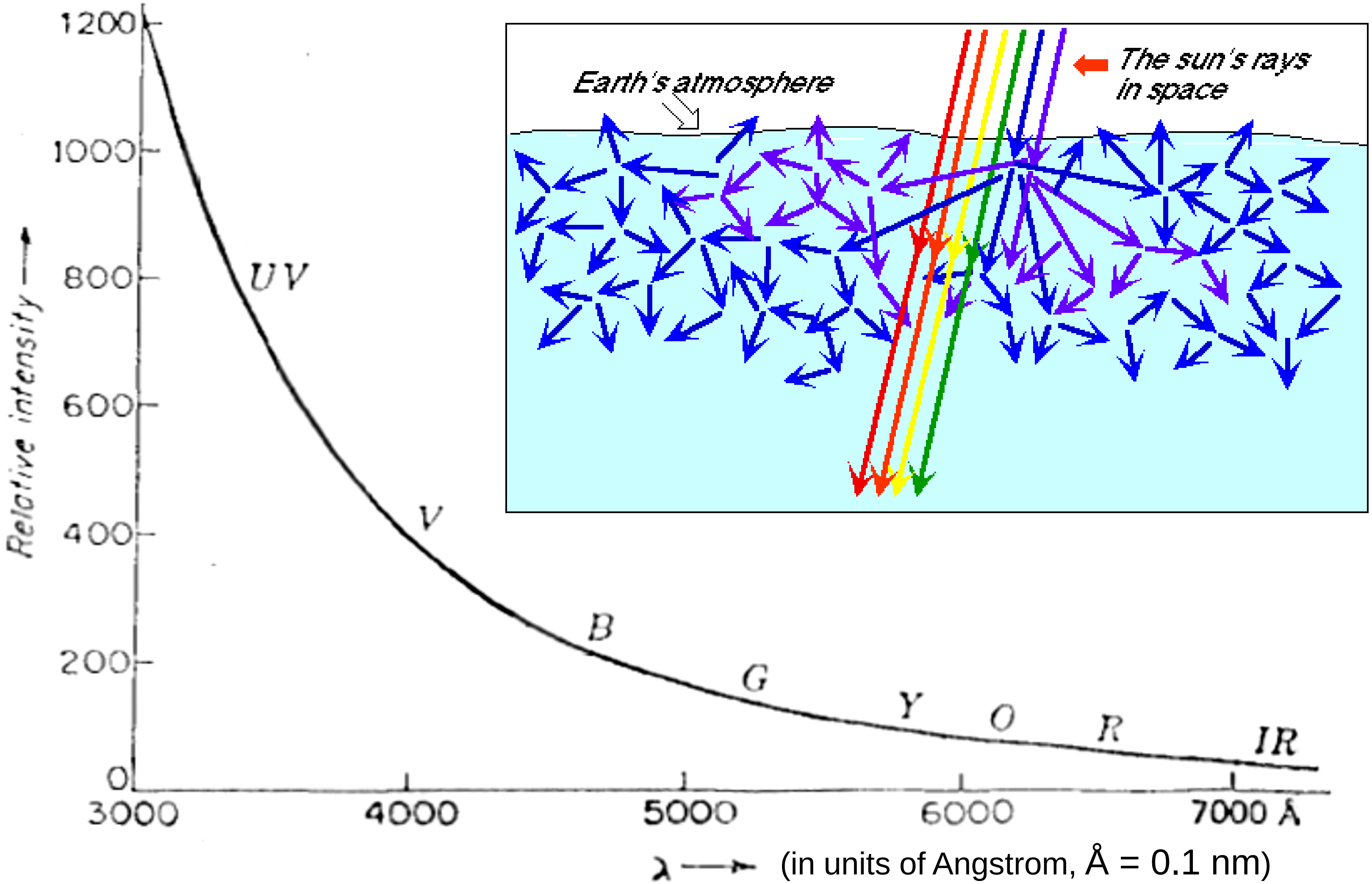
4 Two Internal Reflections

Angular patterns of scattered intensity from particles of different sizes



