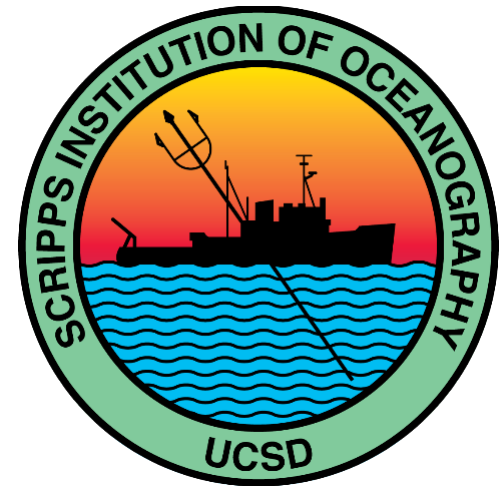


Interaction of Light and Matter

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IOCCG Summer Lecture Series
18 July - 29 July 2022, Villefranche-sur-Mer, France

Light and matter

Emission - birth of a photon

Absorption - death of a photon

Scattering - life of a photon

Emission of Light

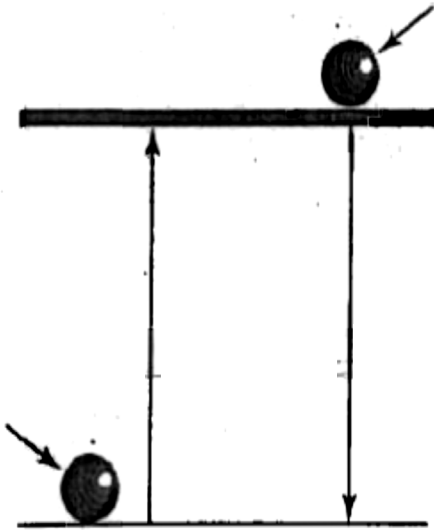
Thermal radiation

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

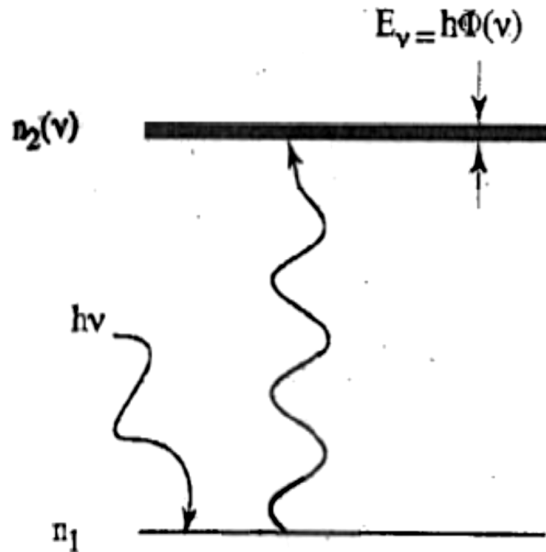
Luminescence

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

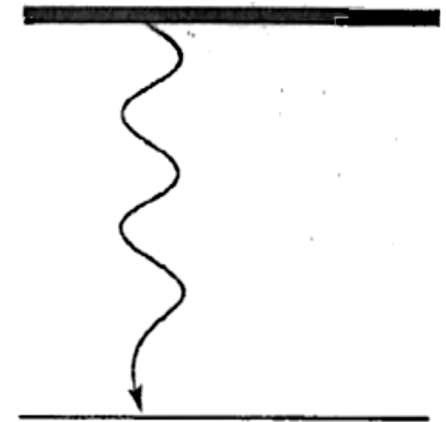
Collisional and radiative processes involved in the energy changes of a two level atom



Collisional
Excitation & Quenching



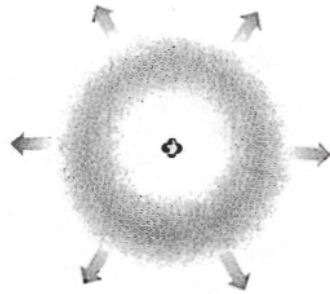
Radiative absorption



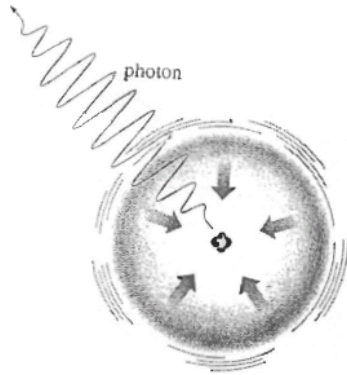
Emission
Spontaneous

(but can also be
stimulated, e.g.
by an incident
photon)

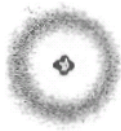
Light and Atoms



Excitation of the ground state



De-excitation with emission of a photon

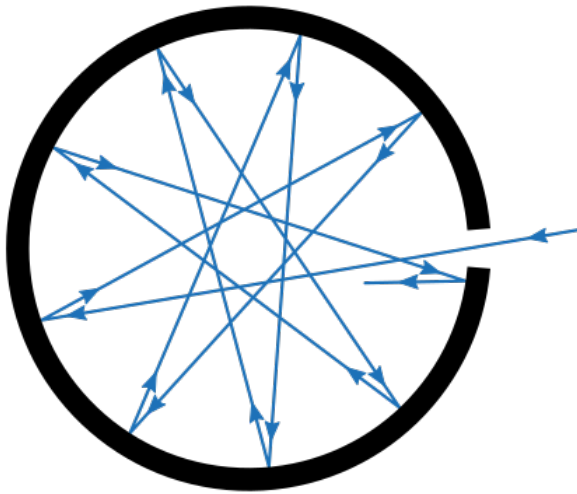


Ground state $\sim 10^{-9} - 10^{-8}$ sec later

A blackbody – a standard concept for thermal radiation

An idealized physical body that absorbs all incident electromagnetic radiation, regardless of frequency/wavelength or angle of incidence.

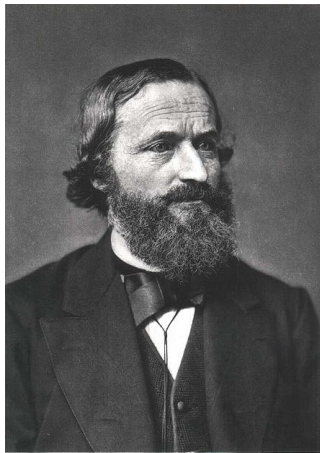
An approximate realization of a blackbody is a small hole in the wall of a large insulated chamber (or cavity) with walls that are opaque to the radiation.



All radiant energy entering the blackbody is absorbed at the internal surfaces. In reverse, an aperture of a heated blackbody (temperature $T > 0^\circ \text{ K}$) is a source of thermal radiation emitted by blackbody. For an ideal blackbody in thermal equilibrium (i.e., at a constant temperature T) the emitted energy equals the absorbed energy.

An ideal blackbody in thermal equilibrium has two notable properties:

- (1) It is an ideal emitter: at every frequency/wavelength, it emits as much or more thermal radiative energy as any other body at the same temperature.
- (2) It is a diffuse emitter: measured per unit area perpendicular to the direction, the energy is radiated isotropically, independent of direction.



Gustav Kirchhoff
(1824 - 1887)

Kirchhoff's Radiation Law

Gustav Kirchhoff stated in 1860 that “at thermal equilibrium, the power radiated by an object must be equal to the power absorbed.” This leads to the observation that if an object absorbs 100 percent of the radiation incident upon it, it must reradiate (emit) the same amount of radiant energy. As already stated, this is the definition of a blackbody radiator.

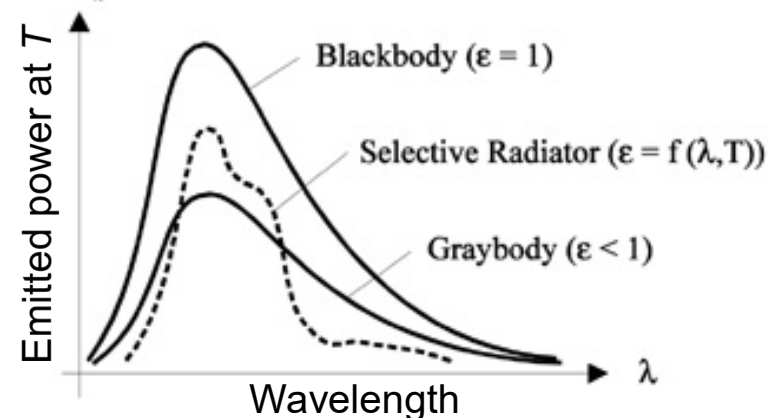
The **absorptivity** (or absorptance), α , is the fraction of incident radiant power that is absorbed by the body/surface. The **emissivity** ϵ of the body/surface is the ratio of the emitted radiant power to the radiant power emitted by a blackbody at the same temperature. In the most general form of the theorem, the power must be integrated over all wavelengths and angles (direction) of radiation. The emissivity and absorptivity can, however, be defined as dependent on wavelength and angle.

At thermal equilibrium, the emissivity of a body/surface equals its absorptivity, $\epsilon = \alpha$.

For a perfect blackbody $\epsilon = \alpha = 1$

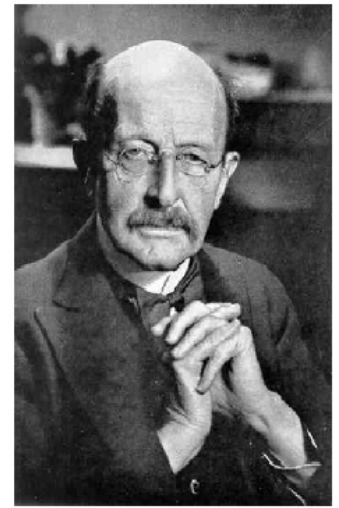
Most radiation sources are not blackbodies. Some of the energy incident upon them may be reflected or transmitted.

$\alpha < 1$ and $\epsilon < 1$



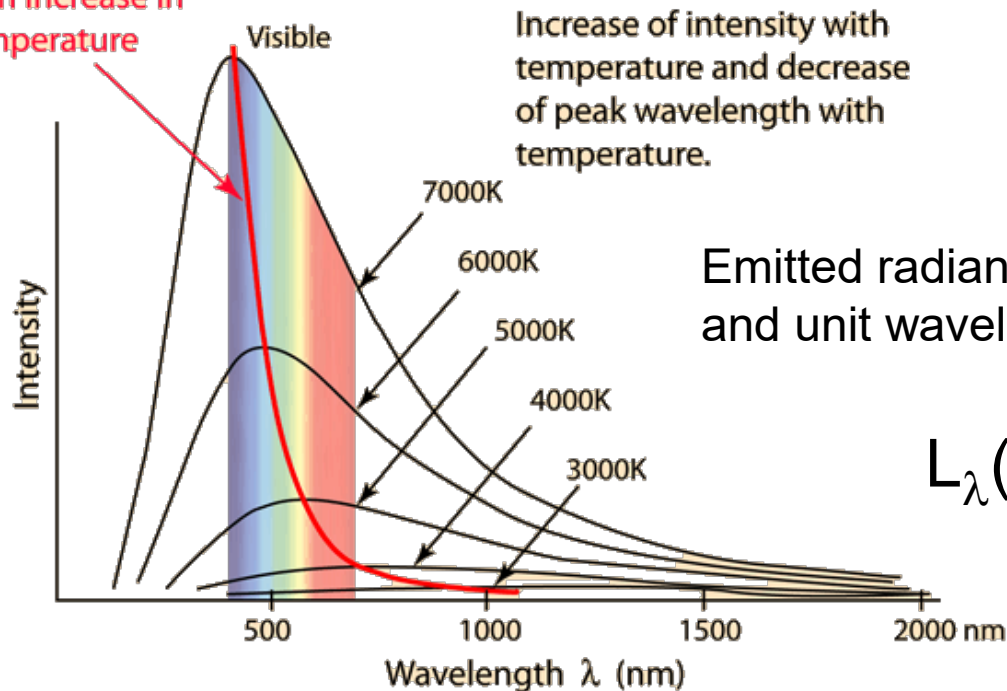
Planck's Radiation Law

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

Decrease of λ_{peak}
with increase in
temperature



Emitted radiance (energy/ (time area steradian and unit wavelength interval)

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

For isotropic blackbody radiance:
Emitted irradiance (hemispherical exitance or emittance) is πL (energy/time area)

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

Stefan-Boltzmann Law

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

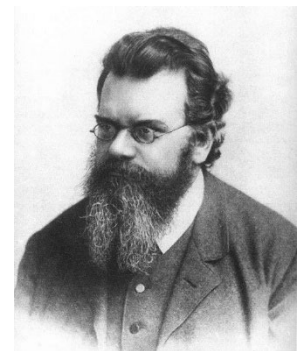
Emitted irradiance or exitance (energy/ (time area))

$$E = \sigma T^4$$

where σ (sigma) = $5.67 \times 10^{-8} \text{ Wm}^{-2} \text{ K}^{-4}$
and T is the temperature in Kelvin



Joseph Stefan
(1835 - 1893)



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)

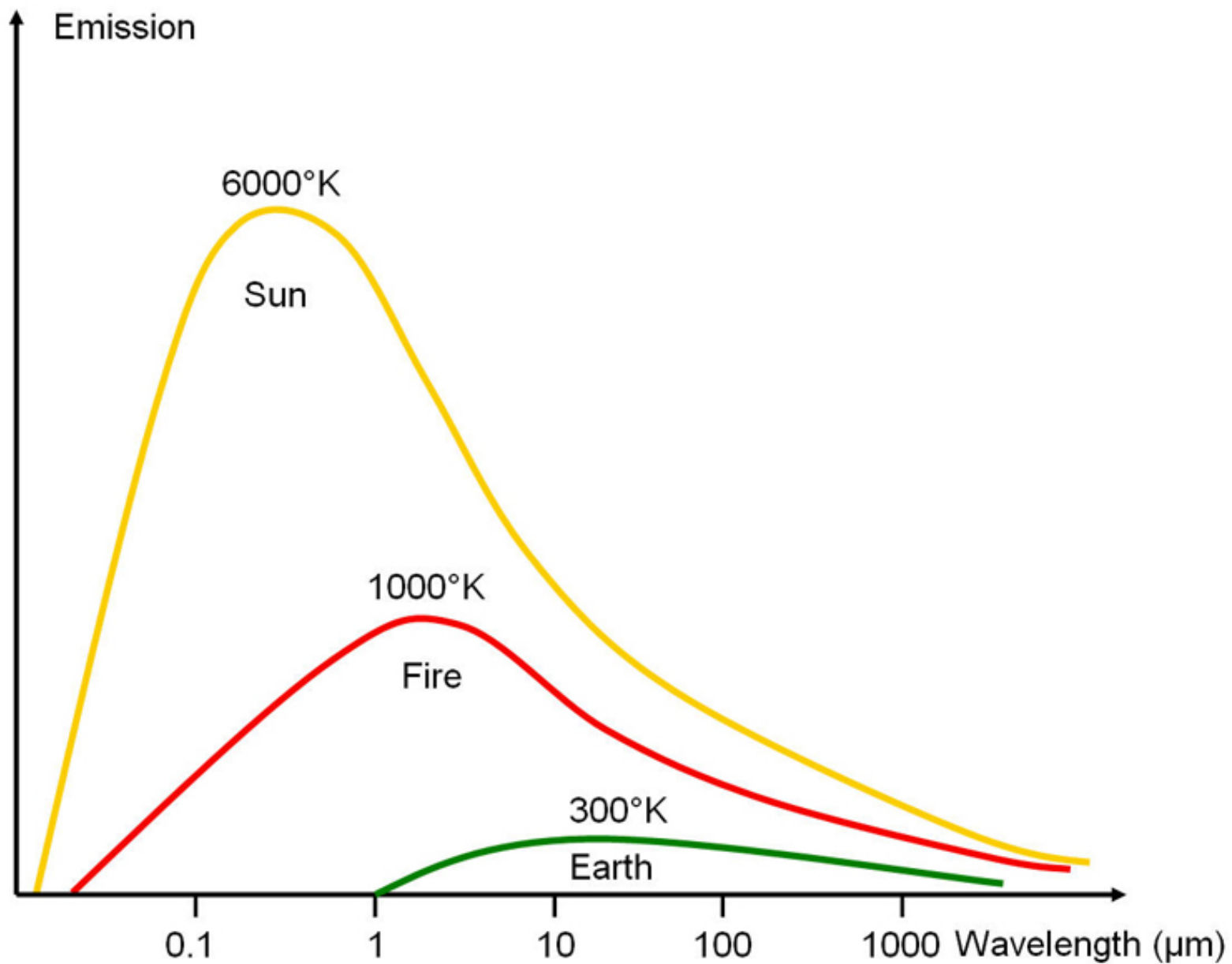
T = temperature of the object (in kelvins)



