Interaction of Light and Matter

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Light and matter

Emission - birth of a photon

Absorption - death of a photon

Scattering - life of a photon

Emission of Light

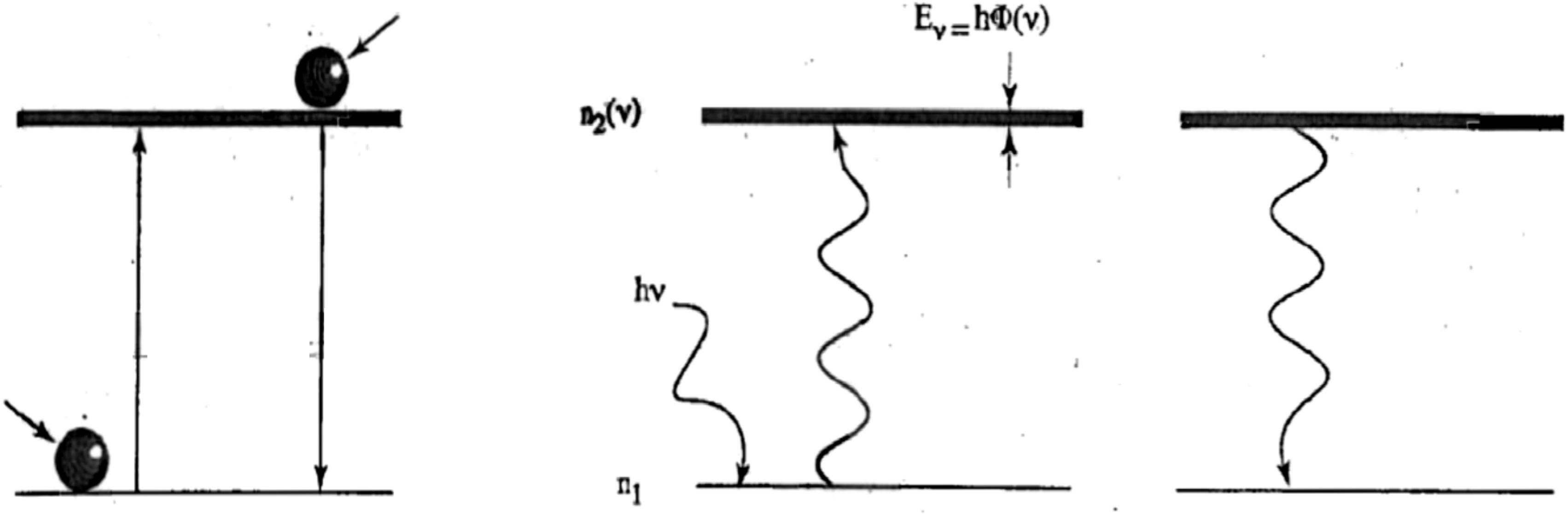
Thermal radiation

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



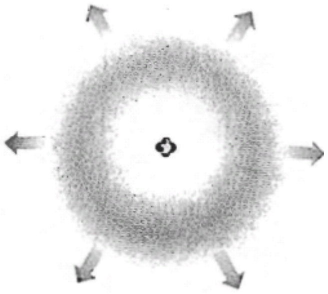
Collisional
Excitation & Quenching

Radiative absorption

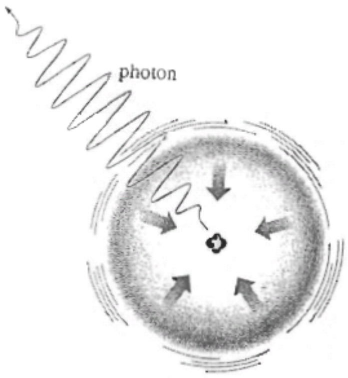
Emission
Spontaneous

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

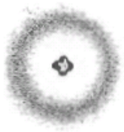
Light and Atoms



Excitation of the ground state



De-excitation with emission of a photon



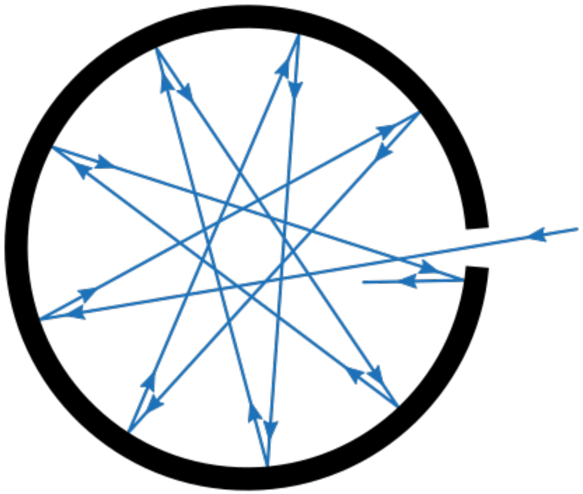
Ground state ~10^{-9} - 10^{-8} sec later

Hecht 1994

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.

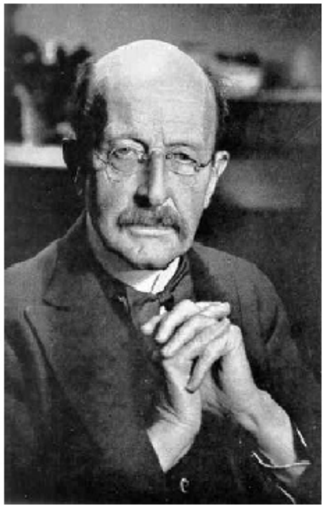


All radiant energy entering the blackbody is absorbed at the internal surfaces. In reverse, an aperture of a heated blackbody (temperature T > 0^o K) is a source of thermal radiation emitted by blackbody. For an ideal blackbody in thermal equilibrium (i.e., at a constant temperature T) the emitted energy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

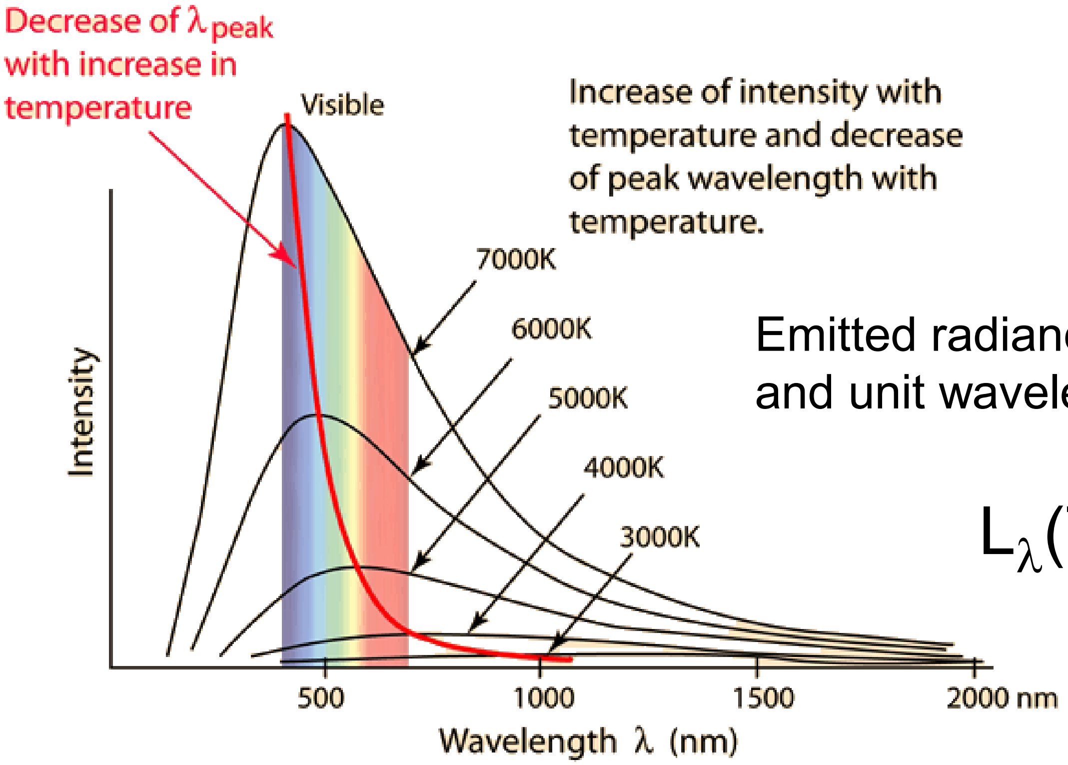
An ideal blackbody in thermal equilibrium has two notable properties:
(1) It is an ideal emitter: at every frequency/wavelength, it emits as much or more thermal radiative energy as any other body at the same temperature.
(2) It is a diffuse emitter: measured per unit area perpendicular to the direction,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

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

Increase of intensity with temperature and decrease of peak wavelength with 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 = $6.626 * 10^{-34}\ J * s$
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 proportional to the fourth power of the Kelvin temperature *T* of the object

Joseph Stefan
(1835 - 1893)

Emitted irradiance or exitance (energy/ (time area)

$$E = \sigma T^4$$

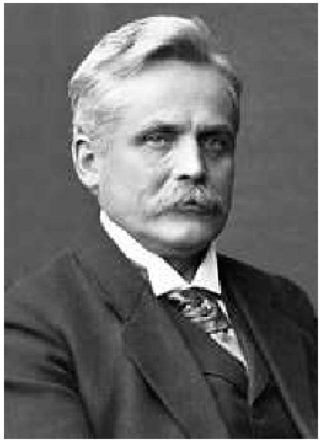
where σ (sigma) = 5.67×10^{-8} Wm^{-2} K^{-4}