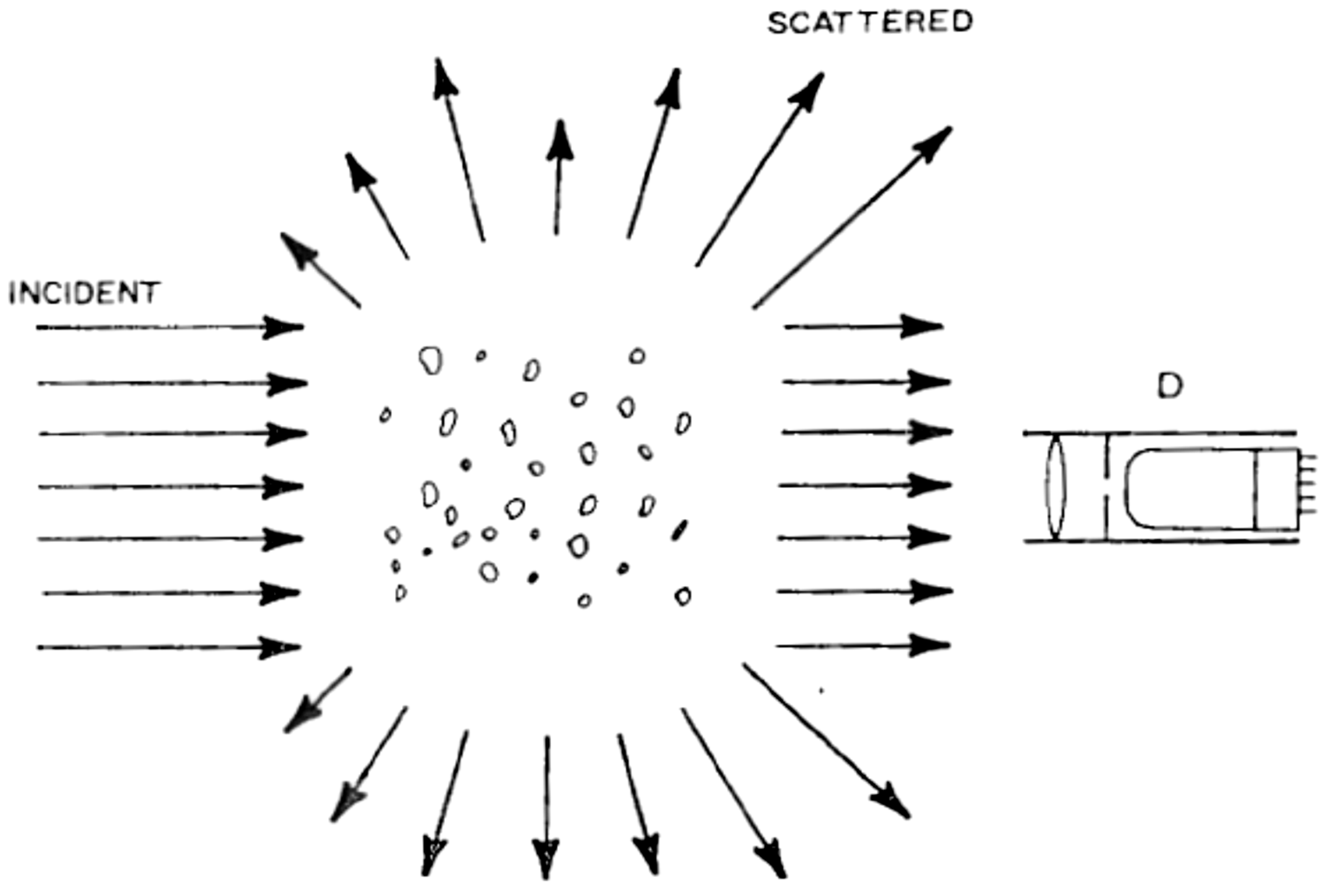
Molecular scattering as a function of light wavelength

Scattered Intensity ~ λ^{-4}



(in units of Angstrom, Å = 0.1 nm)