For example

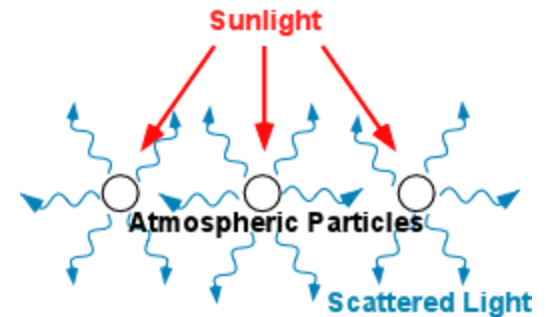
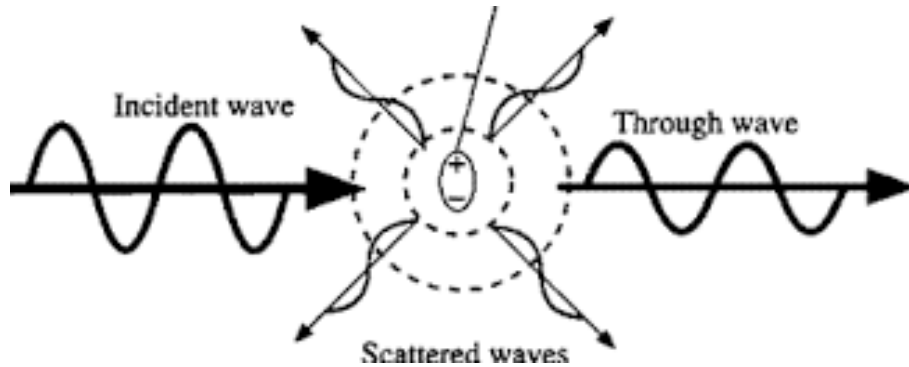
- The Sun, $\lambda_{\max} = 500 \text{ nm} \rightarrow T = 5800 \text{ K}$
- Human body at 37 degrees Celsius or 310 Kelvin $\rightarrow \lambda_{\max} = 9.35 \text{ }\mu\text{m} = 9350 \text{ nm}$
- Earth at 15°C or 288 K $\rightarrow \lambda_{\max} \approx 10 \text{ }\mu\text{m} = 10000 \text{ nm}$

Wilhelm Wien (1864 - 1928)
Nobel Prize 1911

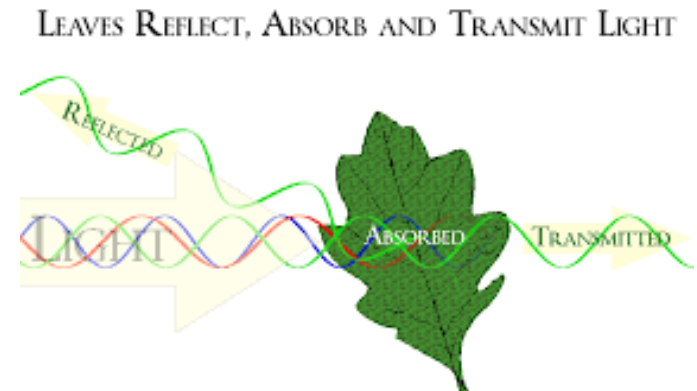
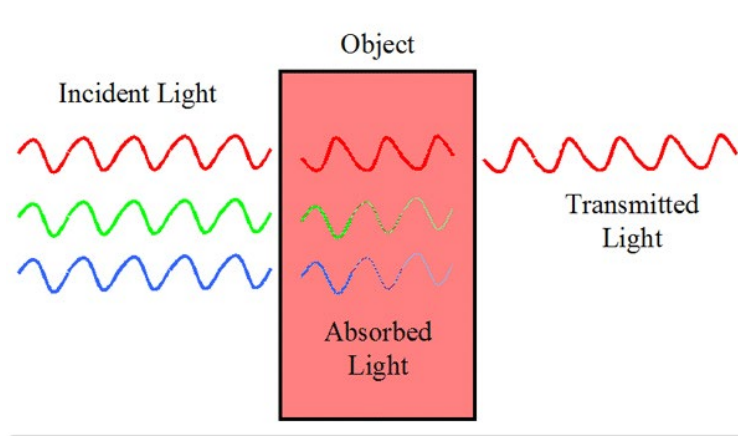


Interaction of Light and Matter

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



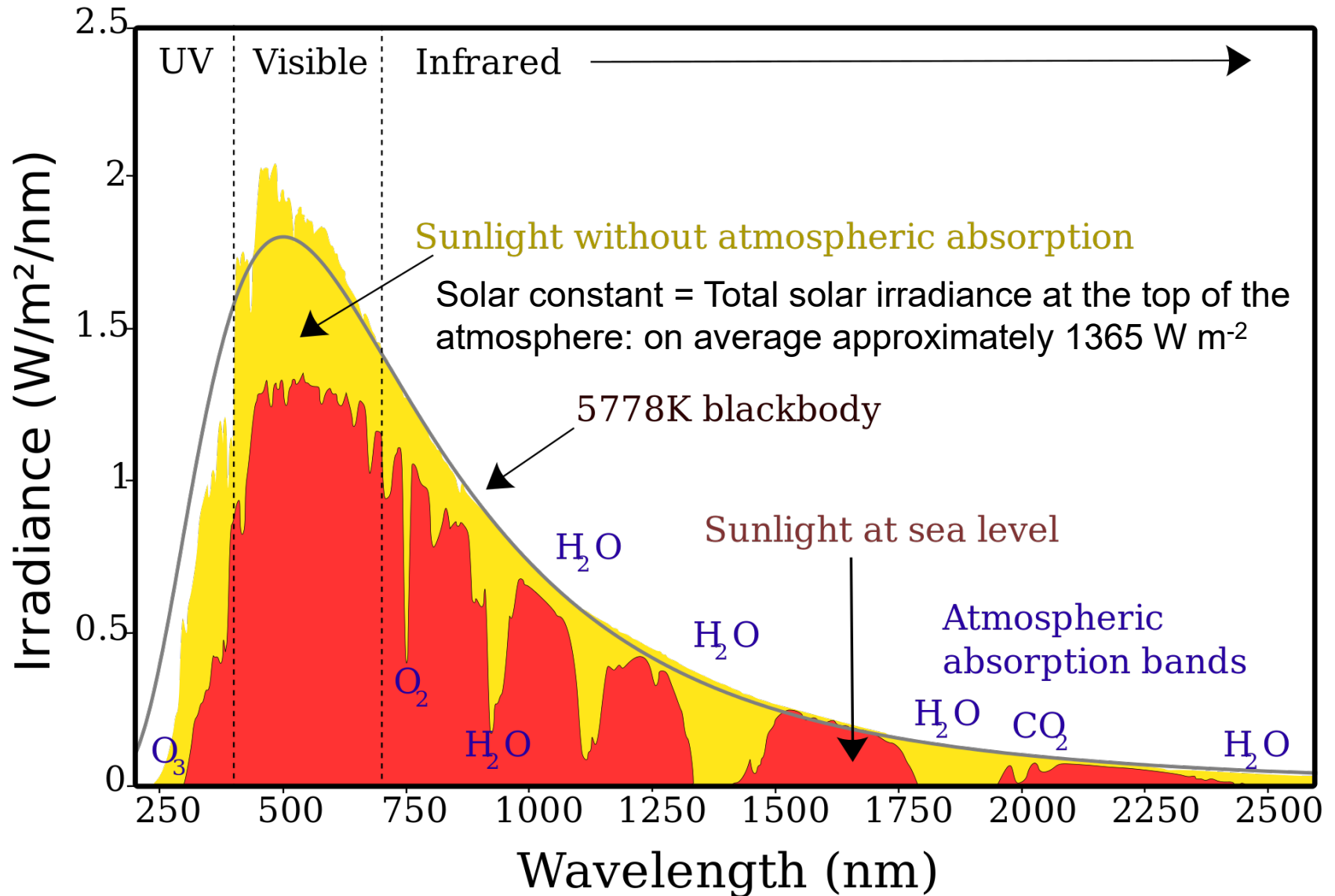
Absorption (death of photon) – transfer of energy to matter



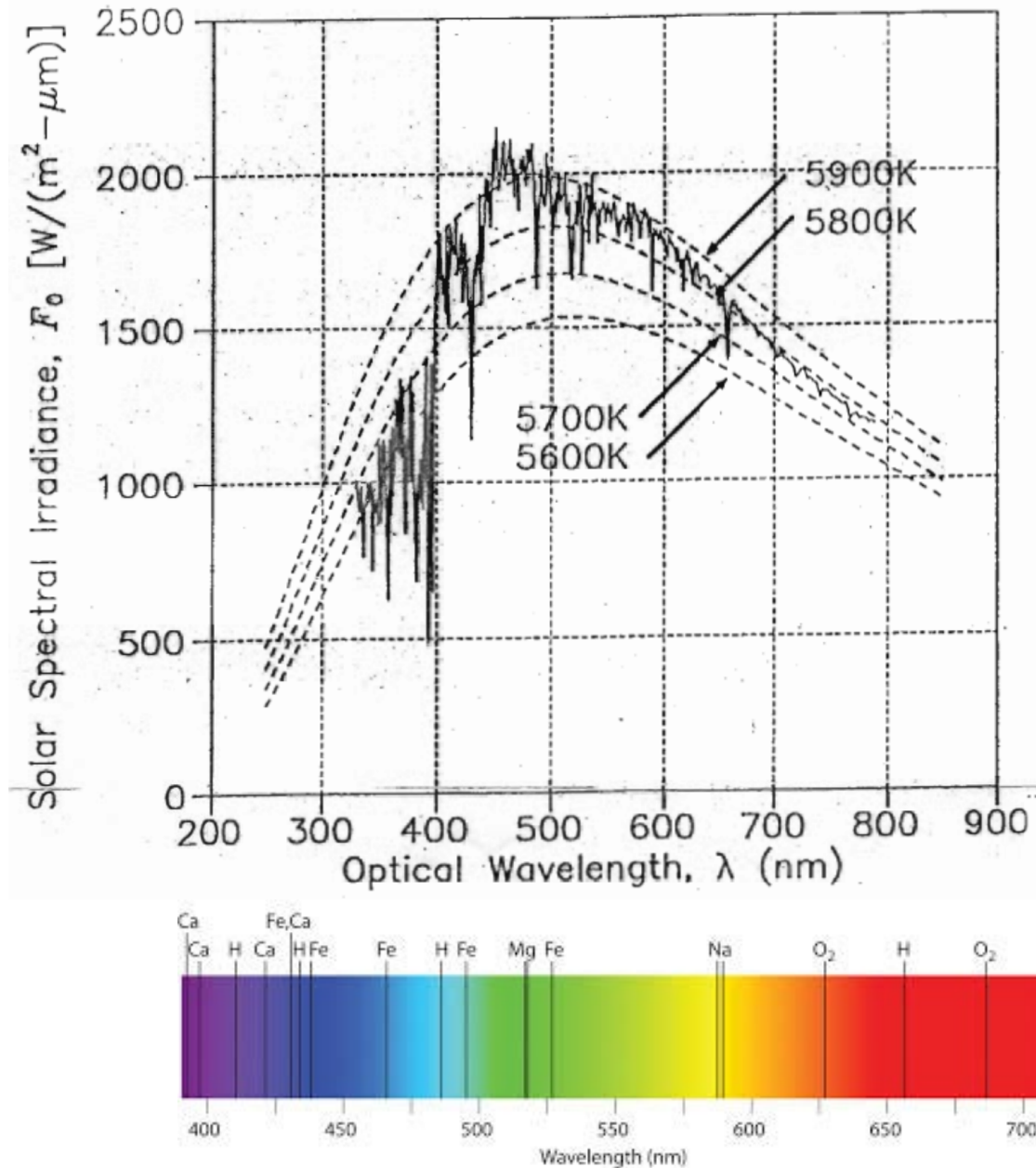
Ocean optics is concerned primarily with the study of relatively narrow range of electromagnetic spectrum from near-UV through visible to near-IR



Spectrum of solar radiation



Solar spectral irradiance outside the Earth's atmosphere



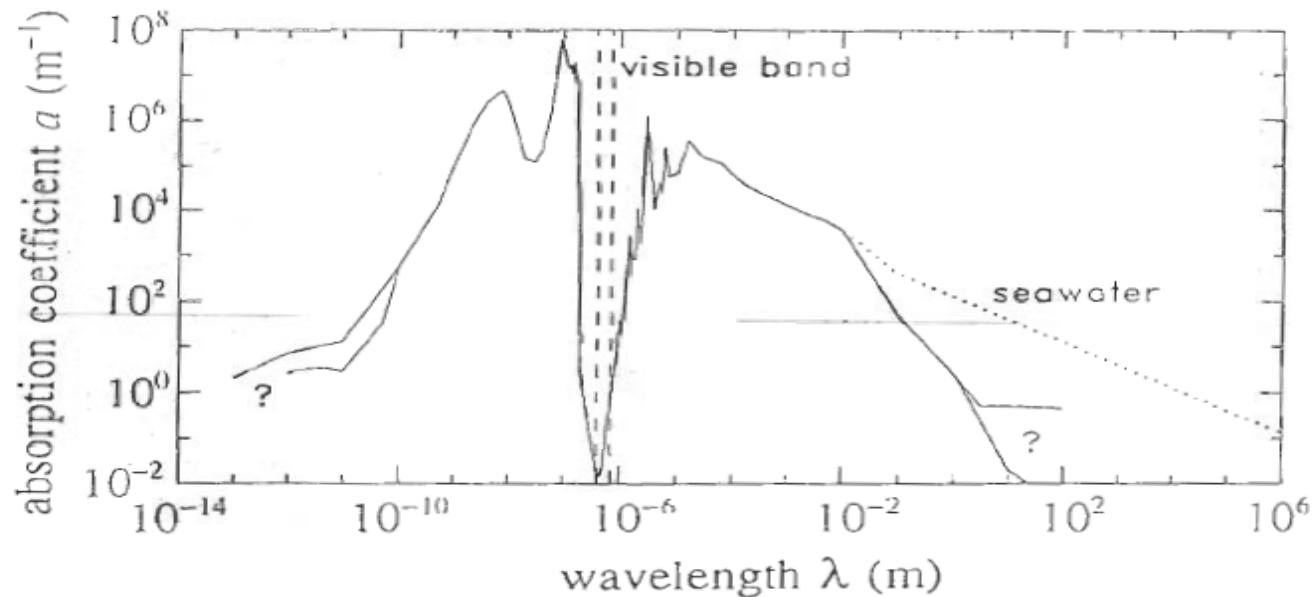
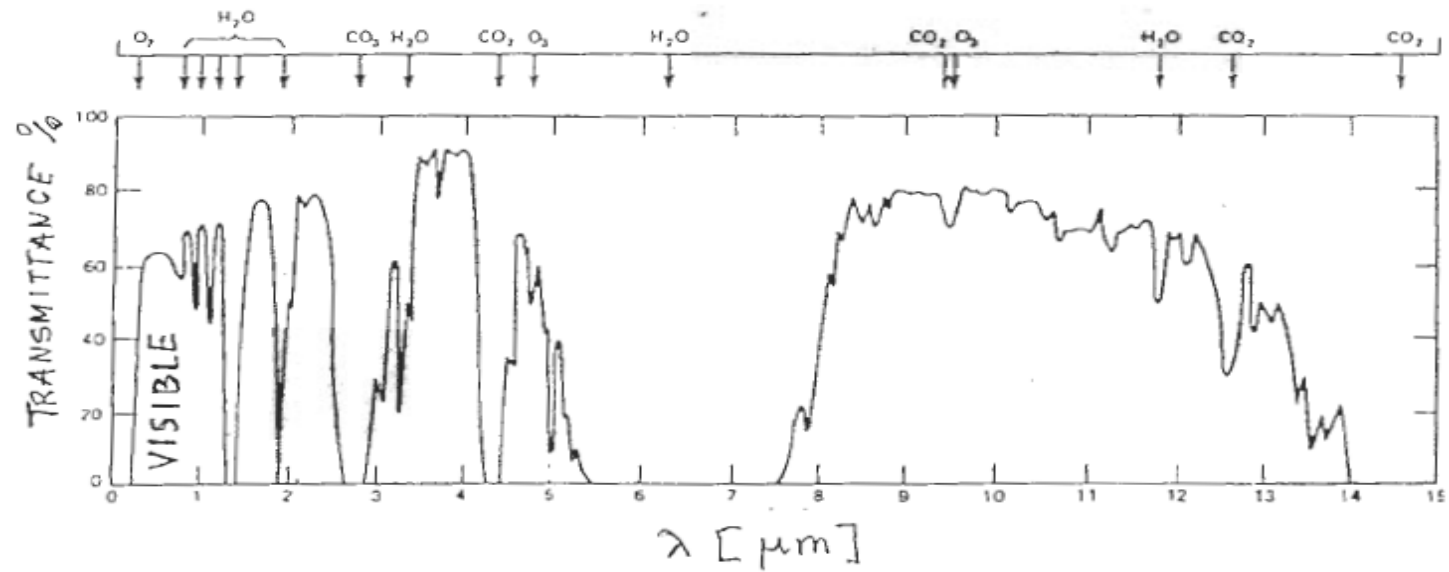
Distribution of the solar constant in various wavelength bands