and T is the temperature in Kelvin

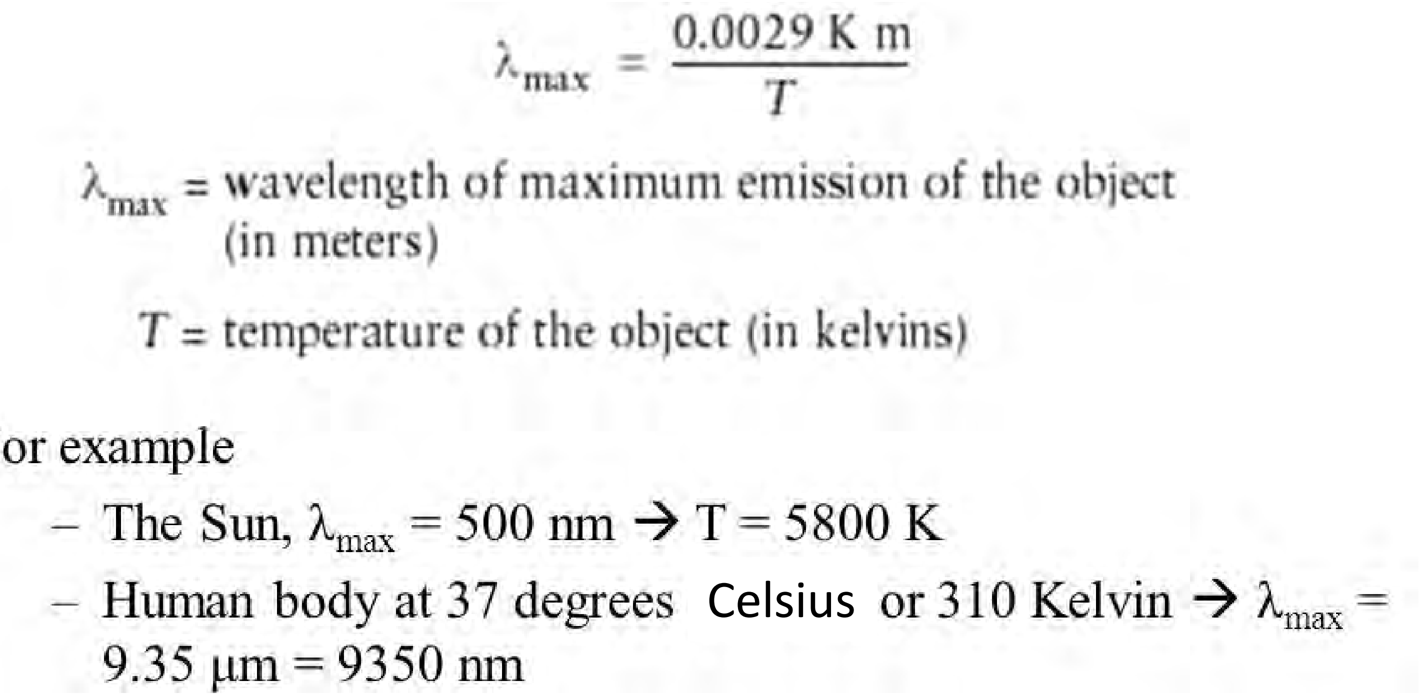
Ludvig Boltzmann
(1844 - 1906)

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



Wilhelm Wien (1864 - 1928)
Nobel Prize 1911



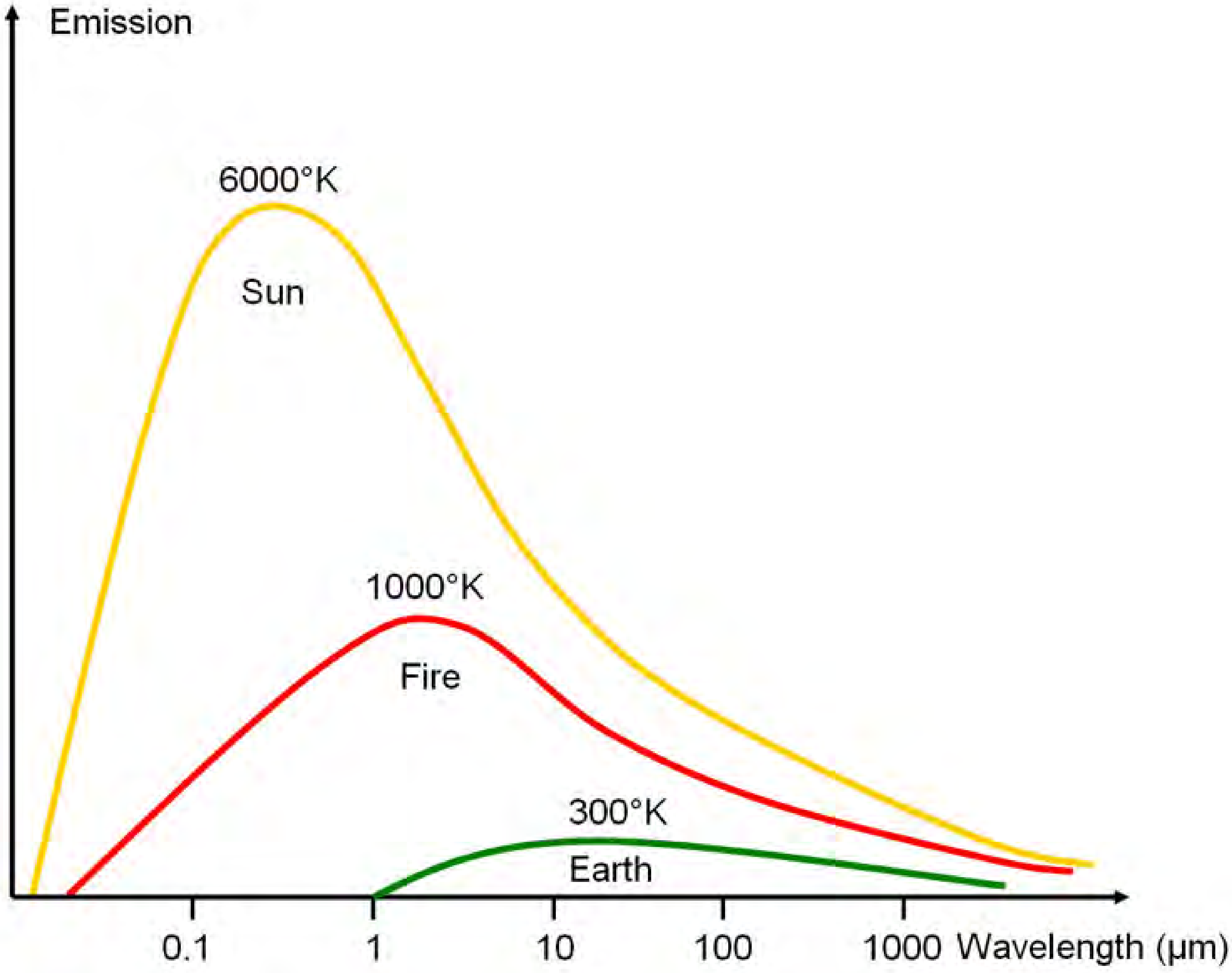
$$\lambda_{\text{max}} = \frac{0.0029\ \text{K m}}{T}$$

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

T = temperature of the object (in kelvins)

For example

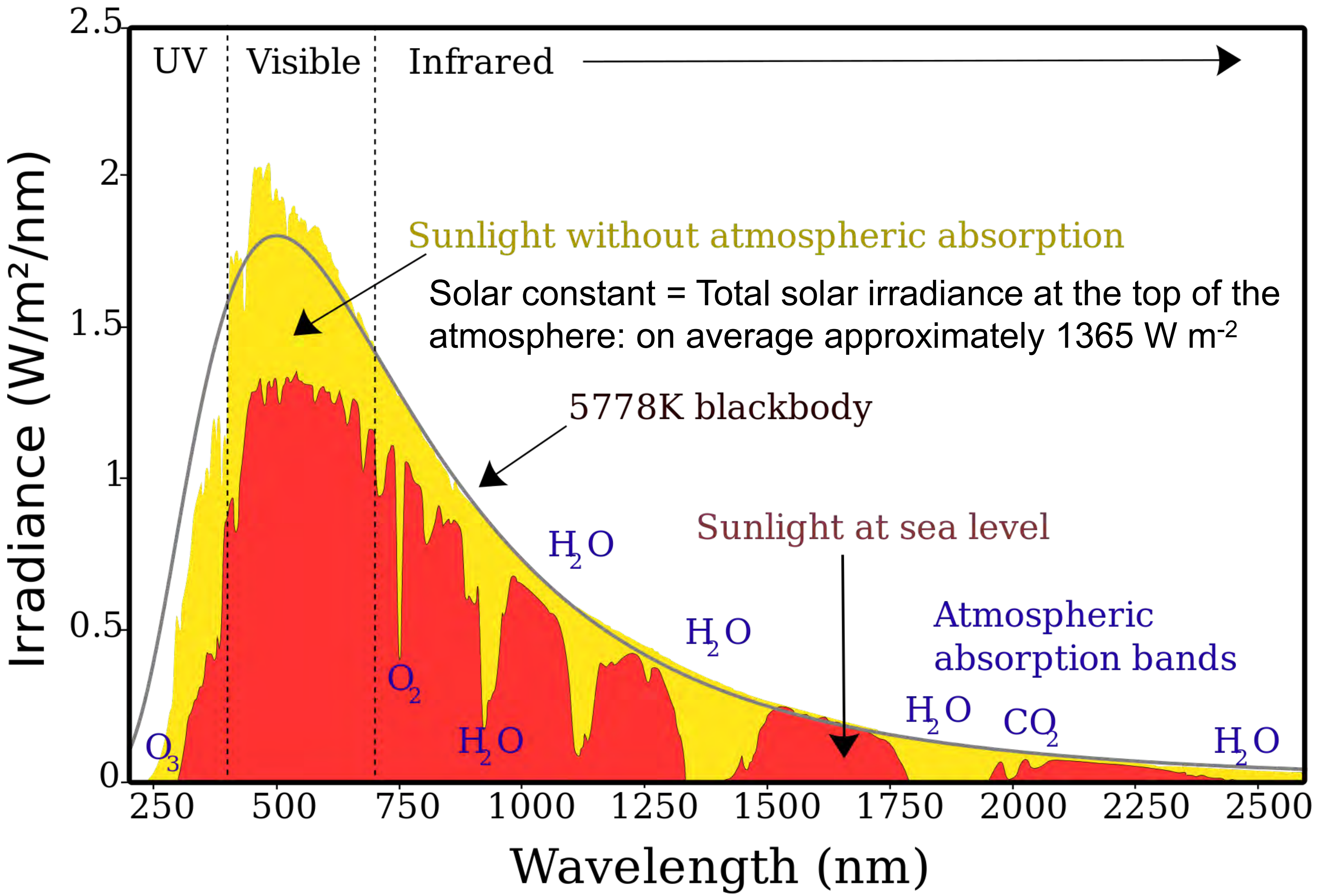
- The Sun, $\lambda_{\text{max}} = 500$ nm → T = 5800 K
- Human body at 37 degrees Celsius or 310 Kelvin → $\lambda_{\text{max}} = 9.35\ \mu\text{m} = 9350$ nm
- Earth at 15°C or 288 K → $\lambda_{\text{max}} \approx 10\ \mu\text{m} = 10000$ nm