Scattering by a collection of particles



Multiple light scattering by a collection of particles

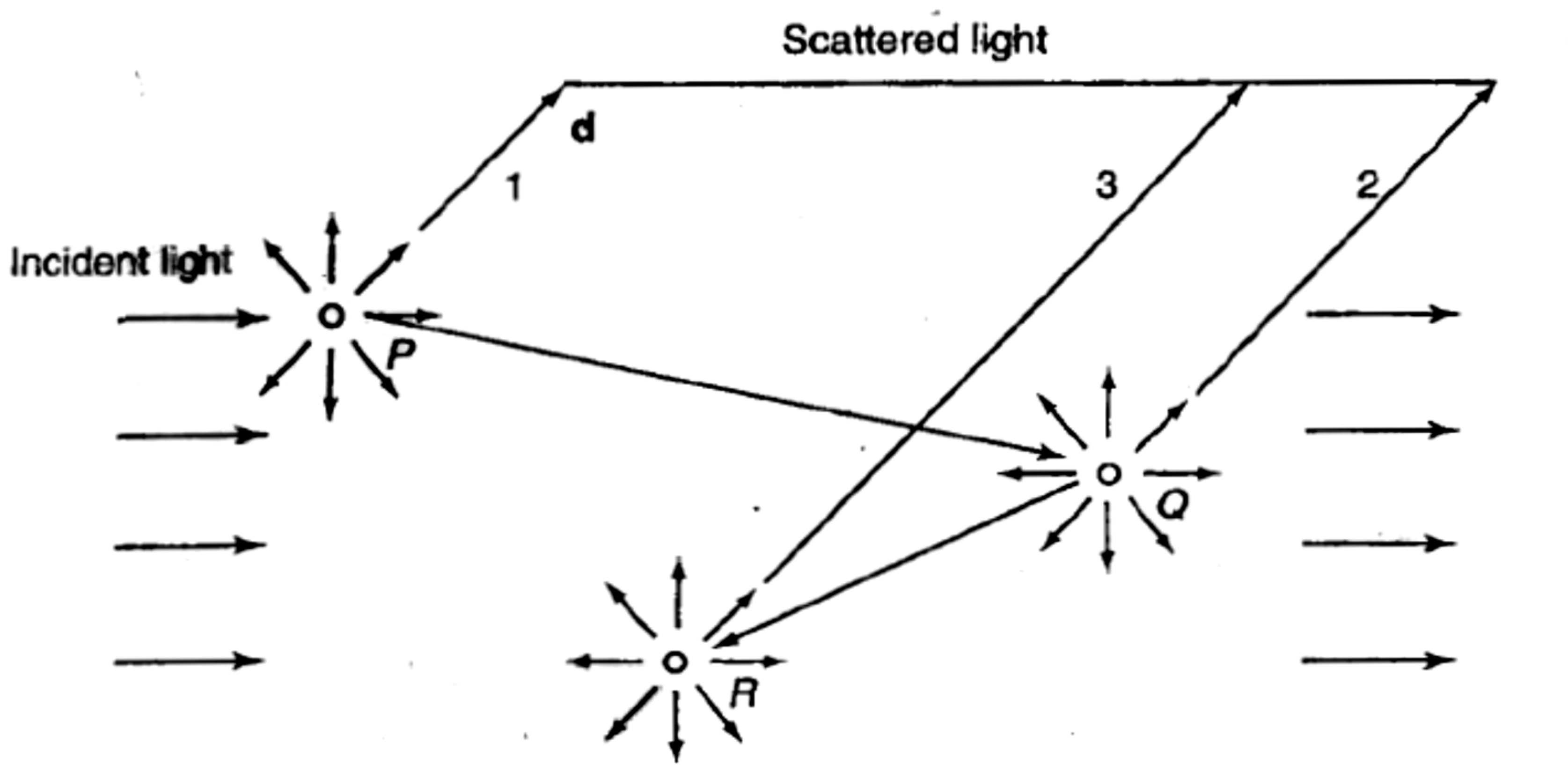


Figure 1.5 **Multiple scattering process involving** first (P), second (Q), and **third (R) order scattering in the direction denoted by d.**

(Liou 2002)