Band	Wavelength interval (nm)	Irradiance (W m^{-2})	Fraction of E_s (percent) ^a
ultraviolet and beyond	< 350	62	4.5
near ultraviolet	350-400	57	4.2
visible	400-700	522	38.2
near infrared	700-1000	309	22.6
infrared and beyond	> 1000	417	30.5
totals		1367	100.0

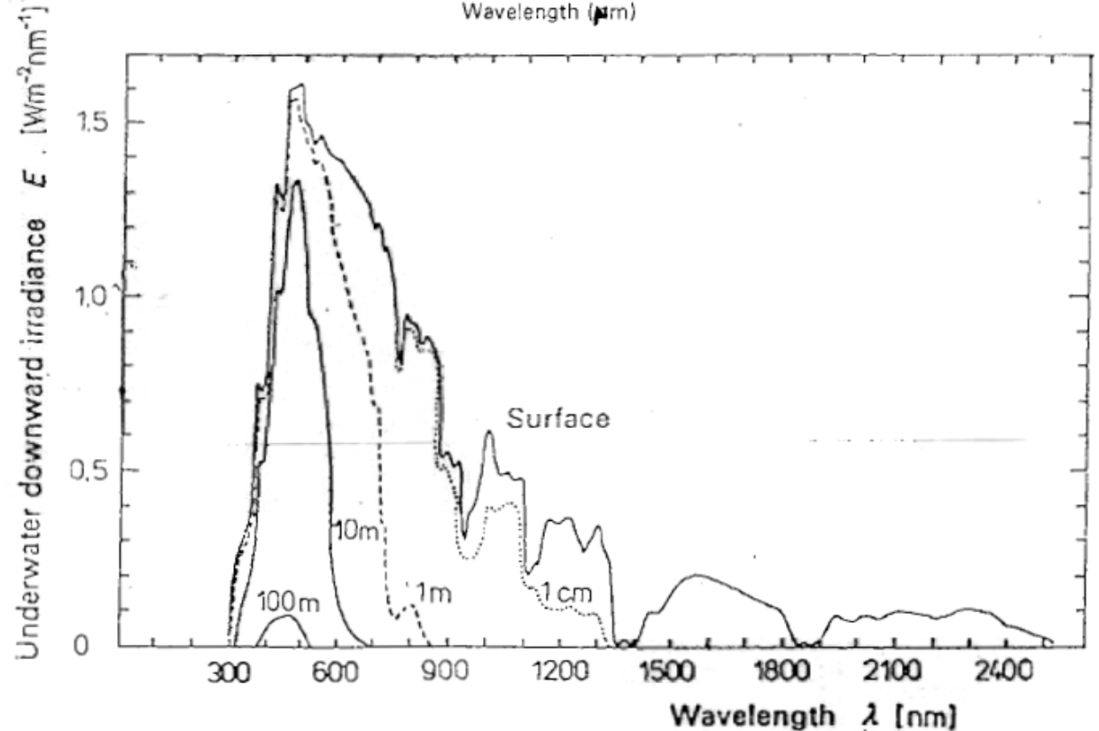
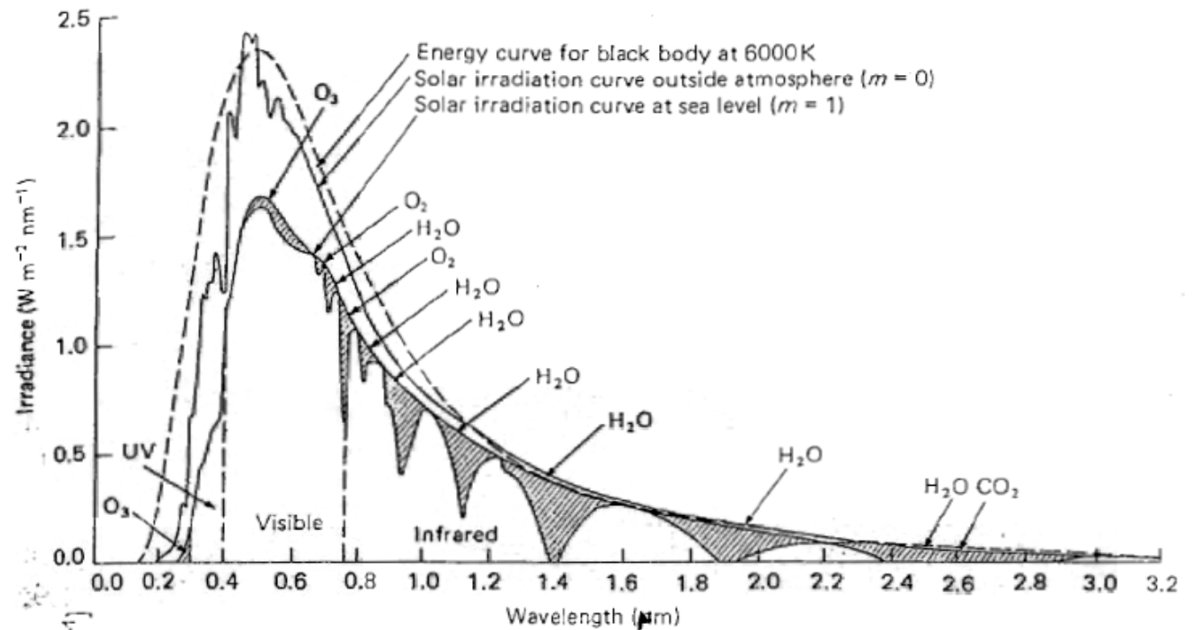
a. Percentages computed from data in Thekaekara (1976)

Solar constant varies by a fraction of a percent on time scales of minutes to decades. In addition, the solar irradiance reaching the Earth varies about the mean solar constant by almost 50 W m^{-2} over the course of the year, owing to the ellipticity of the Earth's orbit around the sun.

Overlap of “window” in atmospheric transmittance with minimum of water absorption in the visible band

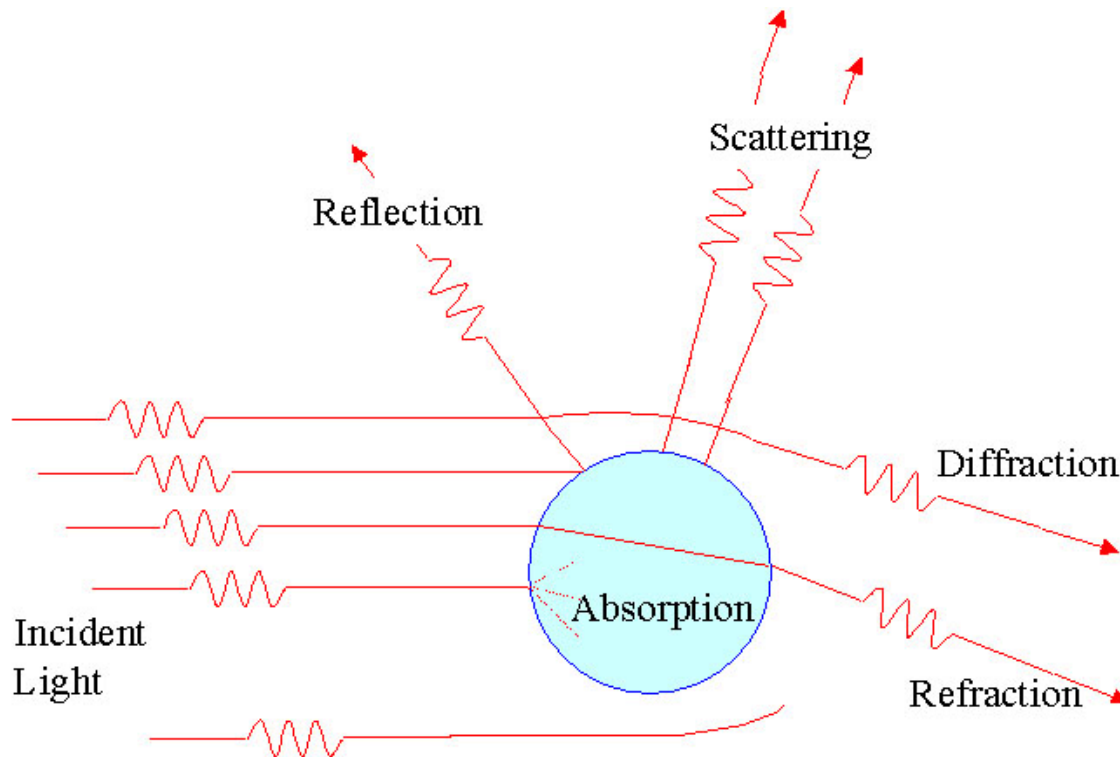


Spectra of Solar Irradiance



Interaction of light and matter

Scattering - life of photon



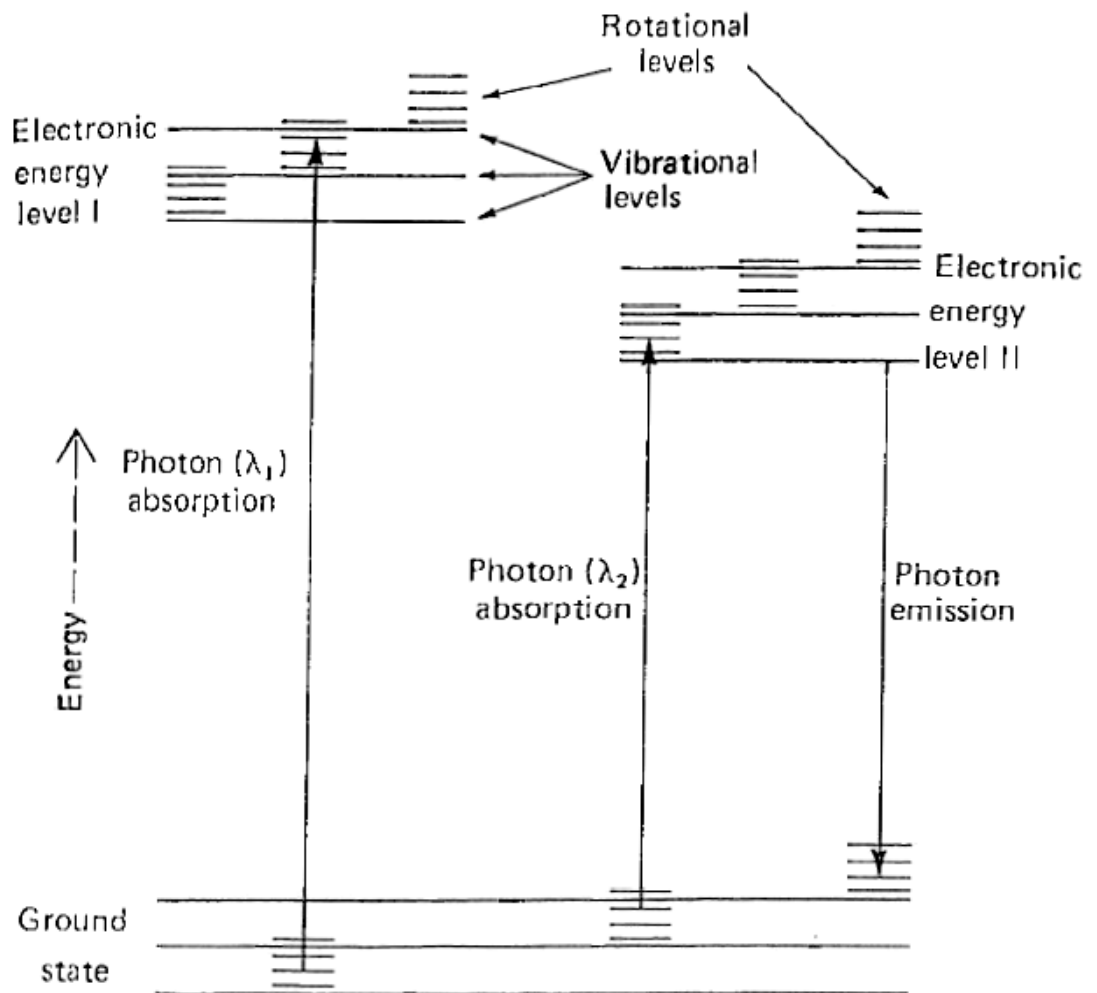
Absorption - death of photon

Internal energy levels and absorption by atoms/molecules

Electronic:
energy ~ 400 kJ/mol
 $\lambda \sim 100 - 1000$ nm

Vibrational:
energy $\sim 4 - 40$ kJ/mol
 $\lambda \sim 1 - 20$ μm

Rotational:
energy $\sim 10^{-2} - 10^{-3}$ kJ/mol
 $\lambda > 20$ μm



For comparison, the average kinetic energy (translatory motion) at room temperature is ~ 4 kJ/mol

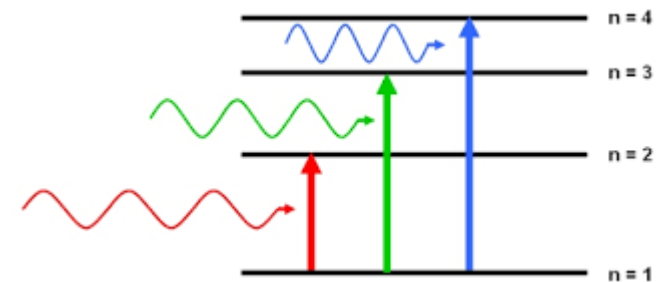
Light and Matter:

Absorption (Electronic & Vibrational) Spectroscopy

<https://www.youtube.com/watch?v=OQwTcl9TeUM>

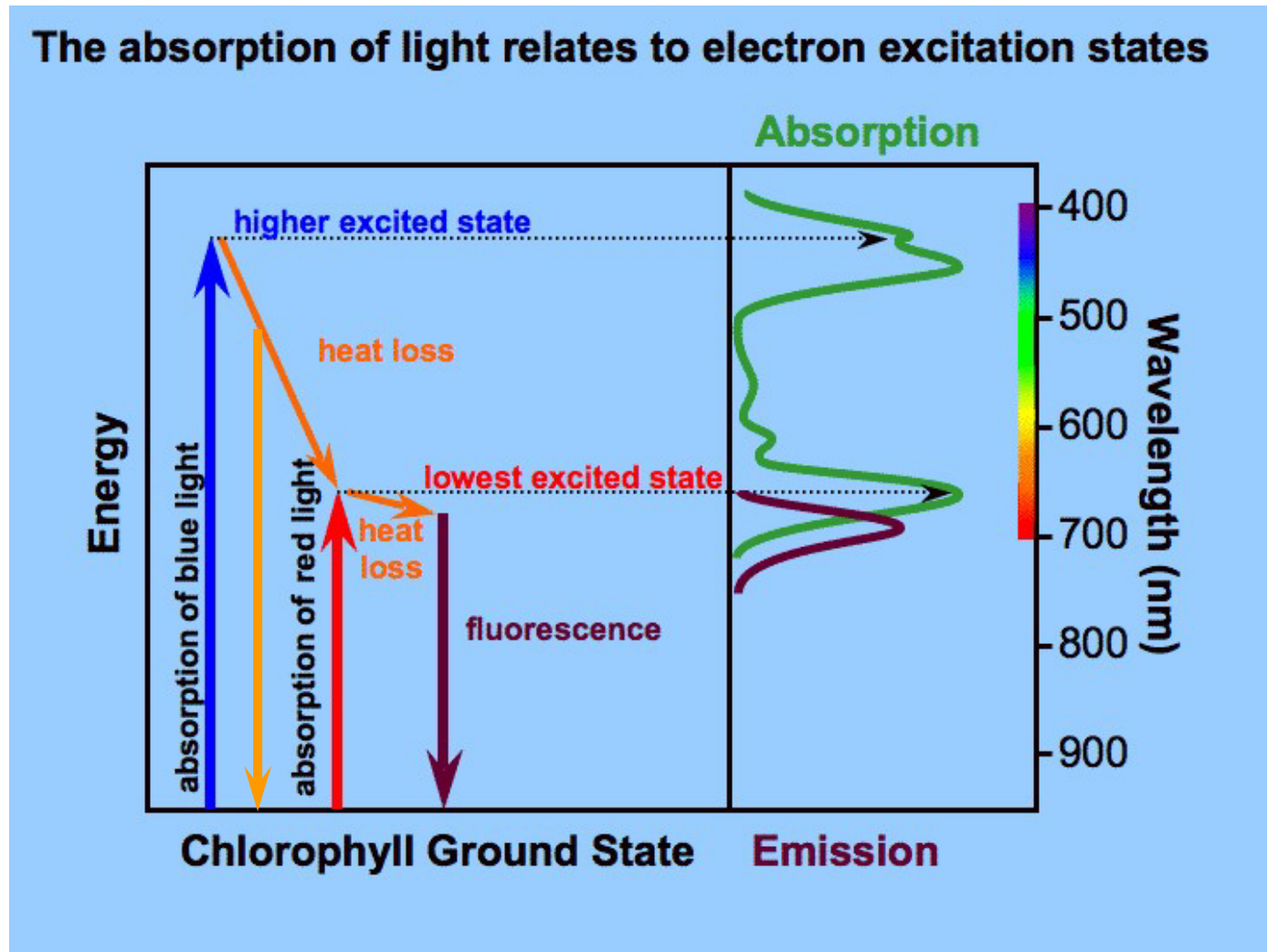
Absorption/Emission (Electronic) Line Spectra of Atoms