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

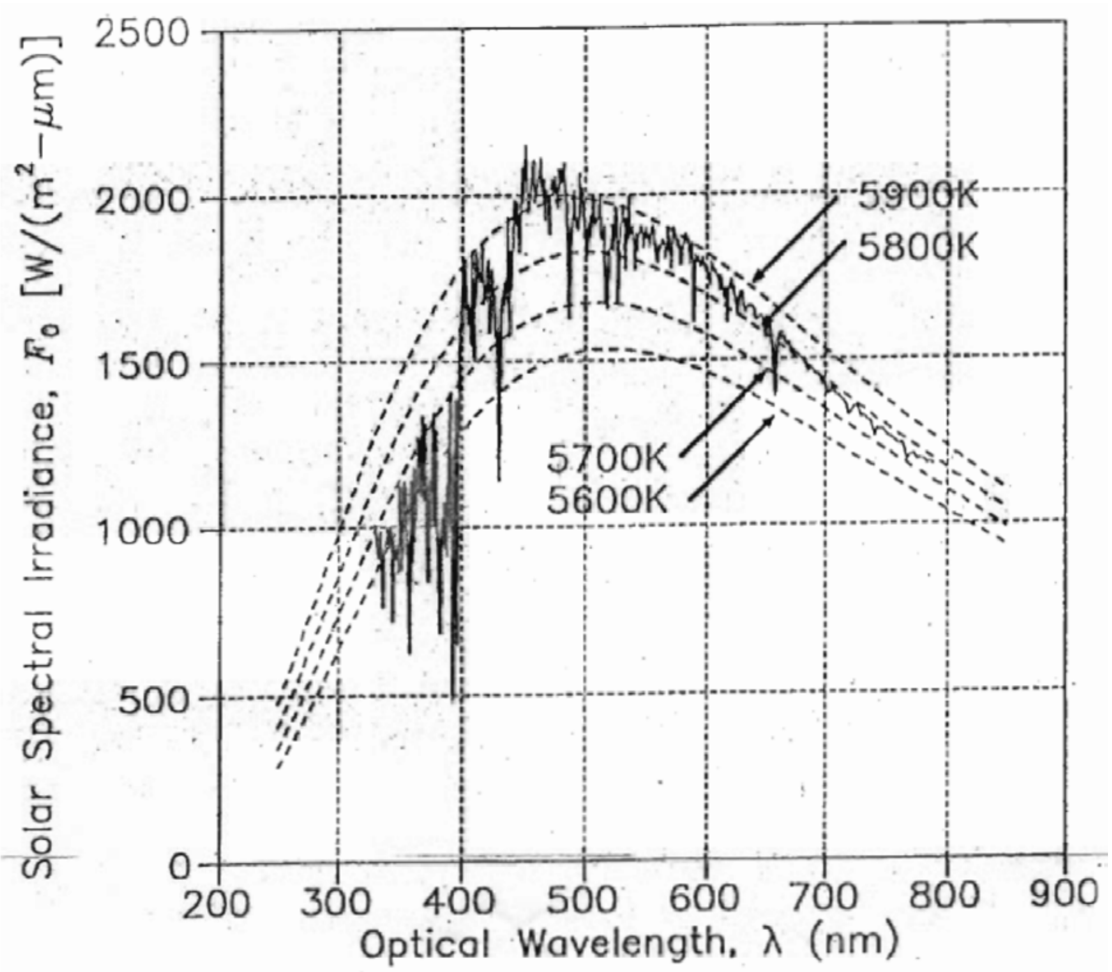
Ocean optics is concerned primarily with the study of relatively narrow range of electromagnetic spectrum from near-UV through visible to near-IR

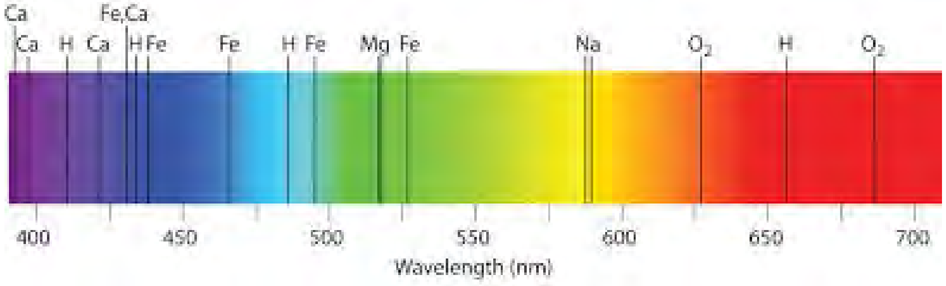
Spectrum of solar radiation



Solar constant = Total solar irradiance at the top of the atmosphere: on average approximately 1365 W m^{-2}

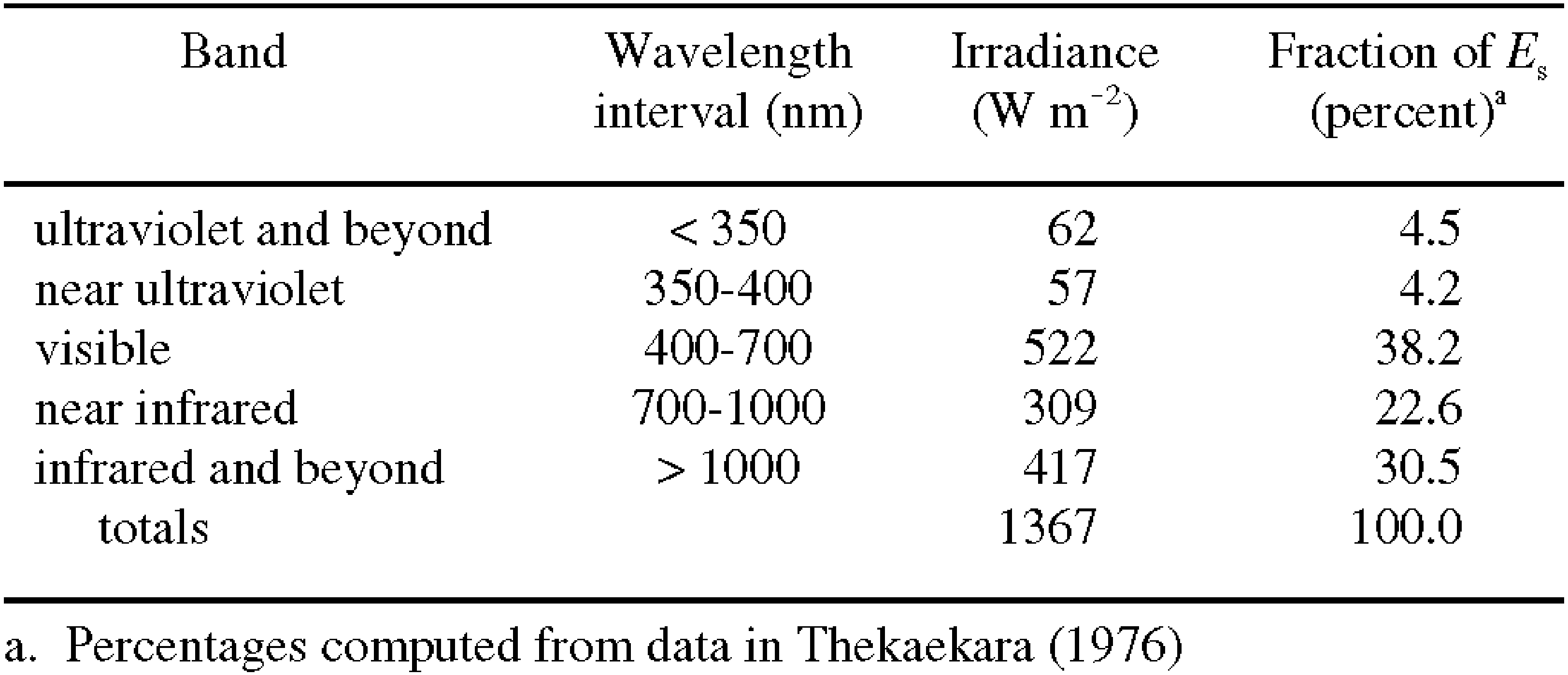
Solar spectral irradiance outside the Earths's atmosphere





Walker 1994

Distribution of the solar constant in various wavelength bands



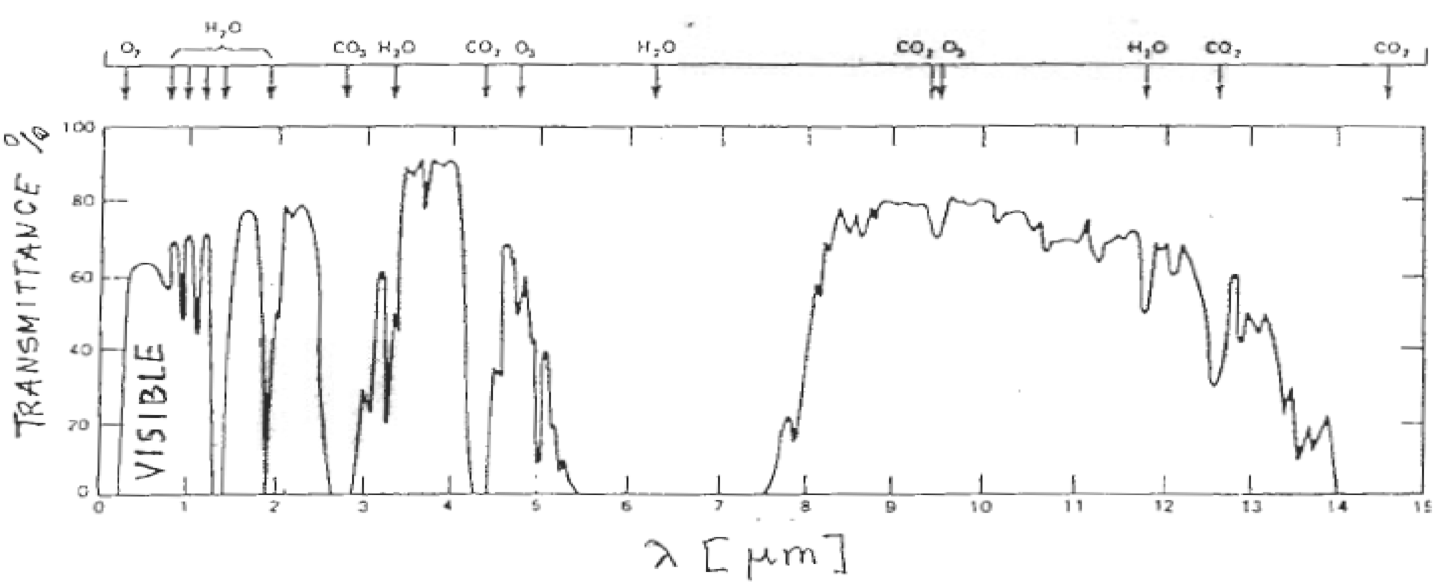
Band	Wavelength interval (nm)	Irradiance (W m^{-2})	Fraction of E_s (percent)[a]
ultraviolet and beyond	< 350	62	4.5
near ultraviolet	350-400	57	4.2
visible	400-700	522	38.2
near infrared	700-1000	309	22.6
infrared and beyond	> 1000	417	30.5
totals		1367	100.0