<https://www.youtube.com/watch?v=uO-sFqoSsPg>

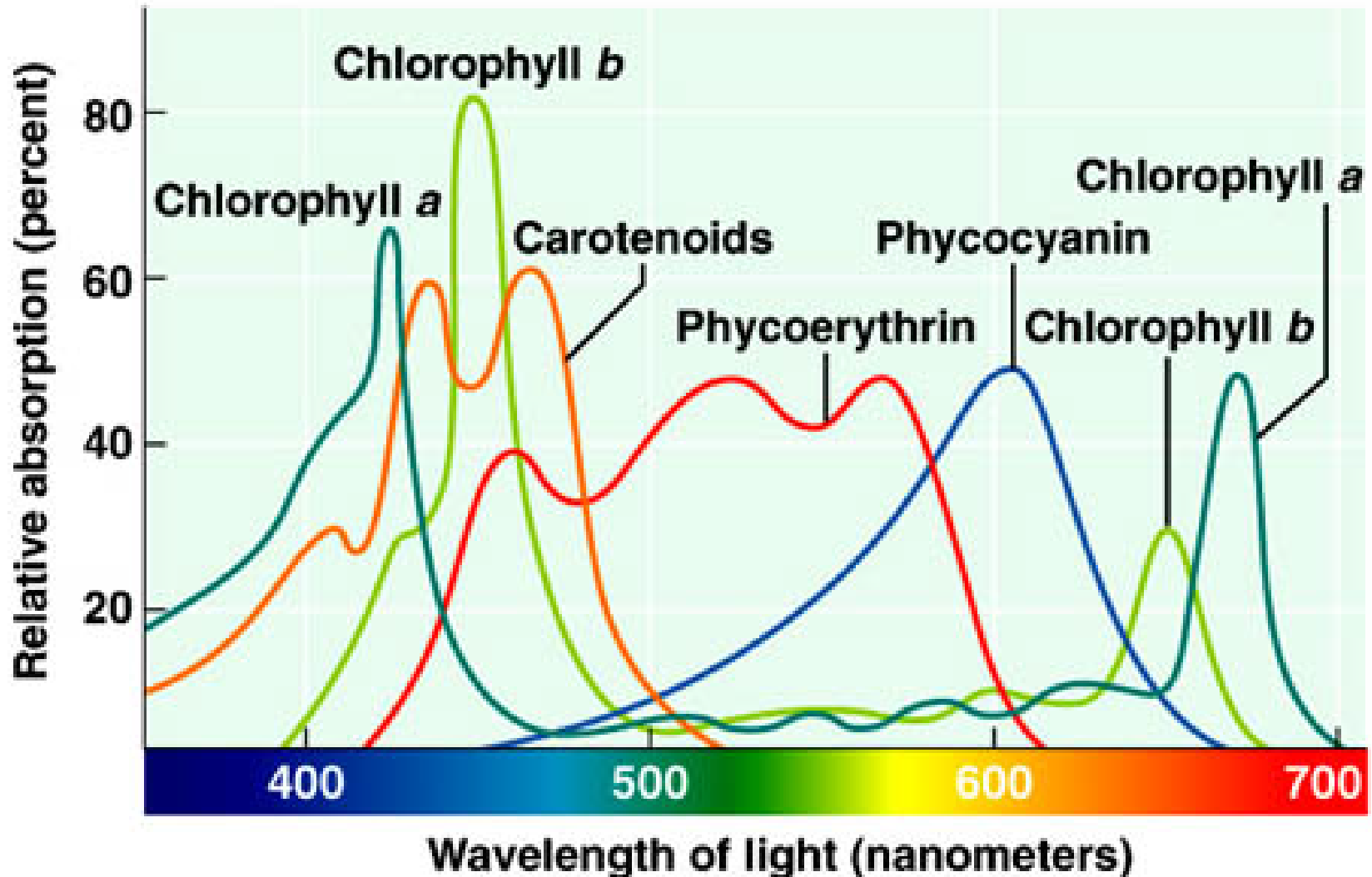


Kirk 1993

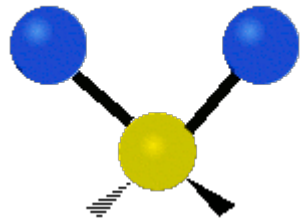
Chlorophyll-a has two electronic states associated with the energy equivalent to **blue** (~440 nm) and **red** (~675 nm) photons



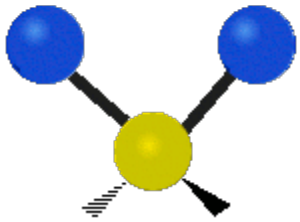
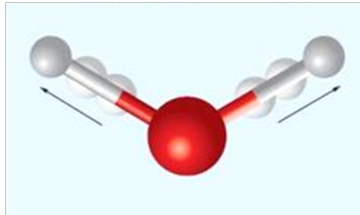
Absorption spectra of plant pigments



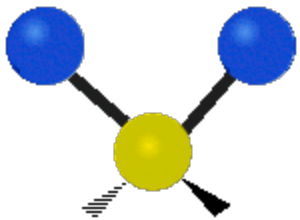
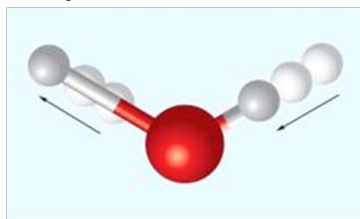
Absorption mechanism associated with water molecule vibrations



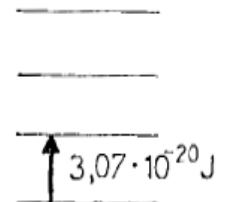
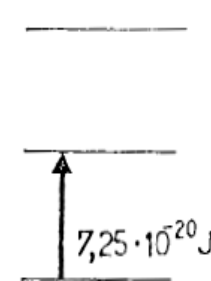
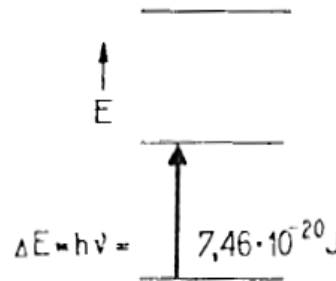
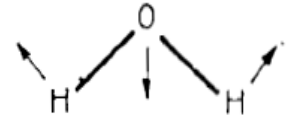
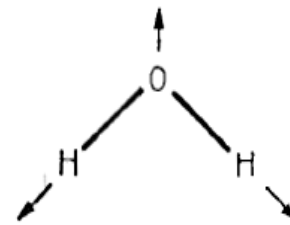
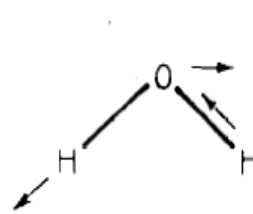
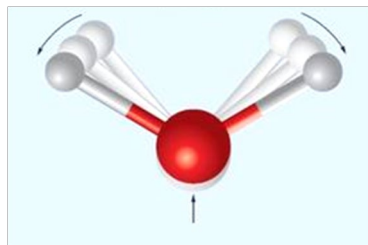
Symmetric stretch



Asymmetric stretch



Bend



$$\nu = 1,1268 \cdot 10^{14} \text{ Hz}$$

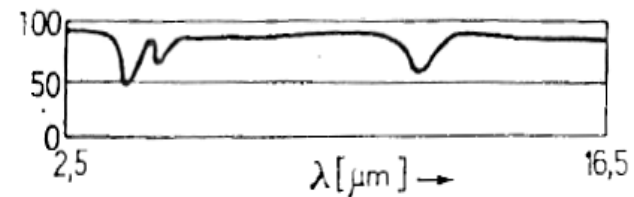
$$\lambda = 2,66 \mu\text{m}$$

$$\nu = 1,0949 \cdot 10^{14} \text{ Hz}$$

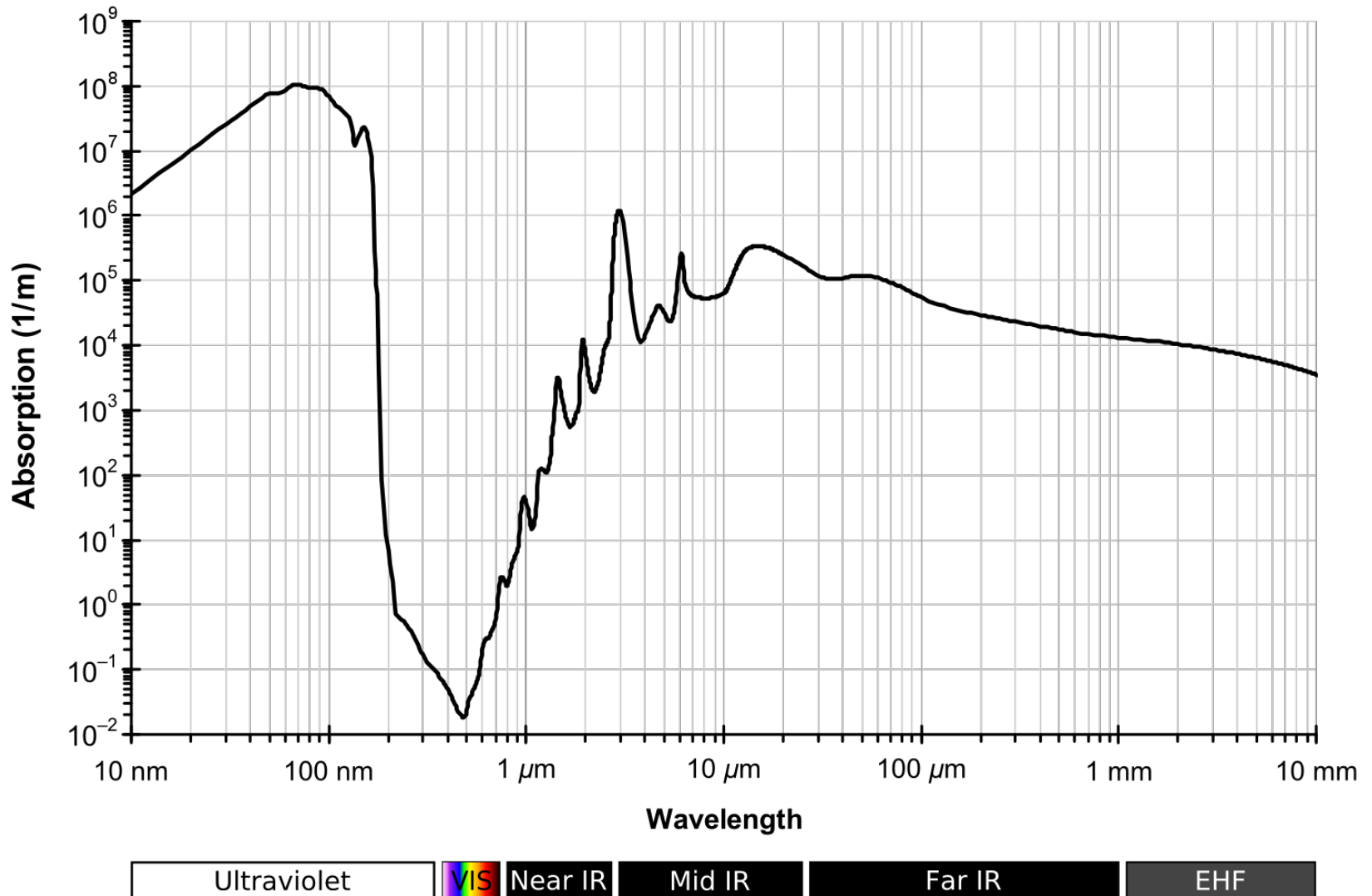
$$\lambda = 2,74 \mu\text{m}$$

$$\nu = 0,4637 \cdot 10^{14} \text{ Hz}$$

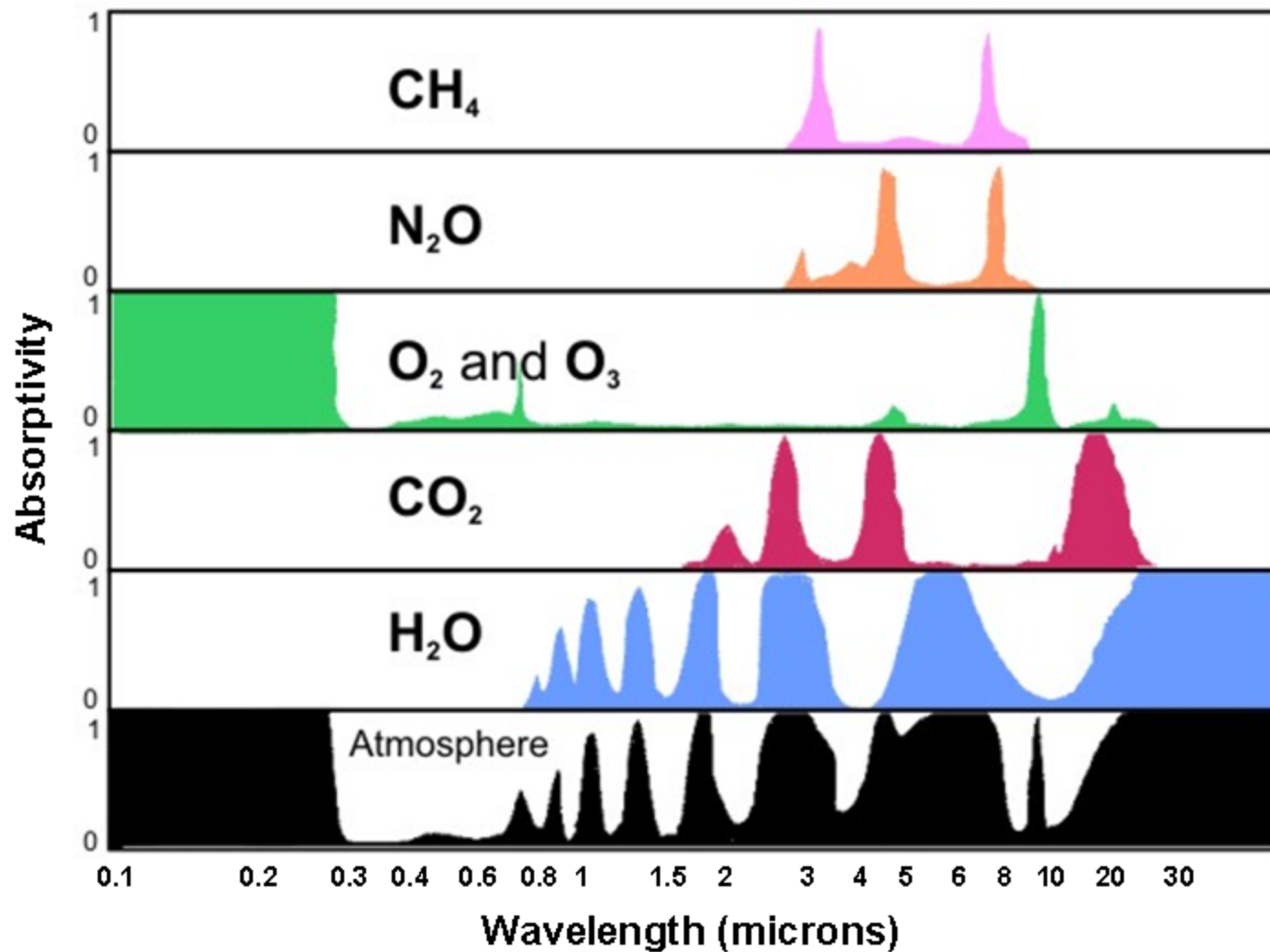
$$\lambda = 6,47 \mu\text{m}$$



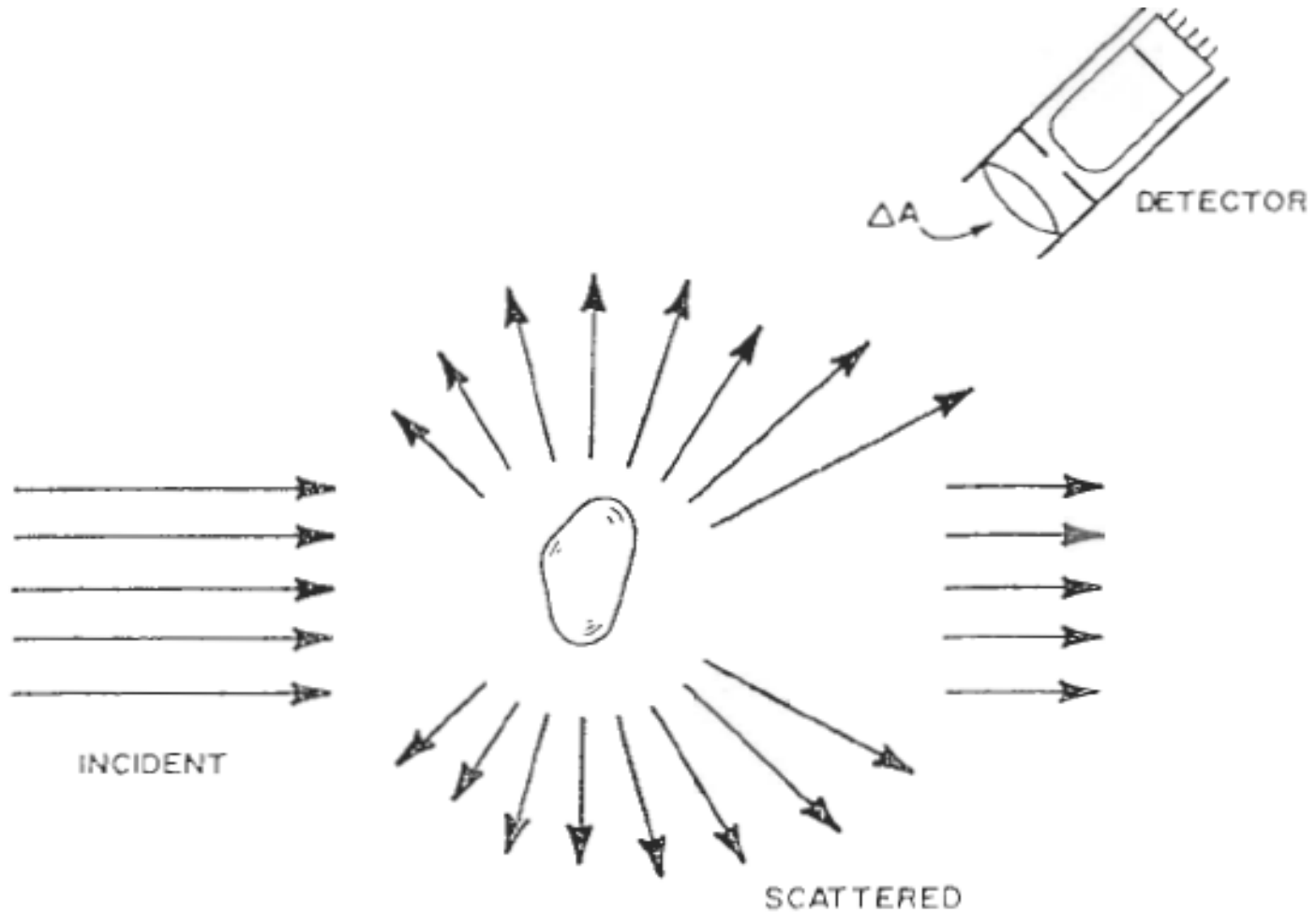
Absorption spectrum of water molecules



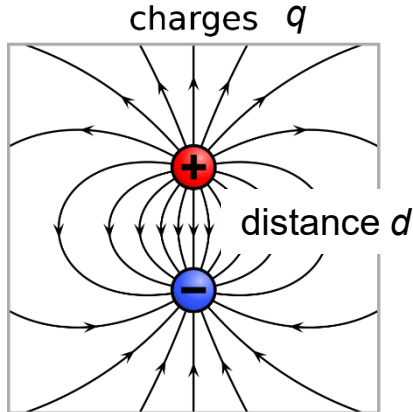
Absorption spectra of atmospheric molecules



Scattering of light by inhomogeneity of the medium

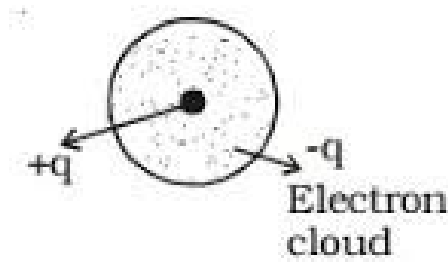


Electromagnetic radiation of an oscillating dipole: Mechanism of light scattering

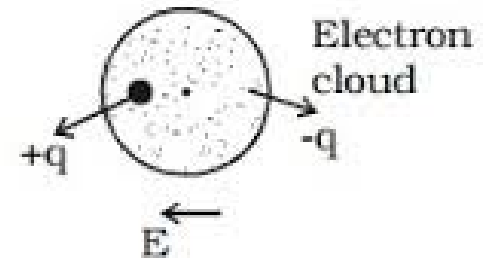


Dipole moment ($p = q d$) is a separation of positive and negative charges

Polarizability (α) is the relative tendency of a charge distribution, like the electron cloud of a molecule, to be distorted from its normal shape by an external electric field, like the one in an electromagnetic wave



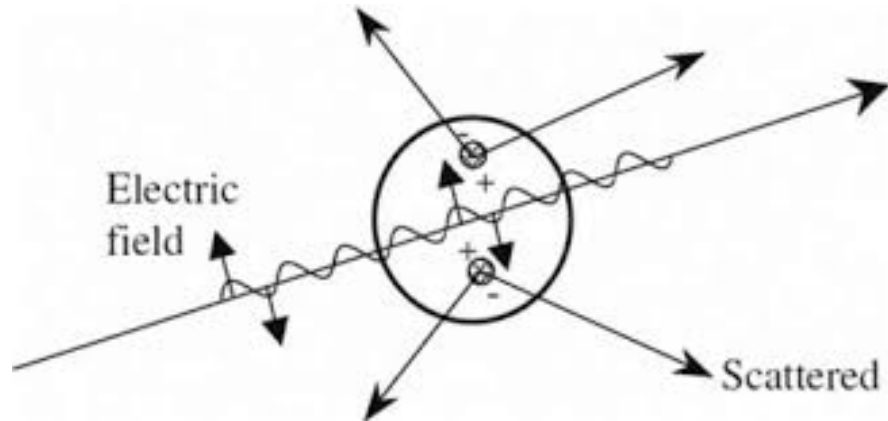
Induced dipole



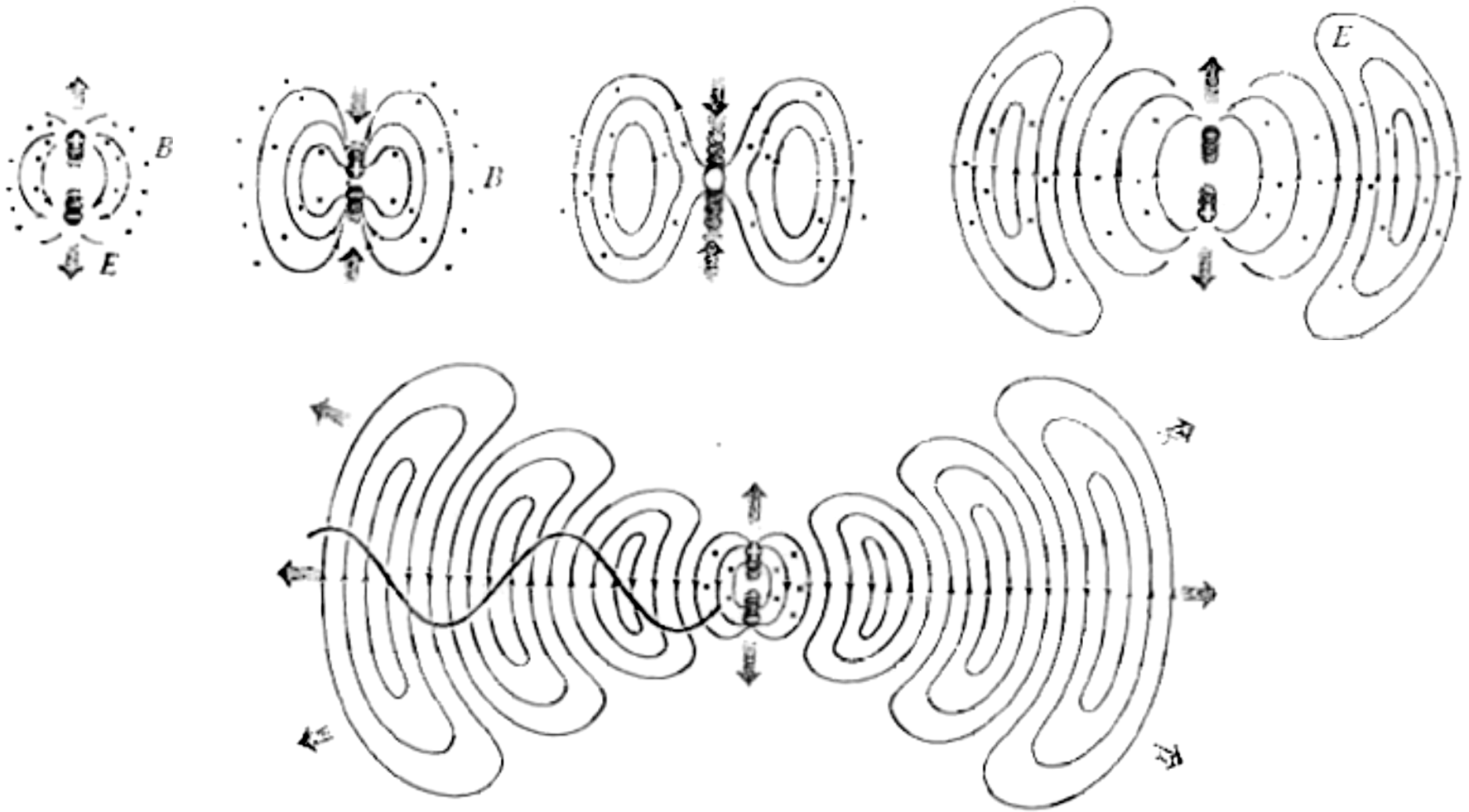
$$p_{\text{induced}} = \alpha E$$

Dipole moment induced by an electric field E

Dipole light scattering



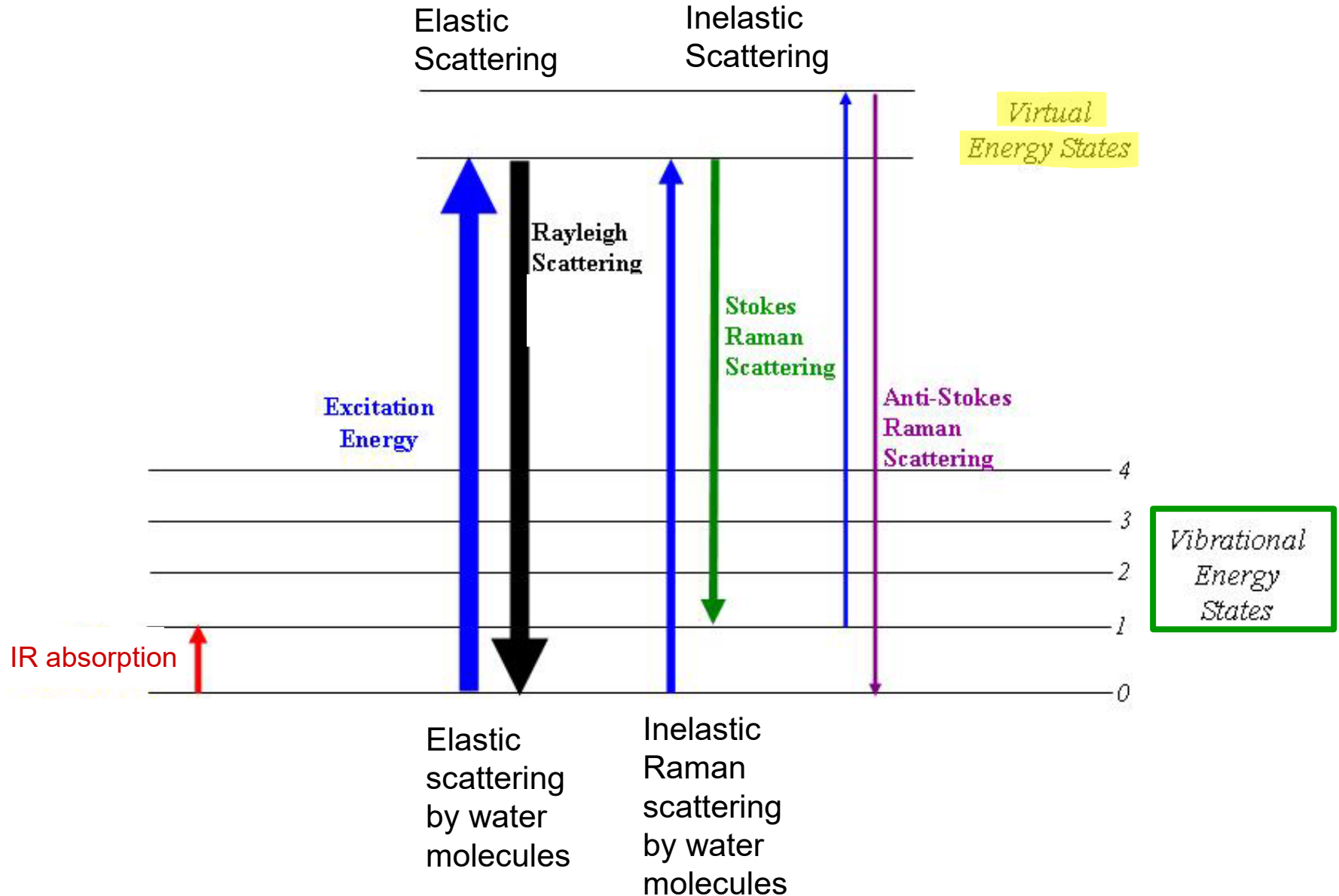
Electromagnetic radiation of an oscillating dipole: Mechanism of light scattering