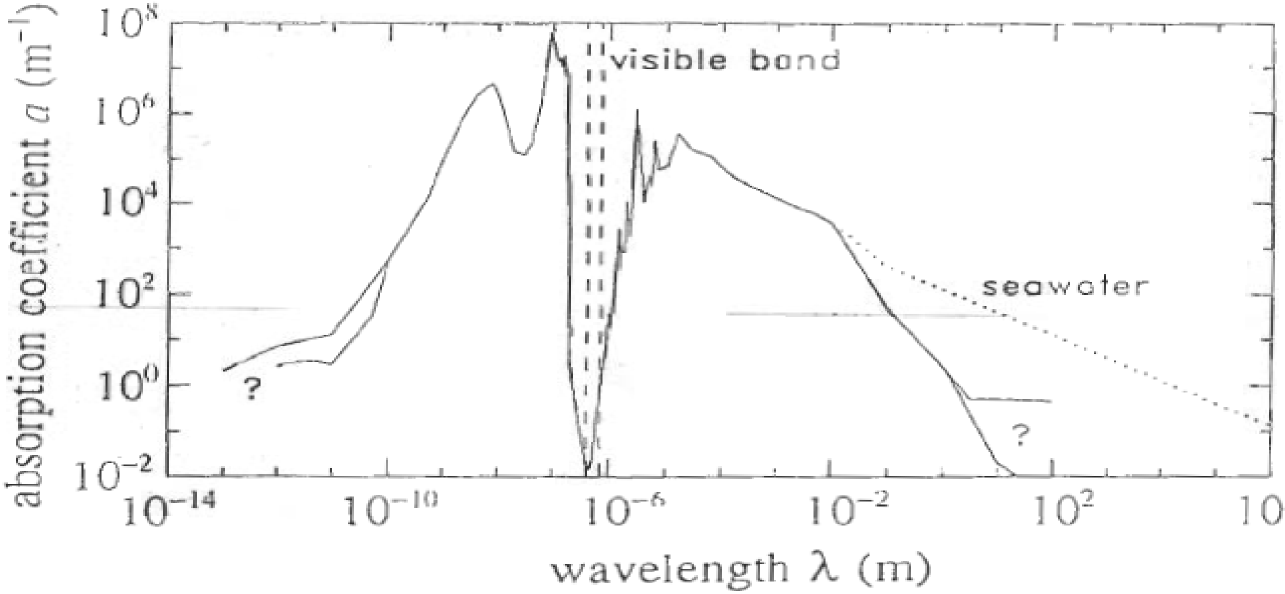
a. Percentages computed from data in Thekaekara (1976)

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.

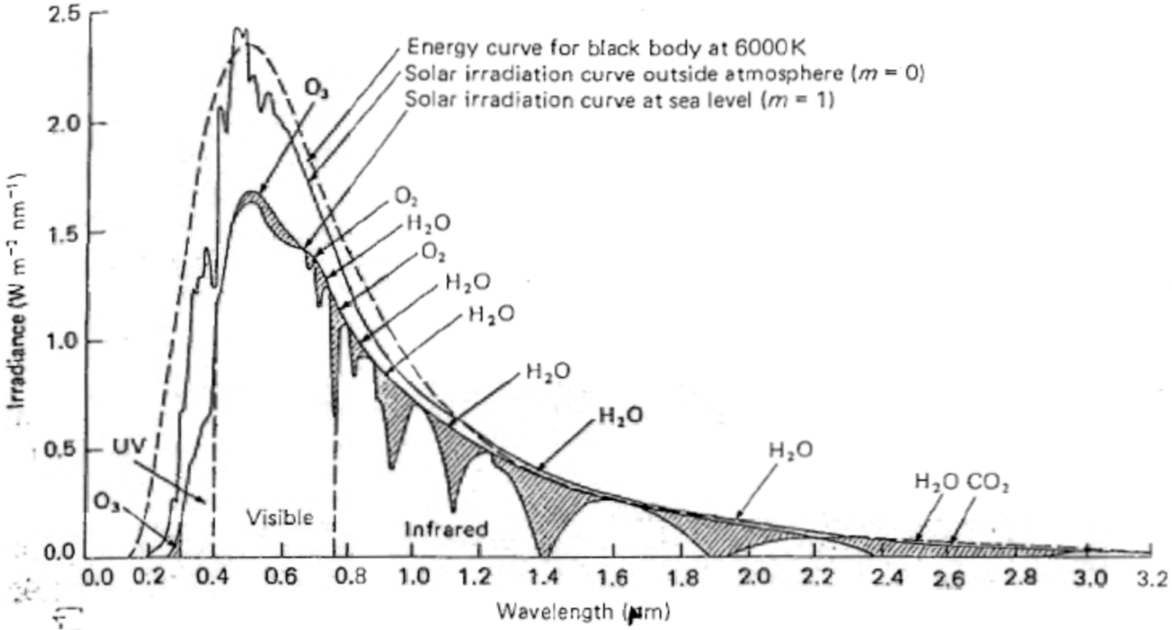
Mobley 1994

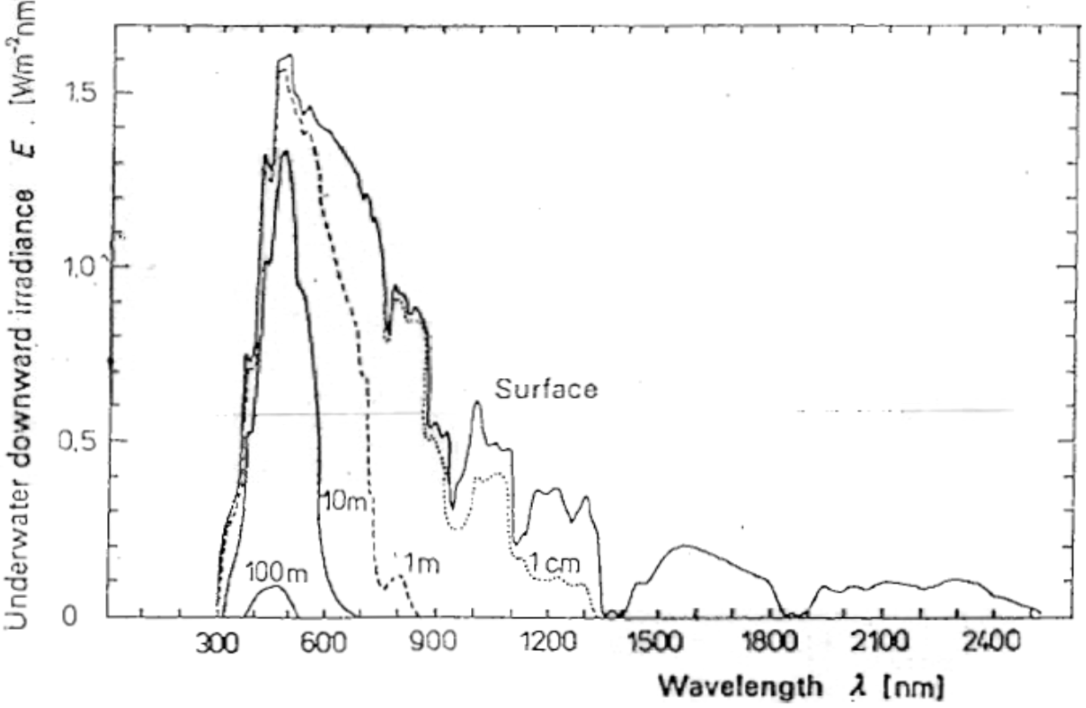
Overlap of “window” in atmospheric transmittance with minimum of water absorption in the visible band