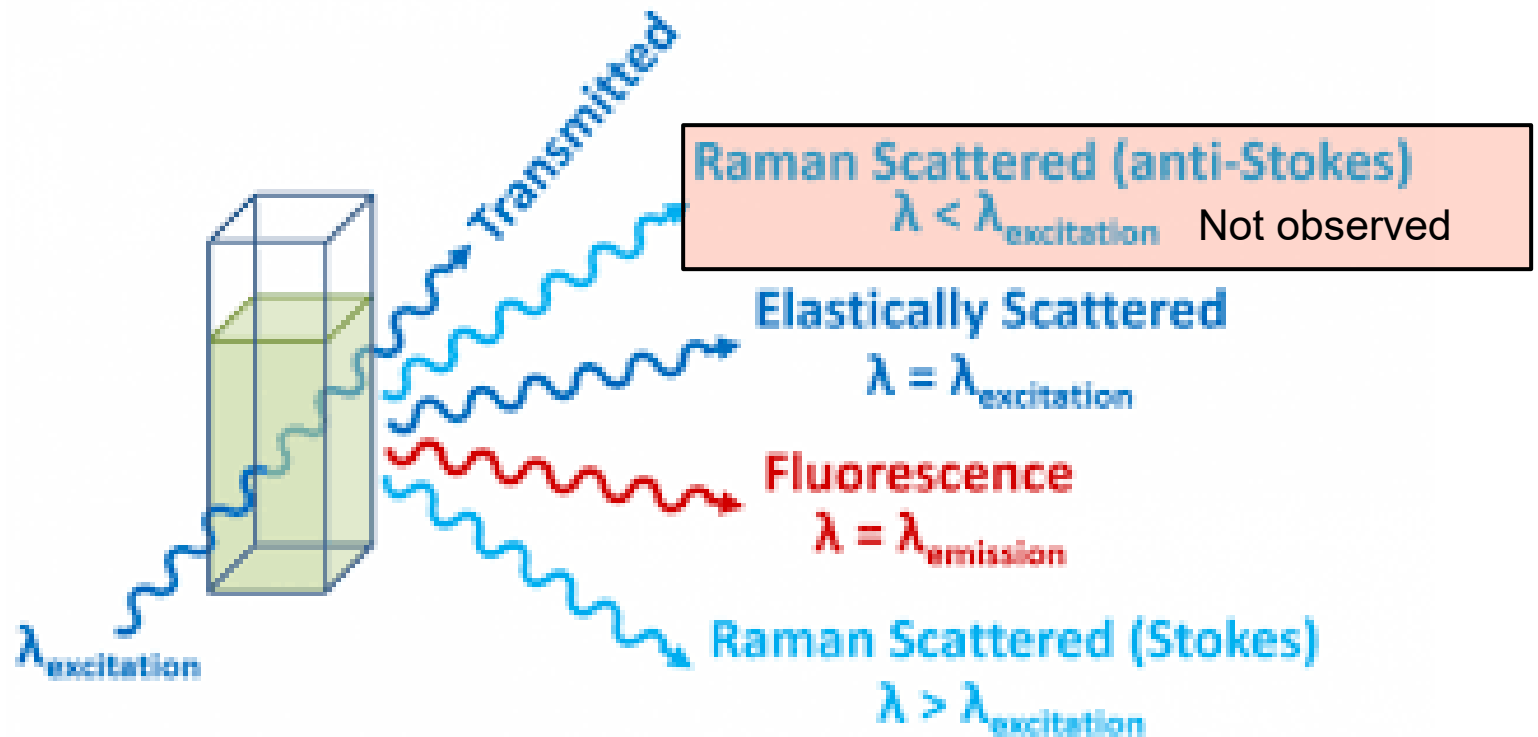
$$p(t)_{\text{induced}} = \alpha E(t)$$

Oscillating dipole moment induced by
varying electric field E

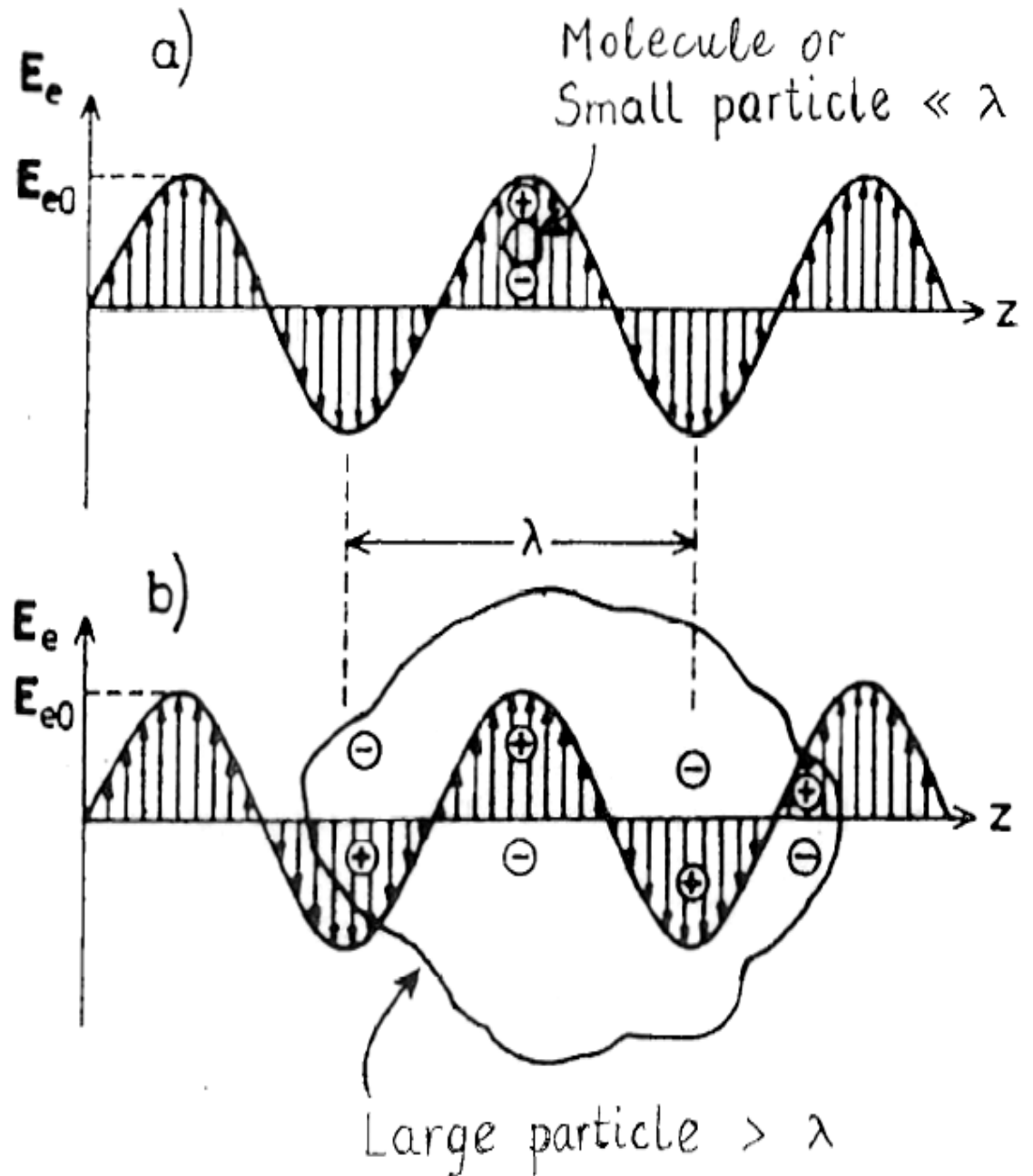
Elastic and inelastic scattering



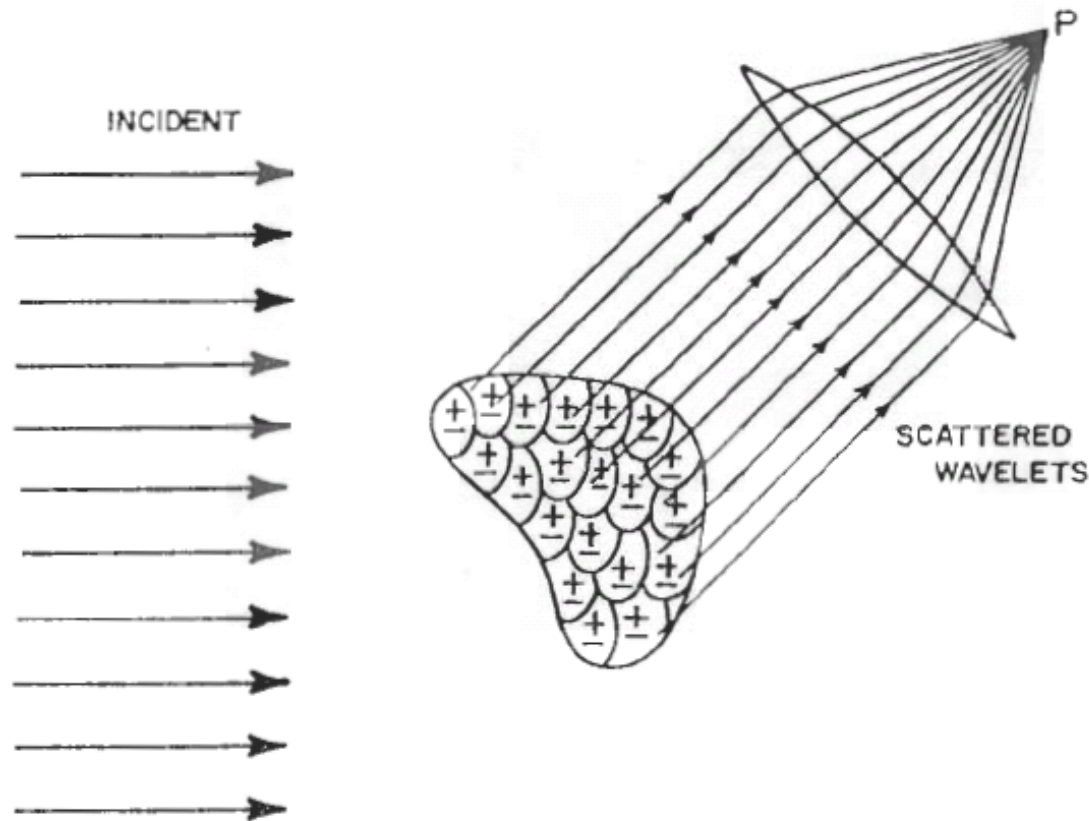
Elastic scattering and inelastic processes of Raman (Stokes) scattering and fluorescence are all relevant to ocean optics



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



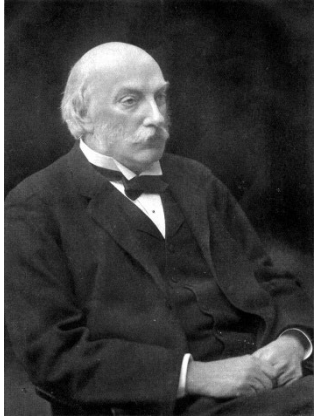
A single particle subdivided into oscillating dipoles



Coherent scattering (separation between dipoles is small and nonrandom):
Scattered wavelets have nonrandom relative phases in the direction of interest. The total scattered intensity is obtained by the superposition of scattered wavelets where phase differences are accounted for.

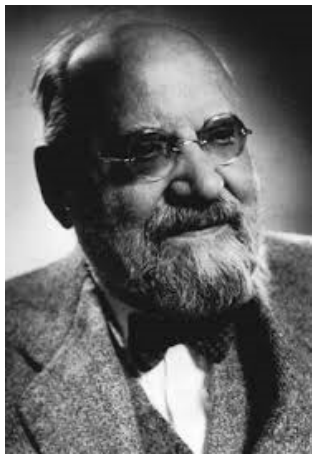
Computations of light scattering: From Rayleigh and Mie theory to geometric ray tracing

Particle size $\ll \lambda$



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

Rayleigh scattering approximation: the elastic scattering of light or other electromagnetic radiation by particles much smaller than the wavelength of the radiation. Rayleigh scattering results from the electric polarizability of very small particles which may be individual atoms or molecules. The oscillating electric field of a light wave acts on the charges within a particle, causing them to move at the same frequency. The particle, therefore, becomes a small radiating dipole whose radiation we see as scattered light.



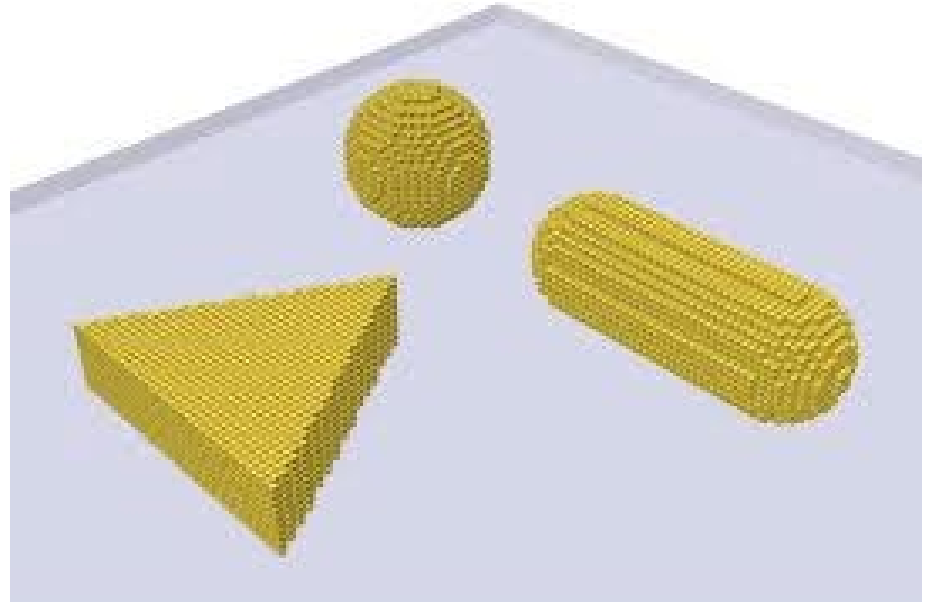
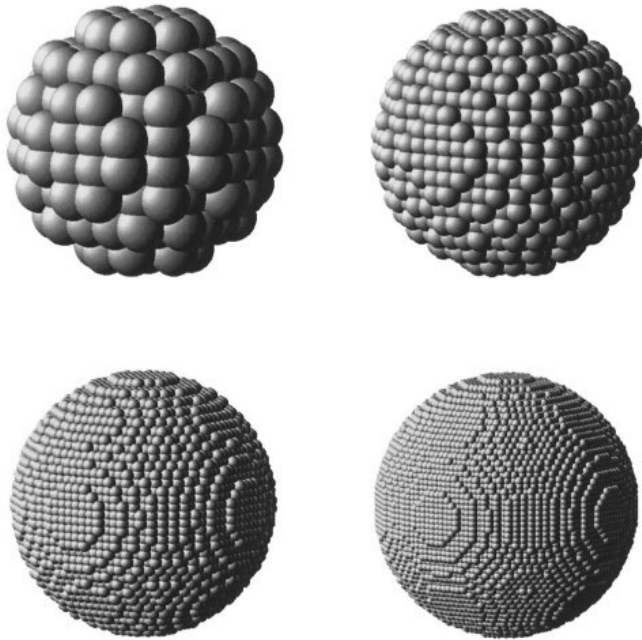
Gustav Mie (1868 - 1957)

Arbitrary size of spherical particles

Mie theory: A complete analytical solution of Maxwell's equations for the scattering of electromagnetic radiation by spherical homogenous particles (arbitrary size and refractive index). Theoretical extensions exist for more complex shapes such as coated and layered spheres, cylinders, and spheroids.

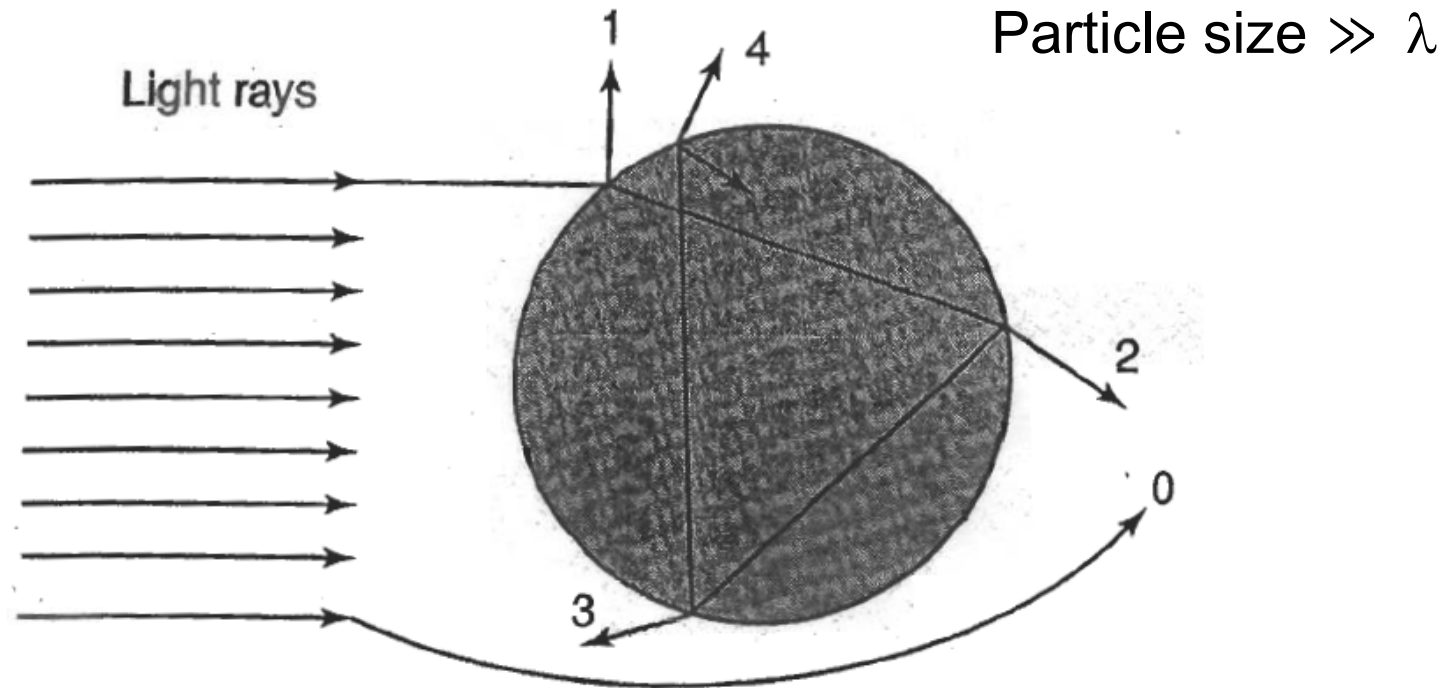
Discrete Dipole Approximation (DDA):

A method for computing scattering by particles of arbitrary shape



In the discrete dipole approximation, an object of arbitrary shape (e.g., a particle) is approximated in terms of a finite array of small electric dipoles. These dipoles acquire dipole moments in response to the local (incident) electric field and produce scattered field.