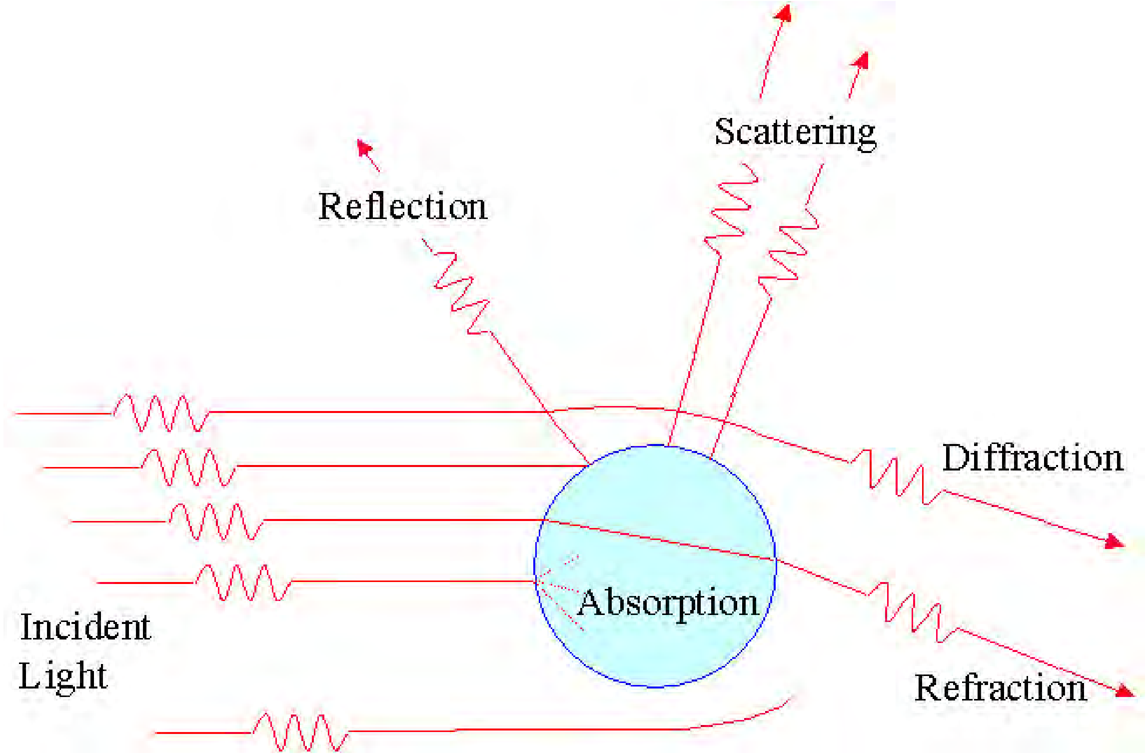
Spectra of Solar Irradiance





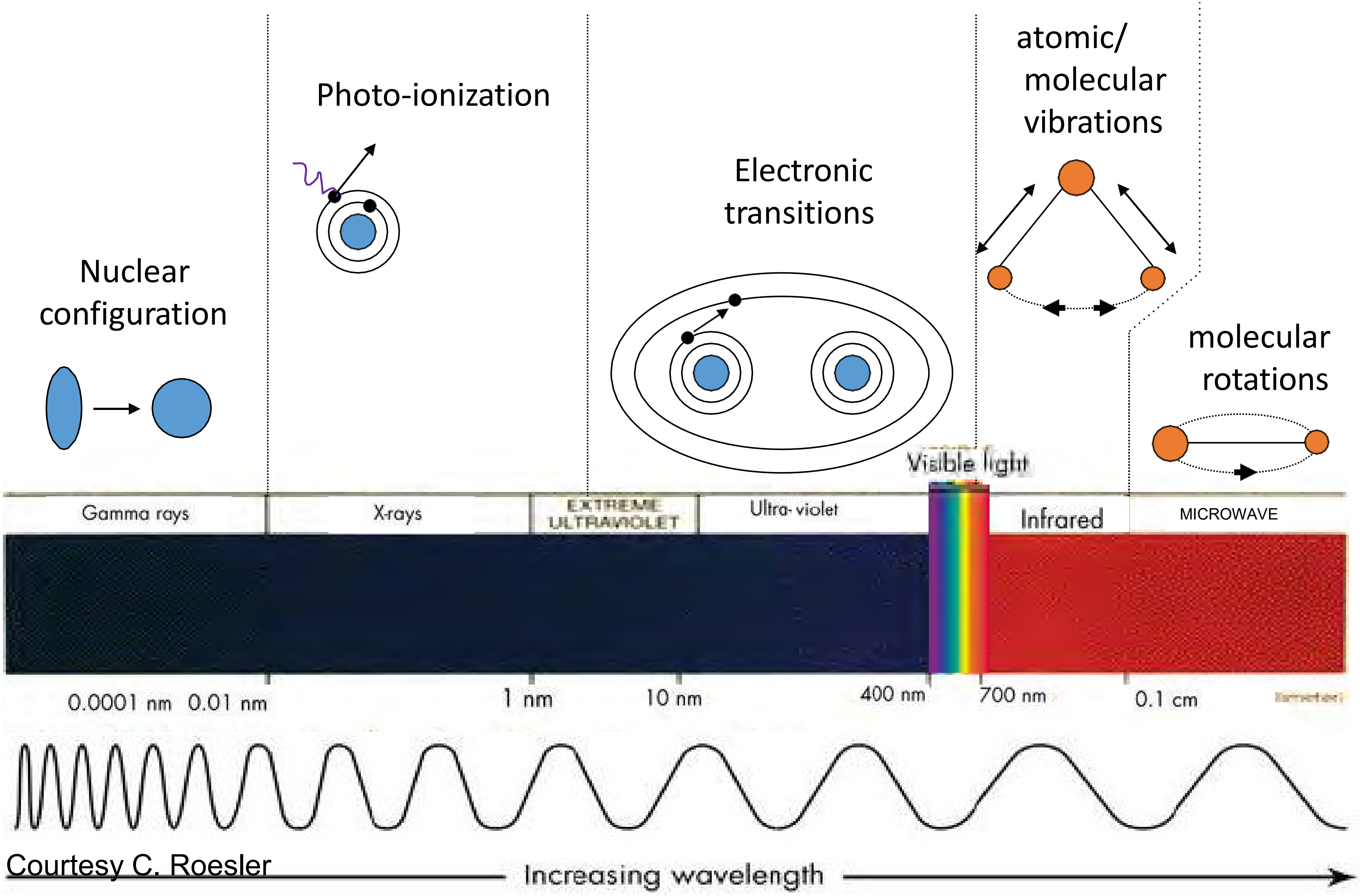
Interaction of light and matter

Scattering - life of photon



Absorption - death of photon

Interactions between radiant energy and matter across the electromagnetic spectrum



Nuclear configuration

Photo-ionization

Electronic transitions

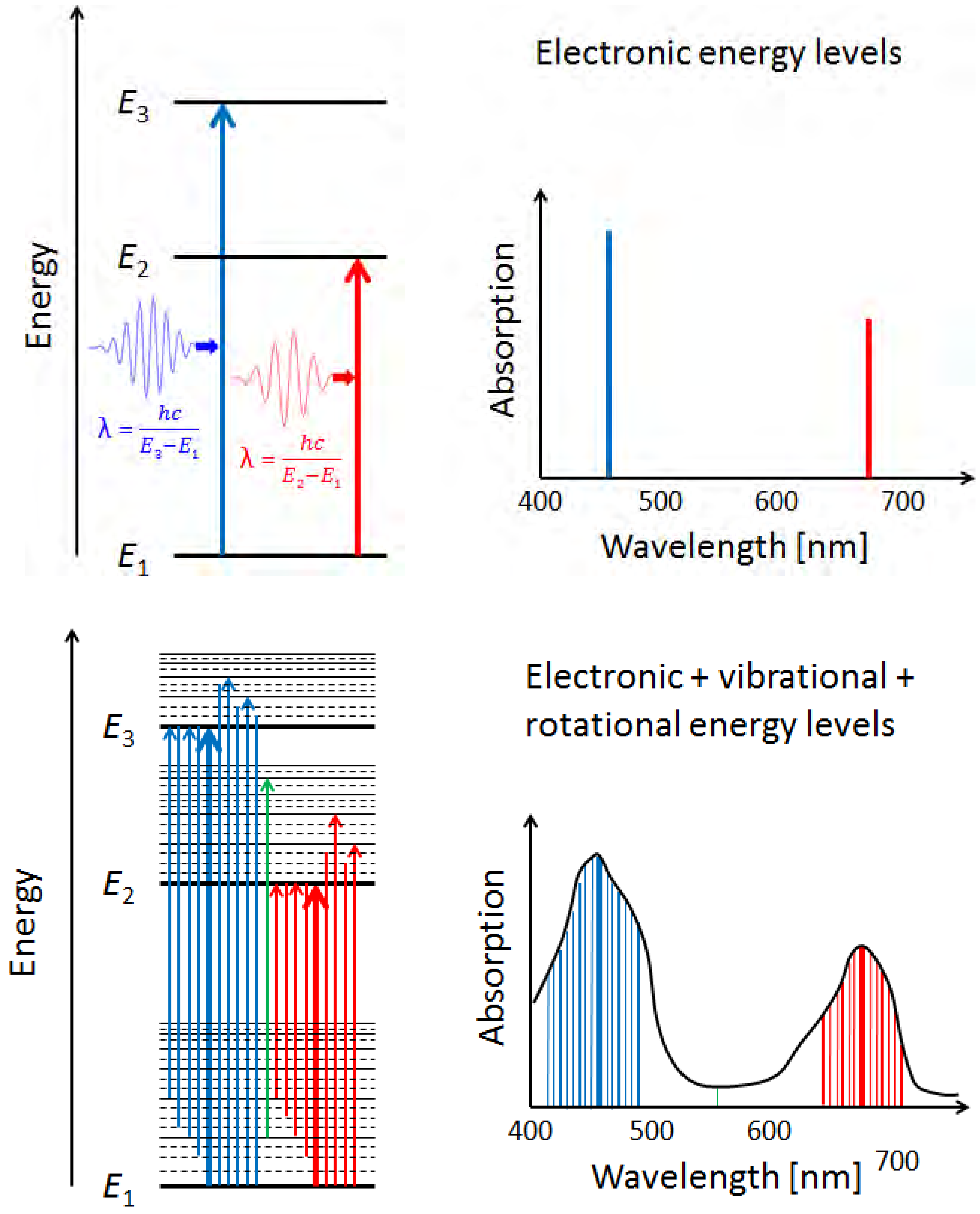
atomic/ molecular vibrations

molecular rotations

Courtesy C. Roesler

Absorption and quantized energy states of atoms/molecules

- Atoms/molecules can absorb quantized amount of radiant energy by moving an electron to another orbital shell, i.e. electronic state transition
- Each electronic state is associated with a series of vibrational and rotational energy states, which are also quantized and can change as a result of absorption of quantized amount of energy. Many substances exhibit continuous absorption spectra due to multiplicity of energy states



Electronic energy levels

Electronic + vibrational + rotational energy levels

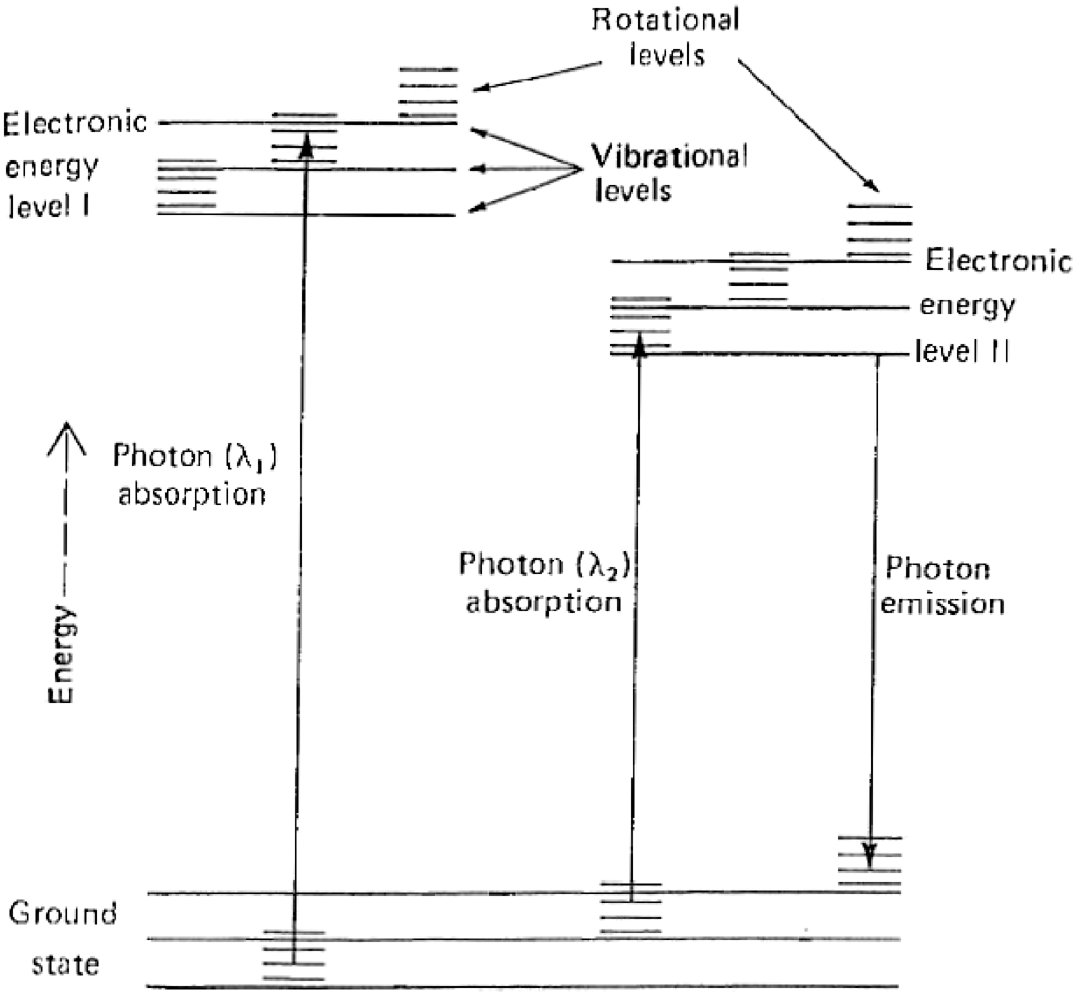
Courtesy C. Roesler

Internal energy levels and absorption by atoms/molecules

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

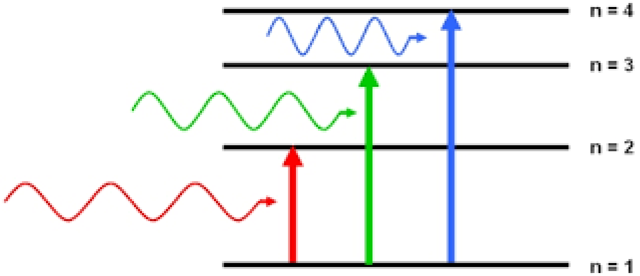
Vibrational:
energy ~4 – 40 kJ/mol
λ ~1 – 20 μm

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



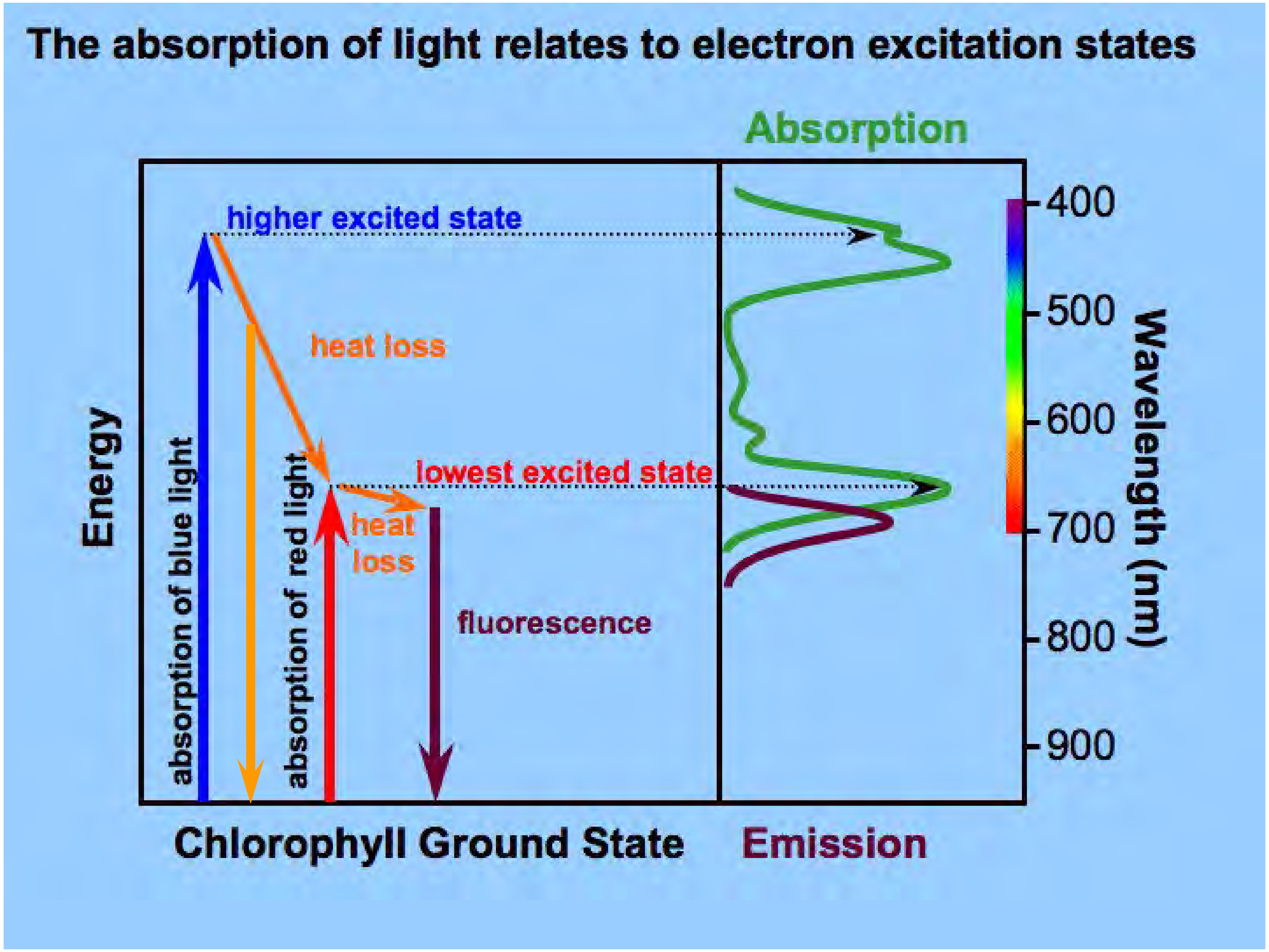
For comparison, the average kinetic energy (translatory motion) at room temperature is ~4 kJ/mol