Geometrical optics approximation for light scattering



0 Exterior Diffraction

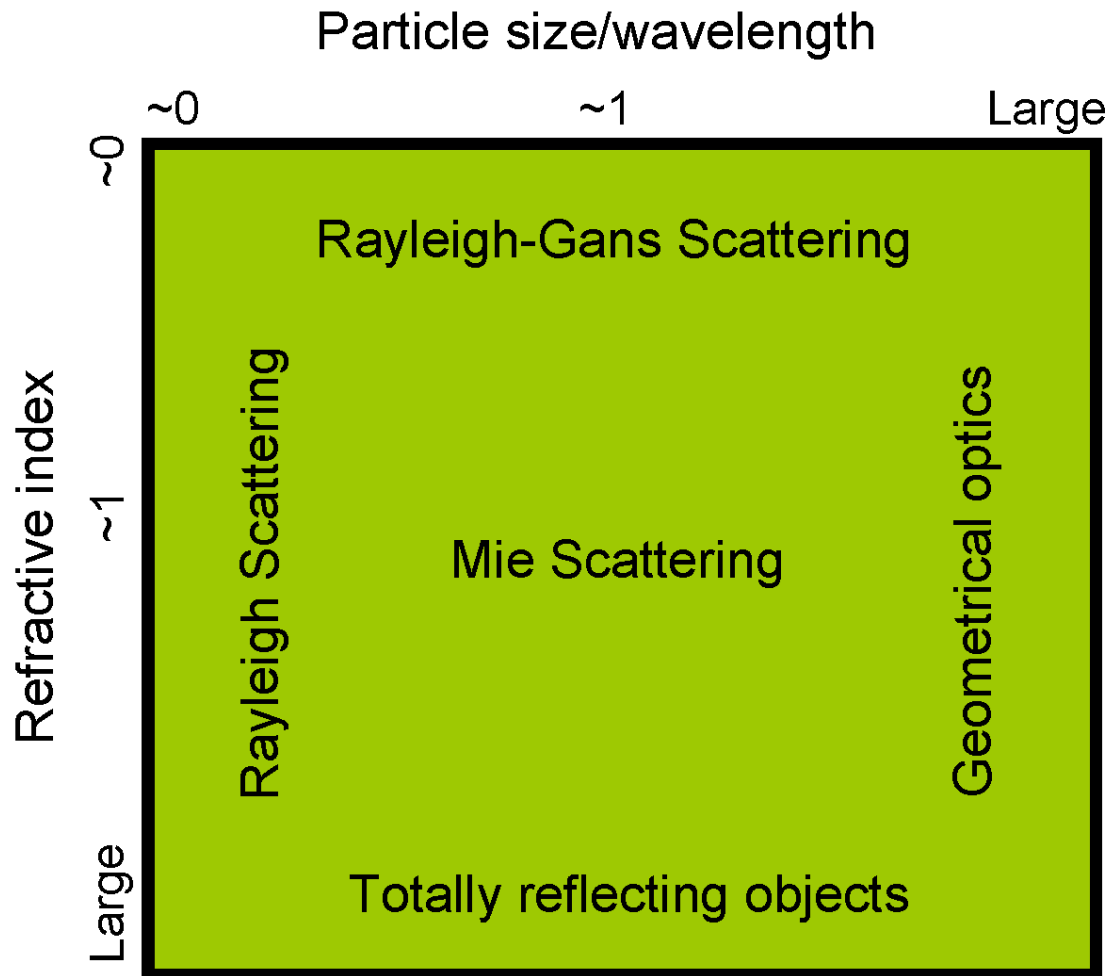
1 External Reflection

2 Two Refractions

3 One Internal Reflection

4 Two Internal Reflections

There are many regimes of particle scattering, depending on the particle size, the refractive index, and the light wavelength. As a result, there are countless observable effects of light scattering although all scattering phenomena are fundamentally the same.



Particle size parameter

$$\alpha \text{ (or } x \text{)} = 2 \pi r / \lambda =$$

$$\pi D / \lambda$$

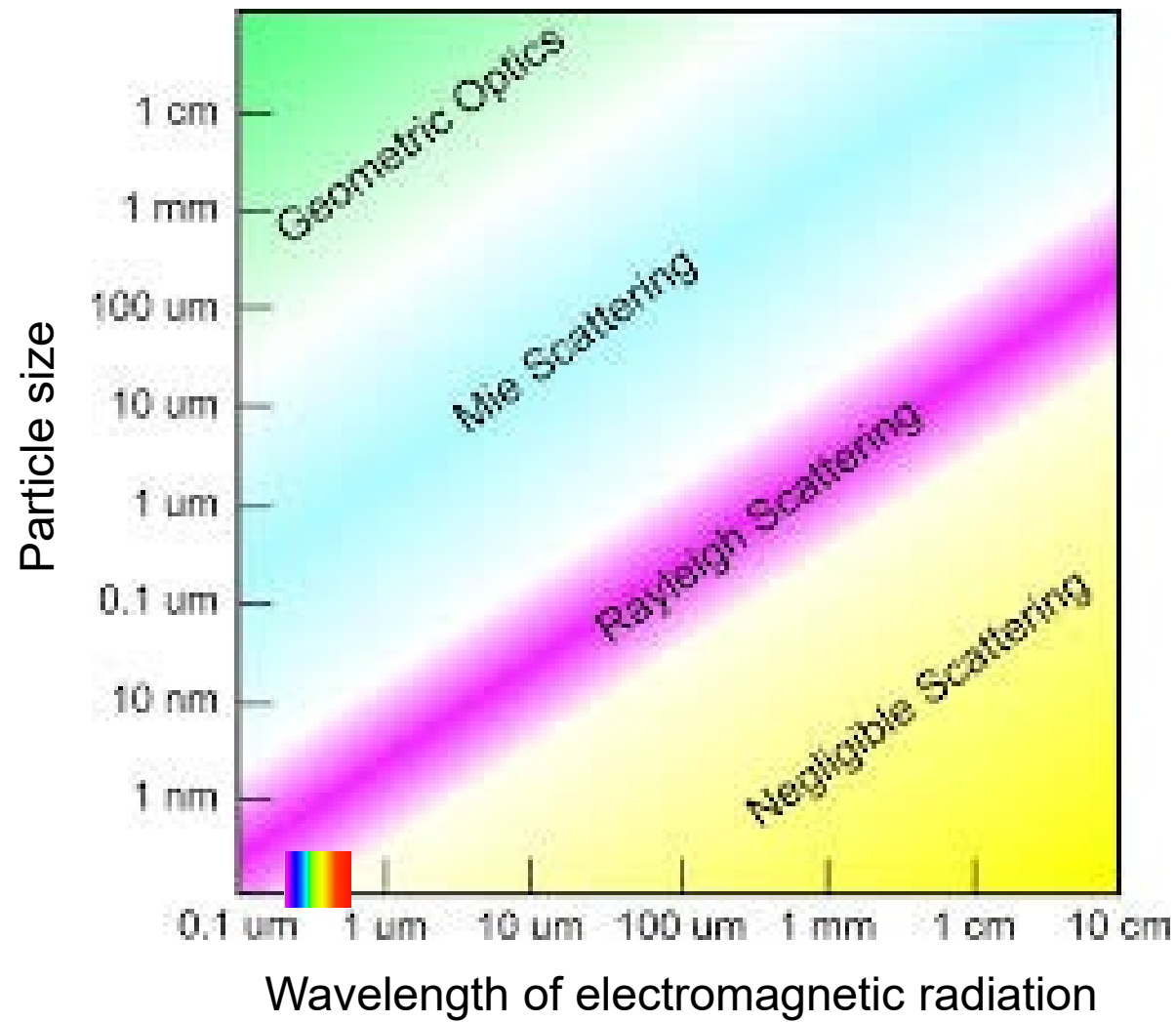
where r is particle radius and D particle diameter

Rayleigh scattering approximation

$$\alpha \ll 1$$

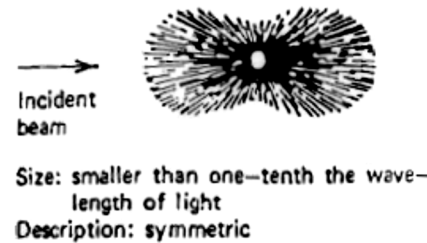
Geometrical optics approximation

$$\alpha \gg 1$$

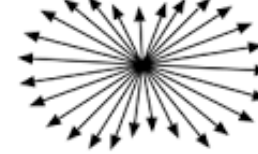


Angular patterns of scattered intensity from particles of different sizes

Very small particles



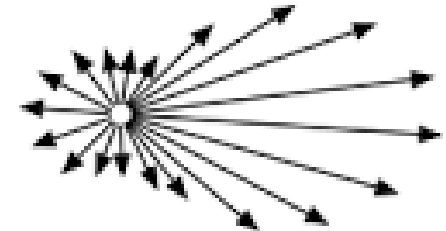
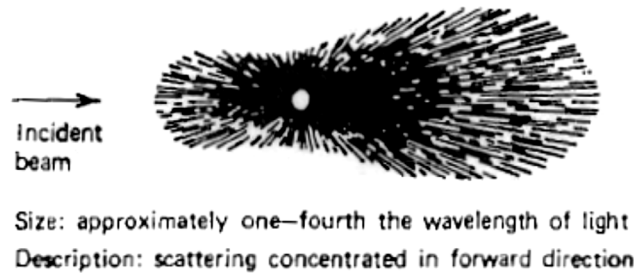
Rayleigh Scattering



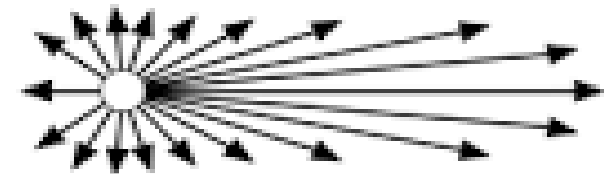
Molecular scattering as a function of scattering angle ψ :

Scattered intensity $\sim (1 + \cos^2\psi)$ for unpolarized incident light

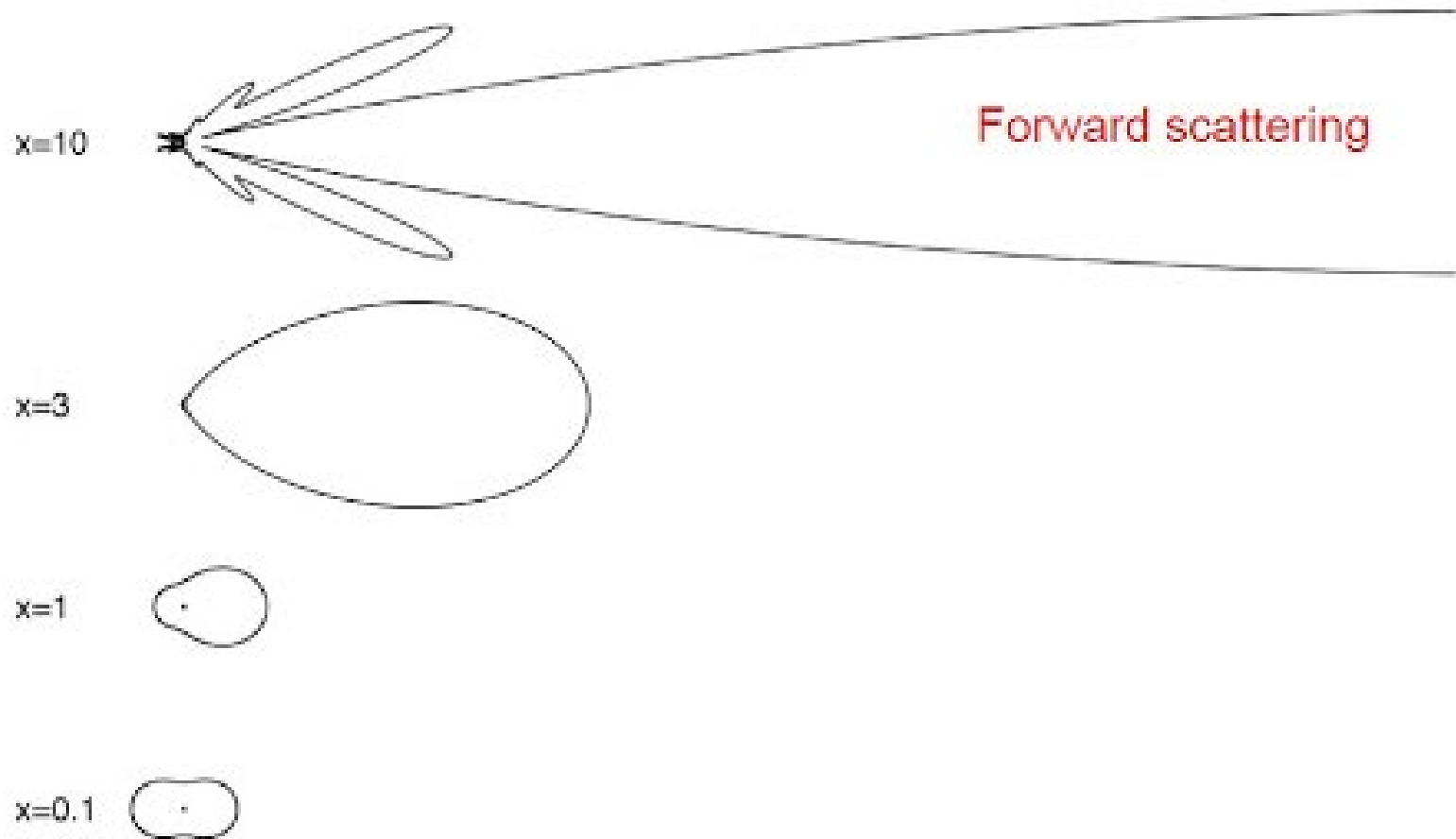
Larger particles (still smaller than the light wavelength)



Very large particles (larger than the light wavelength)