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



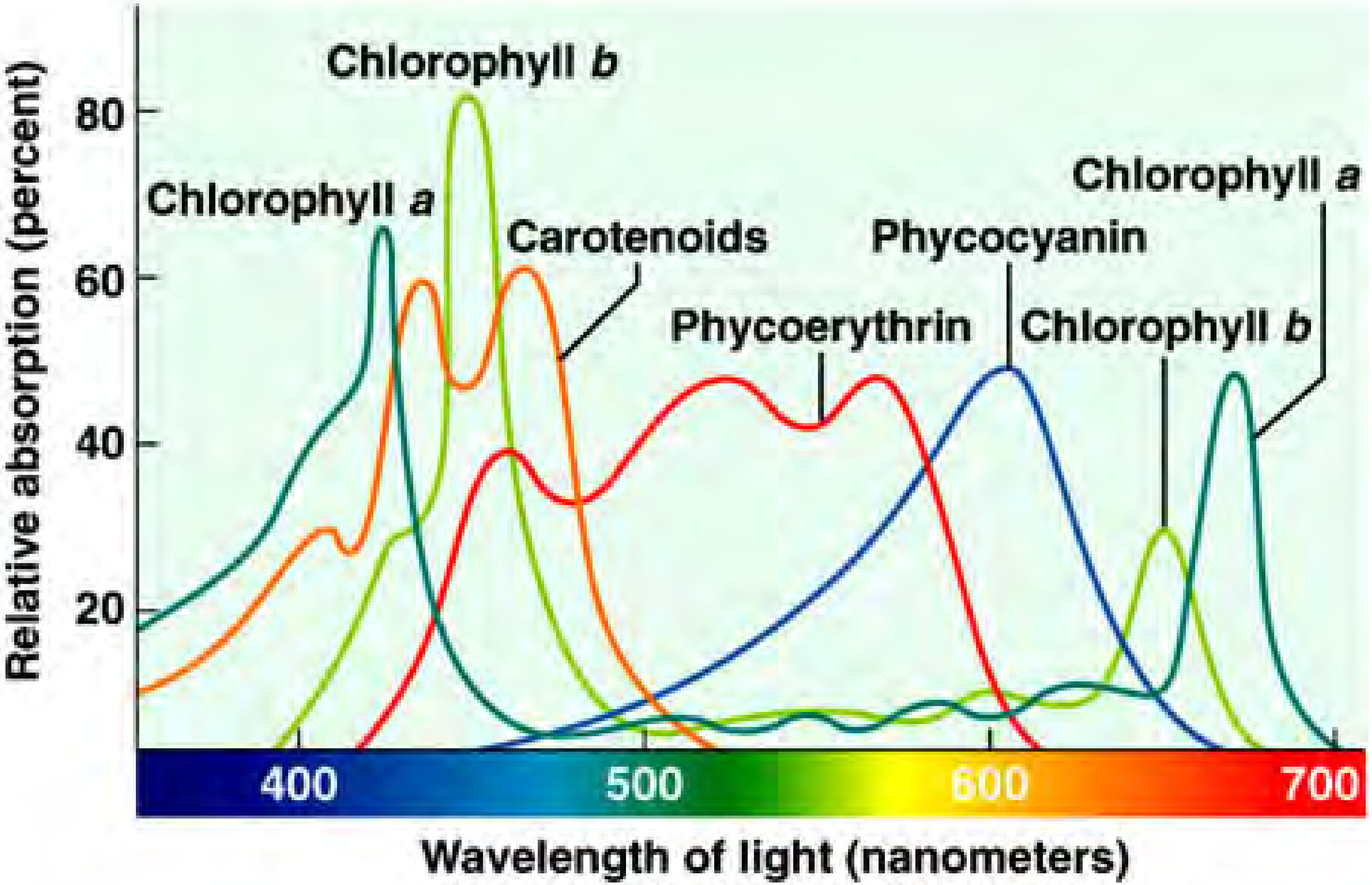
Kirk 1993

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



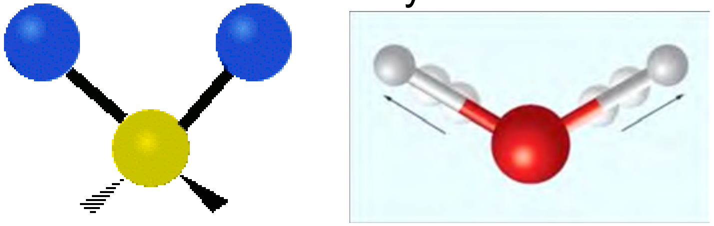
Courtesy C. Roesler

Absorption spectra of plant pigments

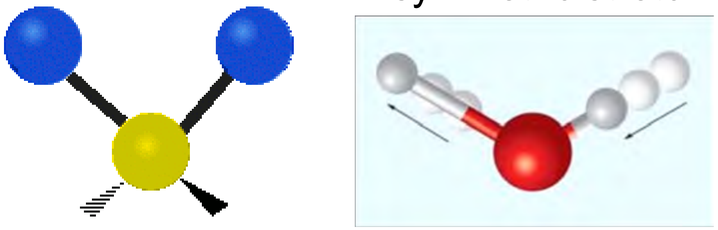


Absorption mechanism associated with water molecule vibrations

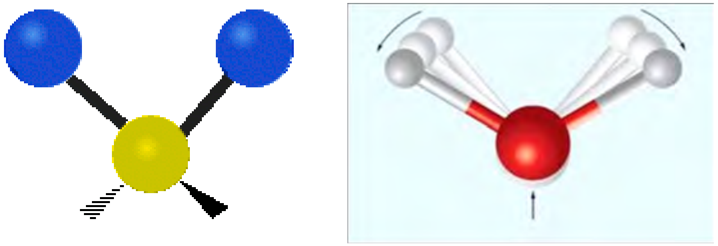
Symmetric stretch

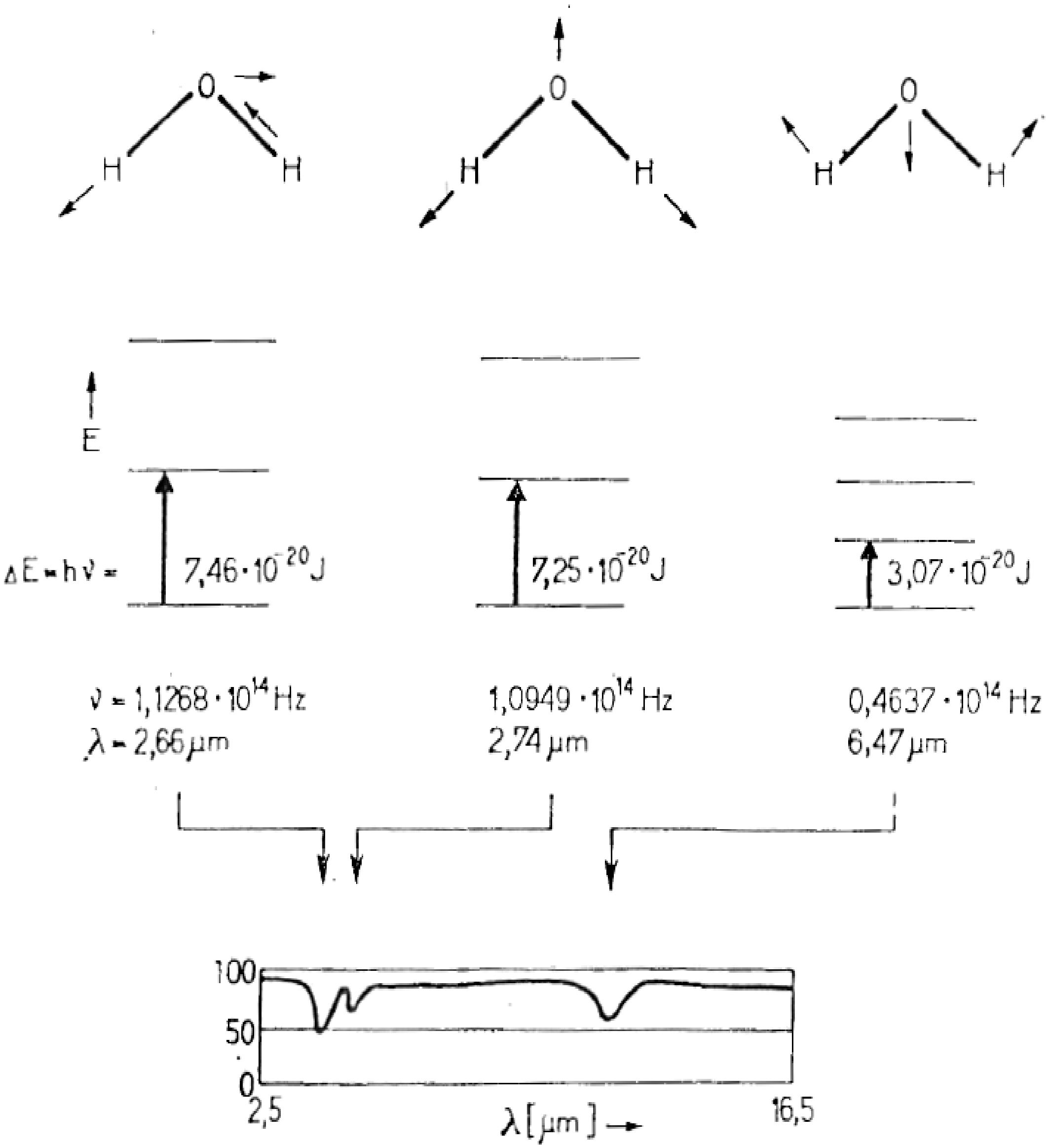


Asymmetric stretch

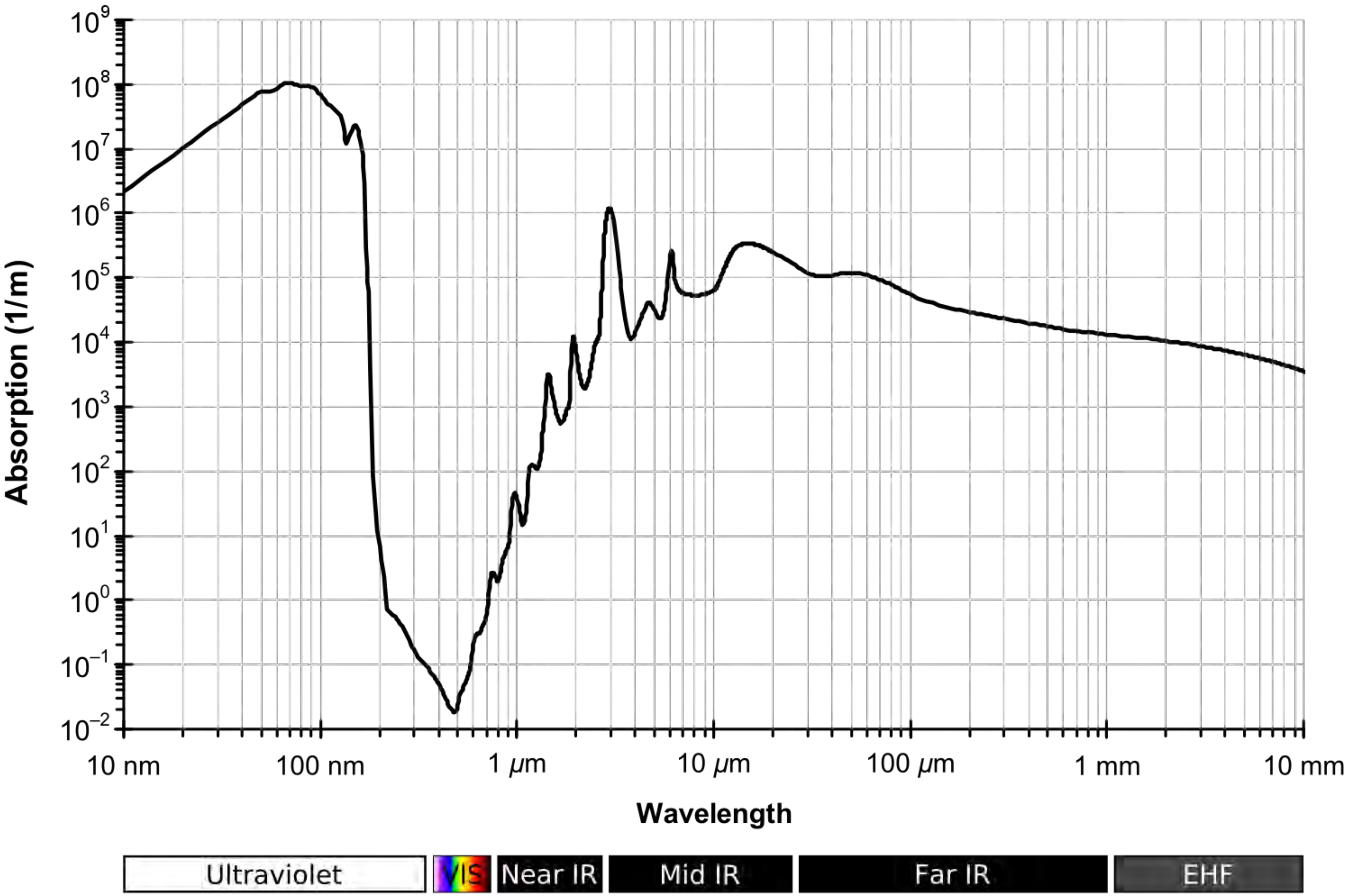


Bend

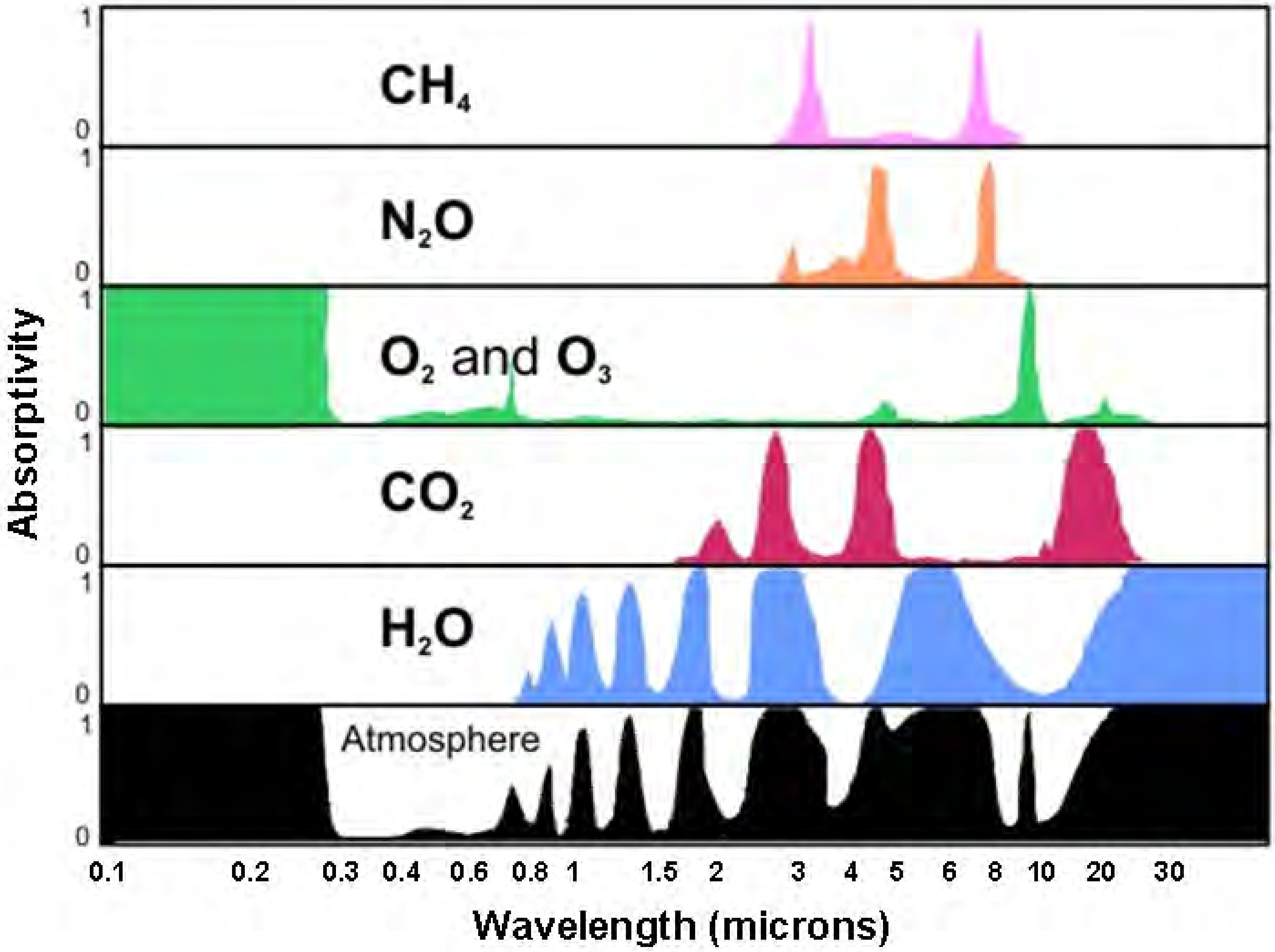




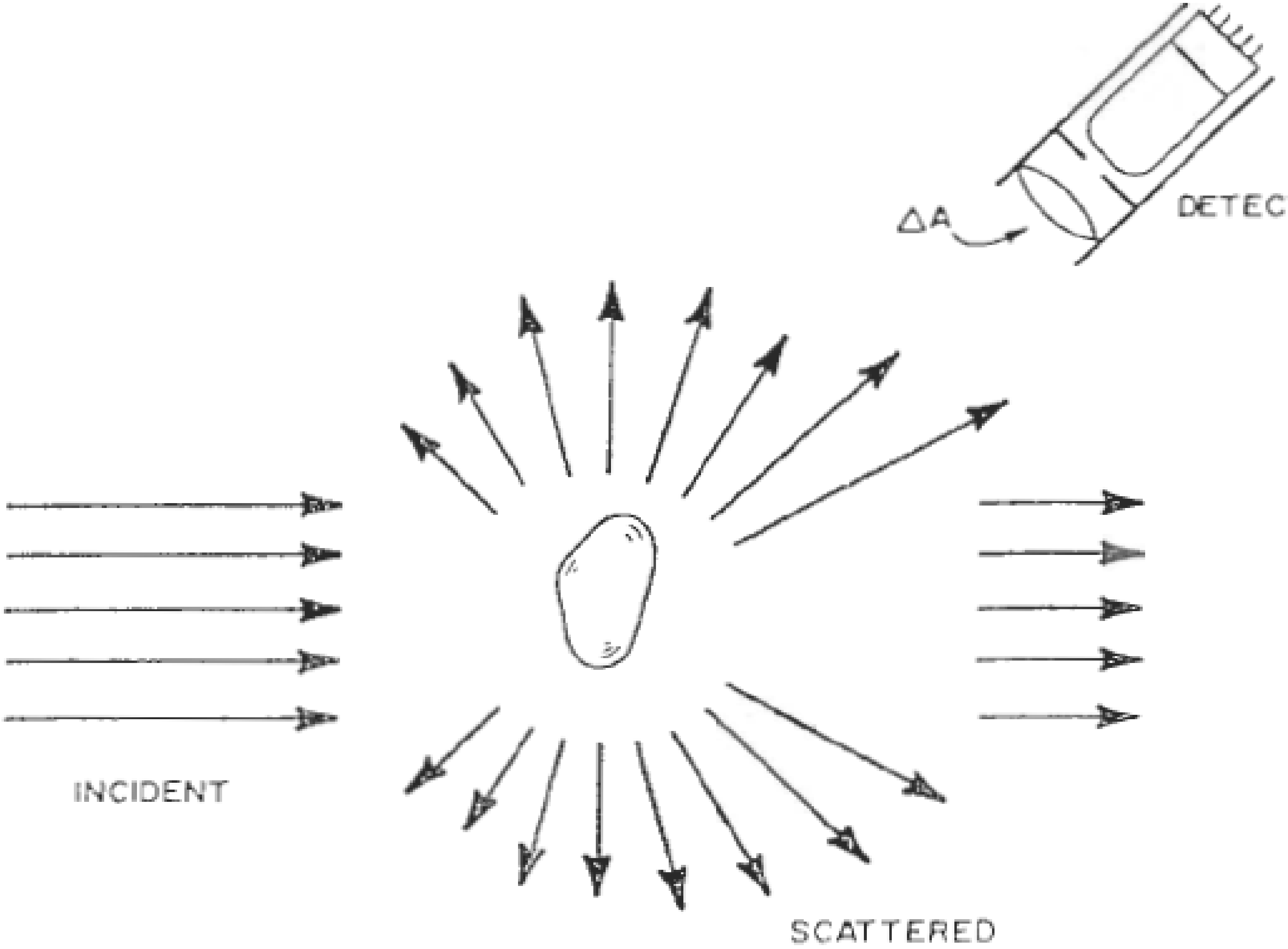
Absorption spectrum of water molecules