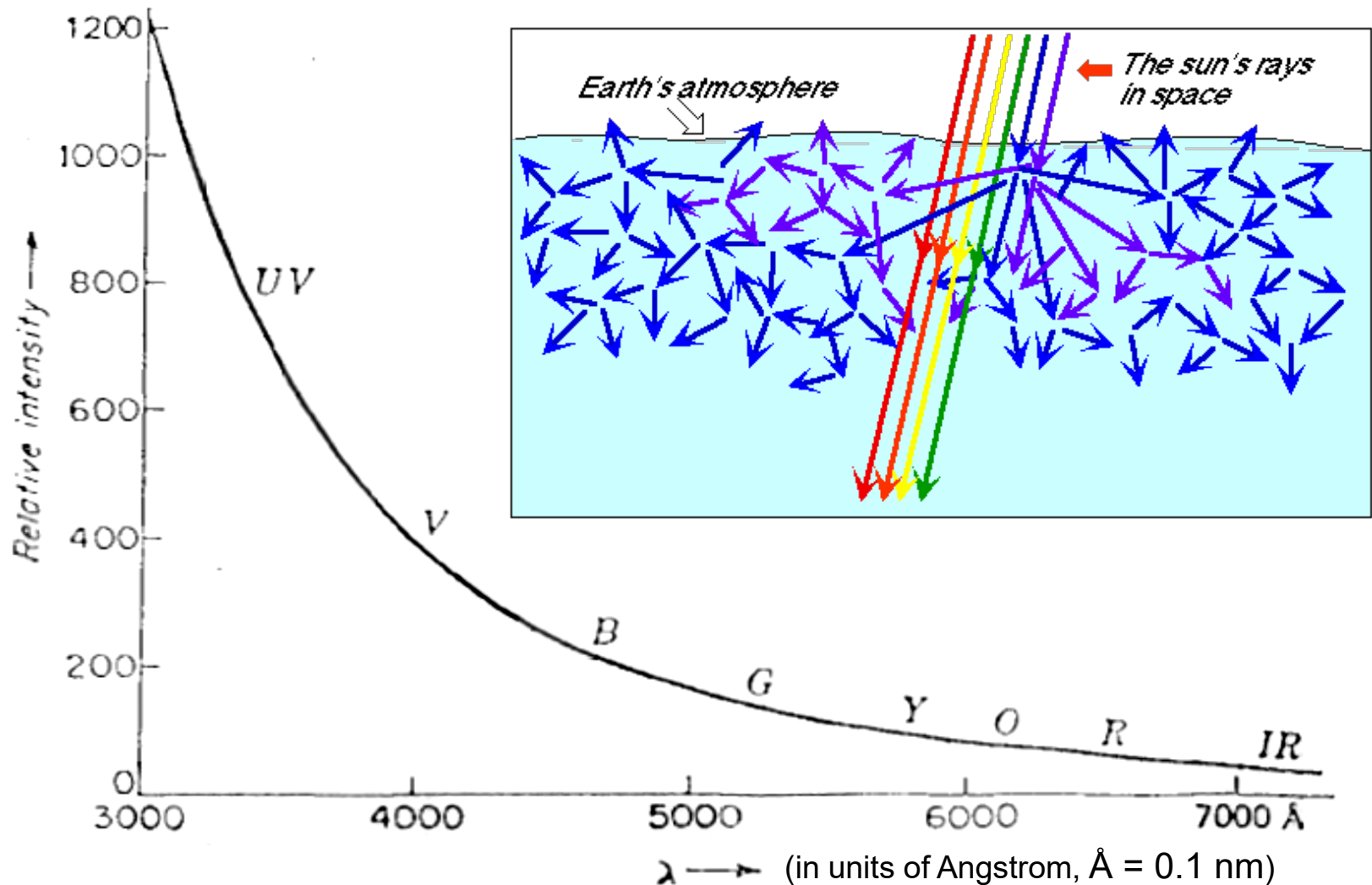


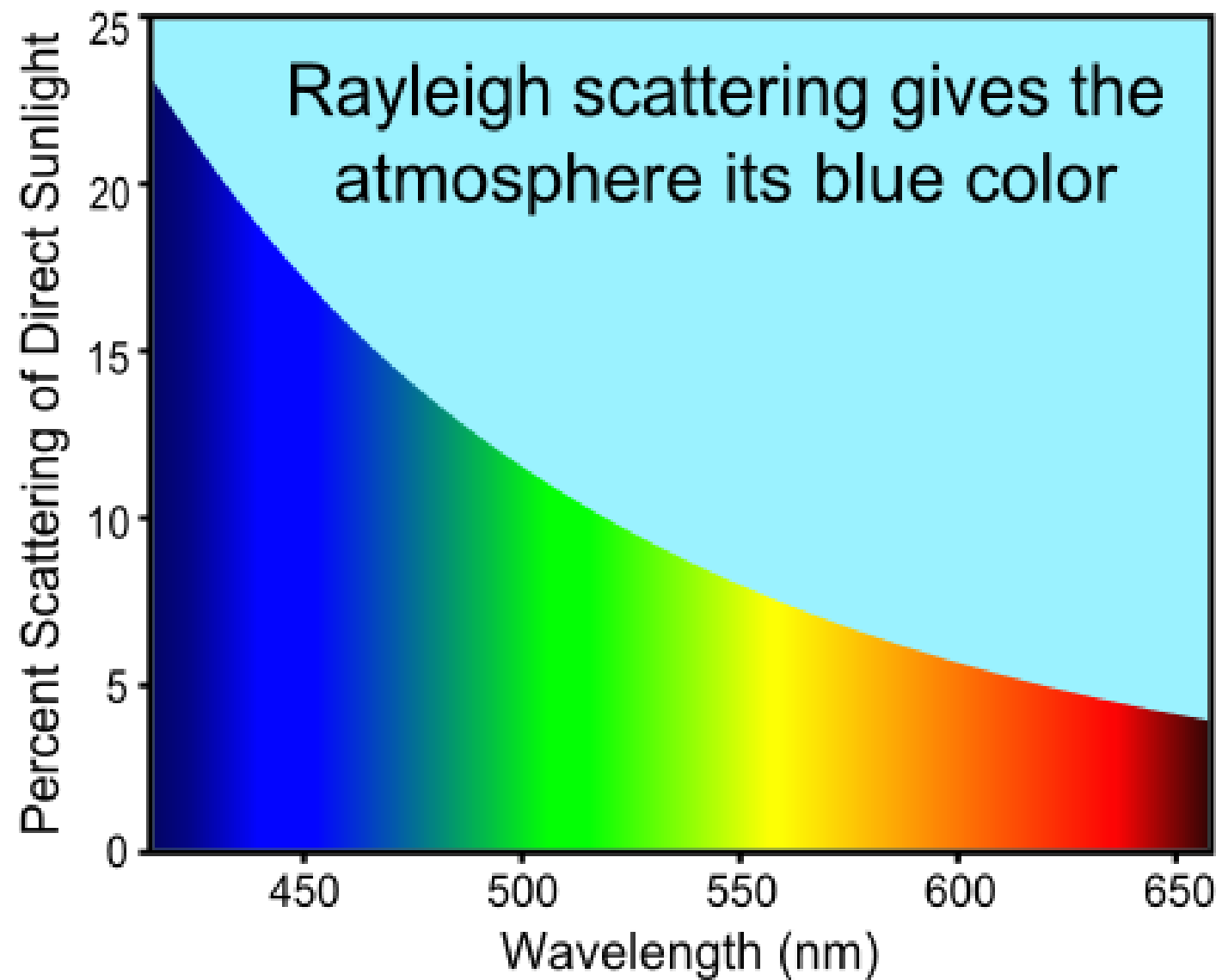
The angular distribution of light intensity scattered by a particle
for a given size parameter $x (\equiv \alpha)$
(results derived from Mie theory for spherical particles)



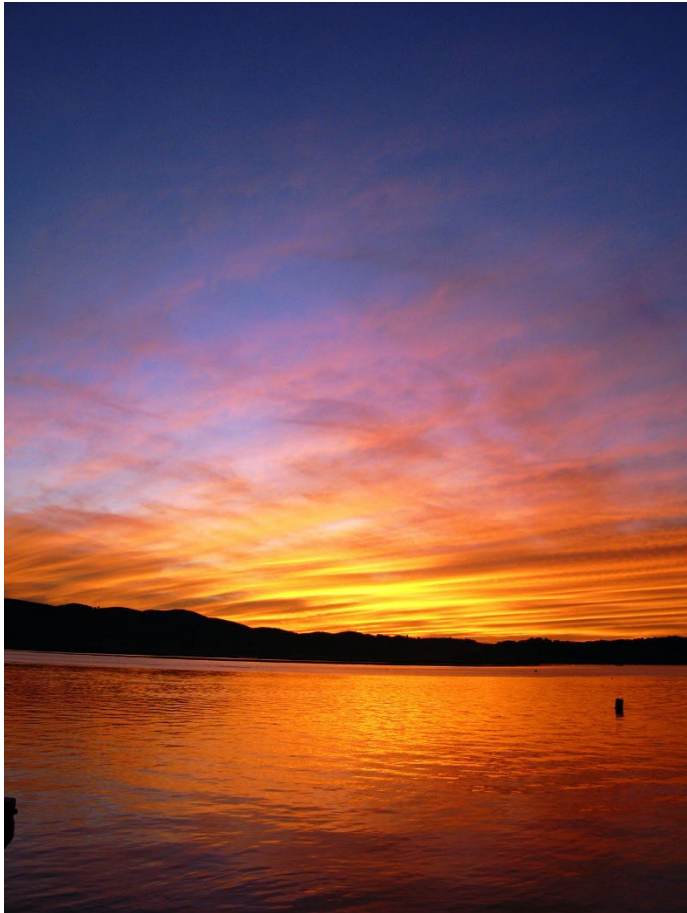
Molecular scattering as a function of light wavelength

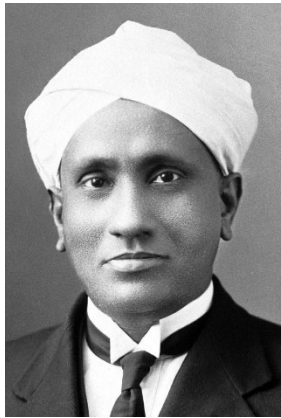
$$\text{Scattered intensity} \sim \lambda^{-4}$$





The change of sky color at sunset (red nearest the sun, blue furthest away) is caused by Rayleigh (molecular) scattering by atmospheric gas particles, which are much smaller than the wavelengths of visible light. The grey/white color of the clouds is caused by scattering by water droplets, which are of a comparable size or larger than the wavelength of visible light, resulting in a weak or no dependence of scattering on light wavelength.





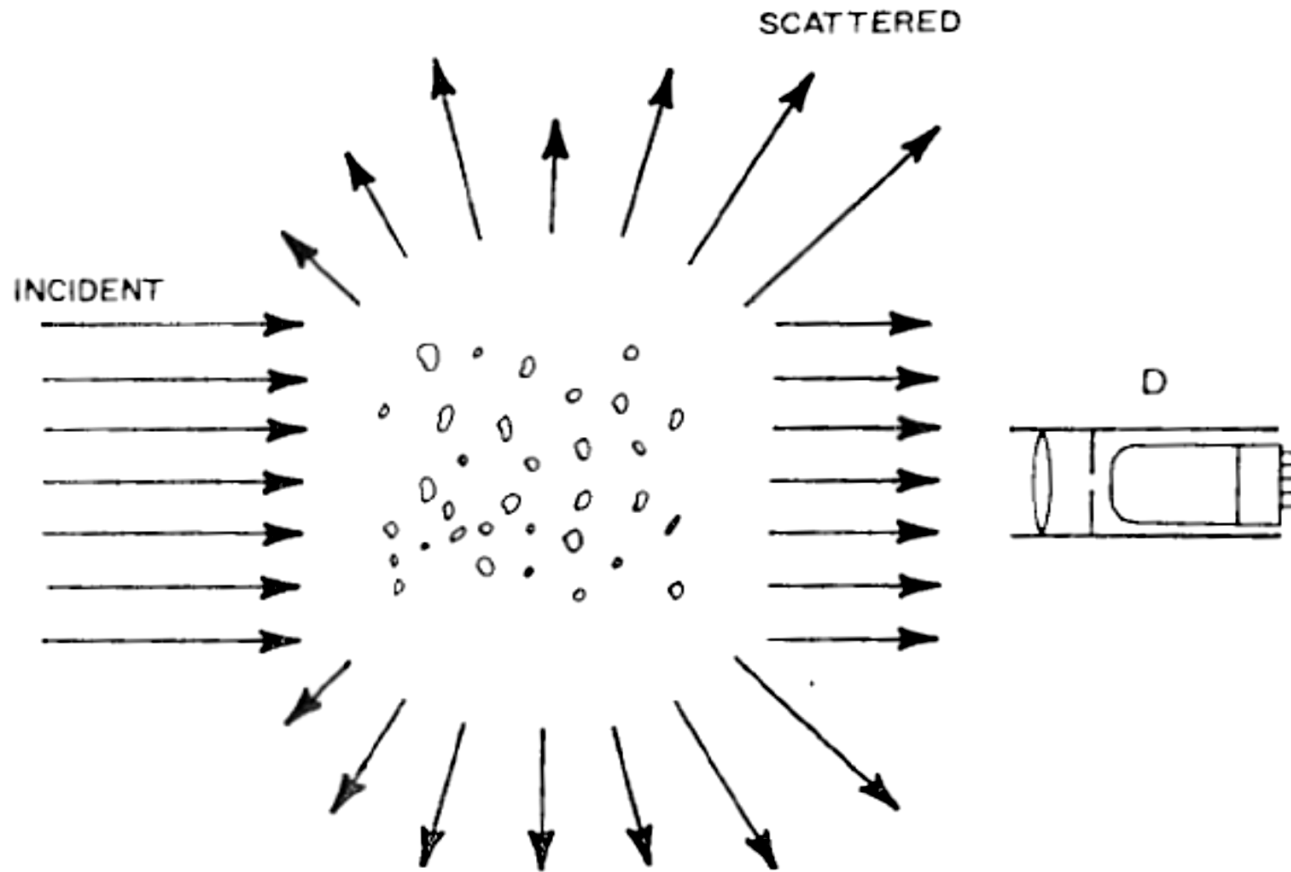
Chandrasekhara
Venkata Raman
(1888 -1970)
Nobel Prize 1930

"In the opinion of the writer, it would make for progress... to recognize that the **observed colour of the sea is primarily due to the water itself**, and that **suspended matter**, if present at all in appreciable quantity **is to be regarded as a disturbing factor**, of which the effect requires to be assessed in each individual case"

Raman, C.V. 1922, "On the molecular scattering of light in water and the colour of the sea", Proc. R. Soc. London A, 101: 64-80



Scattering by a collection of particles



Incoherent (independent) scattering (separation between particles is large and random): Scattered wavelets have random relative phases in the direction of interest. The total scattered intensity is the sum of intensities scattered by individual particles (the addition of intensities without regard to phases).

Multiple light scattering by a collection of particles

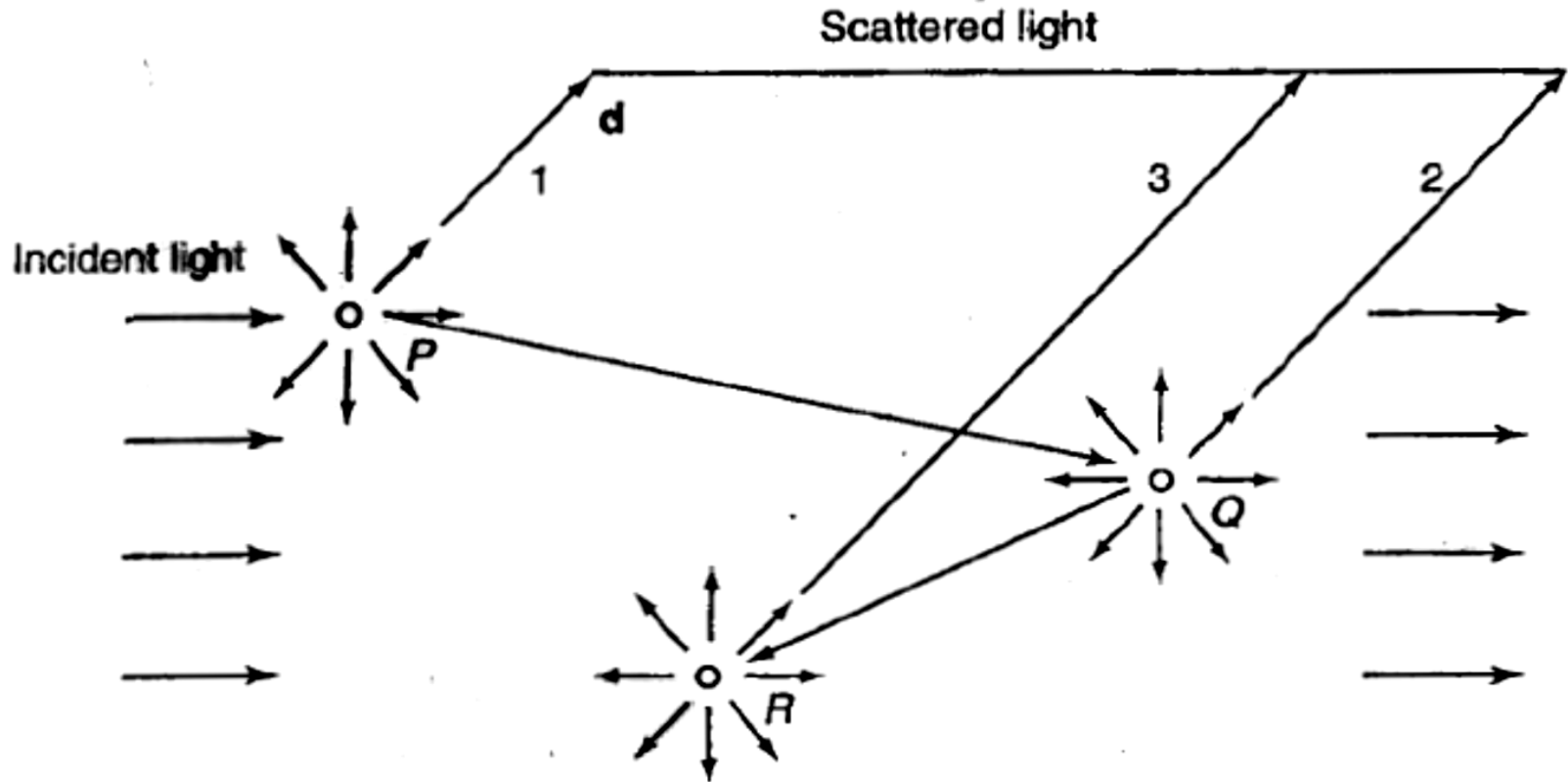


Figure 1.5 Multiple scattering process involving first (P), second (Q), and third (R) order scattering in the direction denoted by \mathbf{d} .