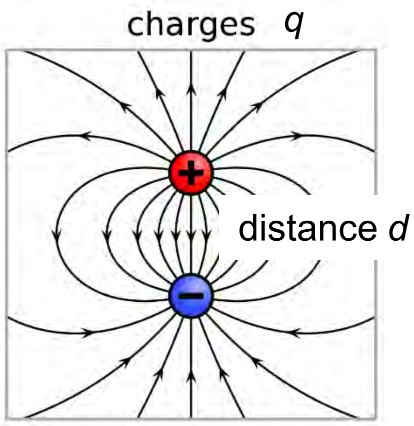
Absorption spectra of atmospheric molecules



Scattering of light by inhomogeneity of the medium

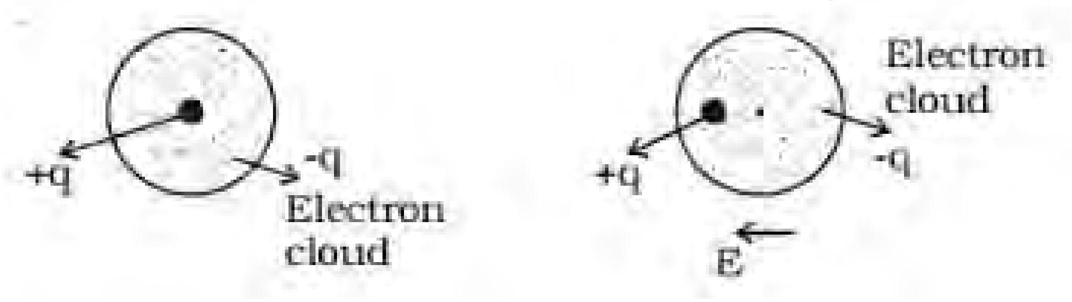


Electromagnetic radiation of an oscillating dipole: Mechanism of light scattering



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

Induced dipole

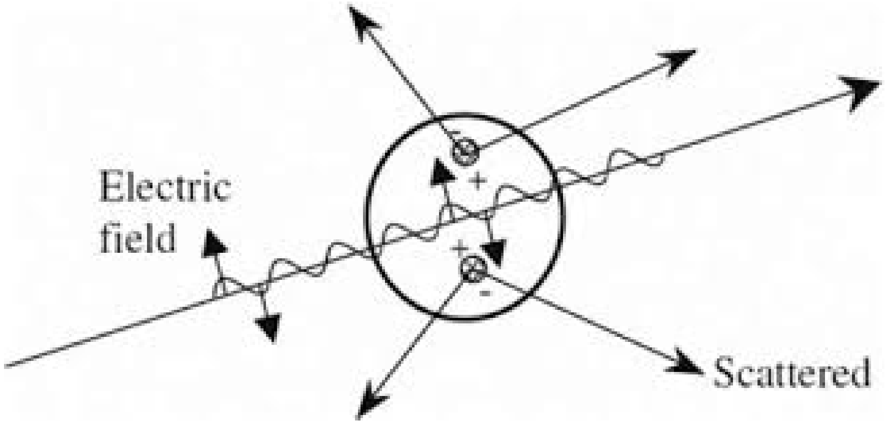


$$p_{\text{induced}} = \alpha\ E$$

Dipole moment induced by an electric field E

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

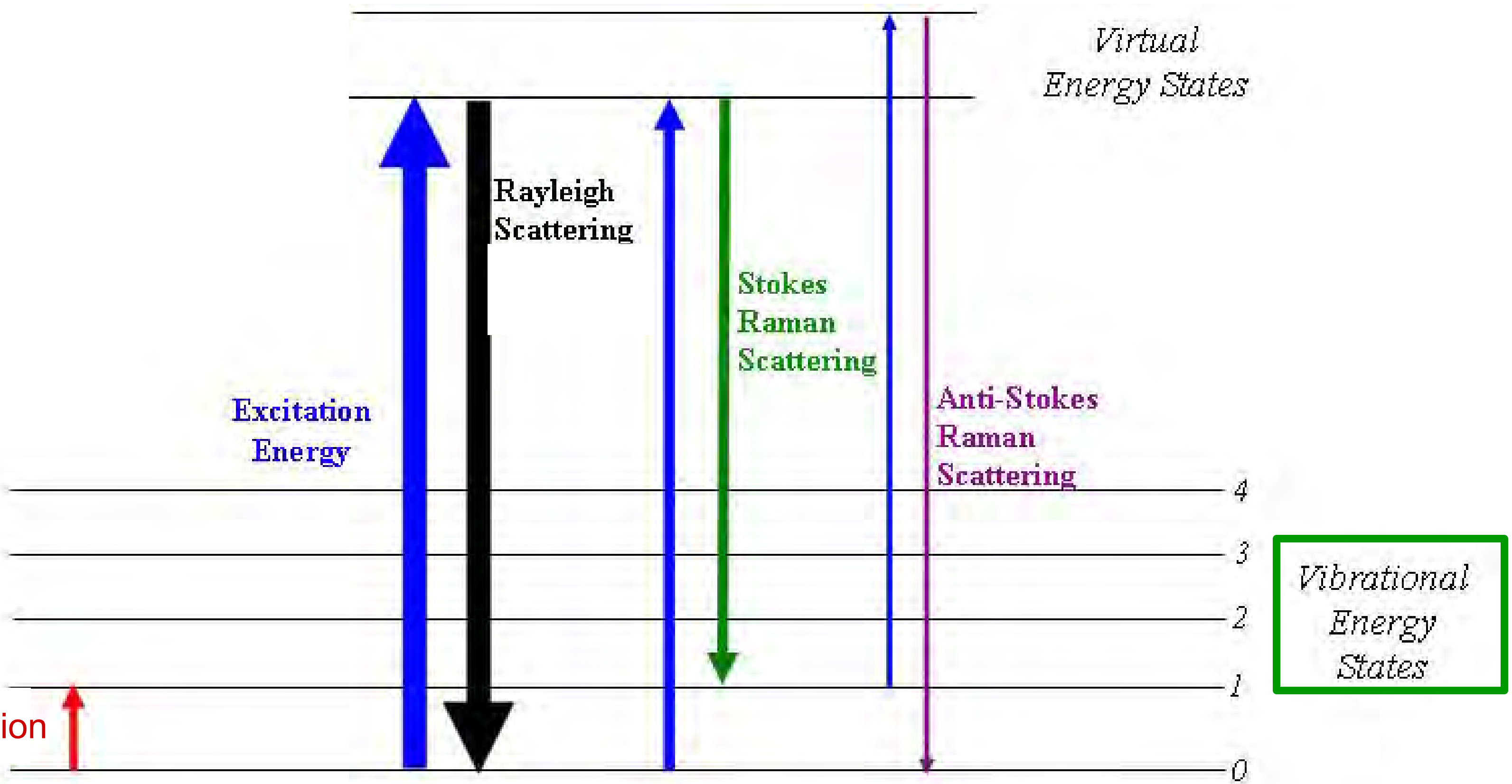
Dipole light scattering



Elastic and inelastic scattering

Elastic Scattering

Inelastic Scattering

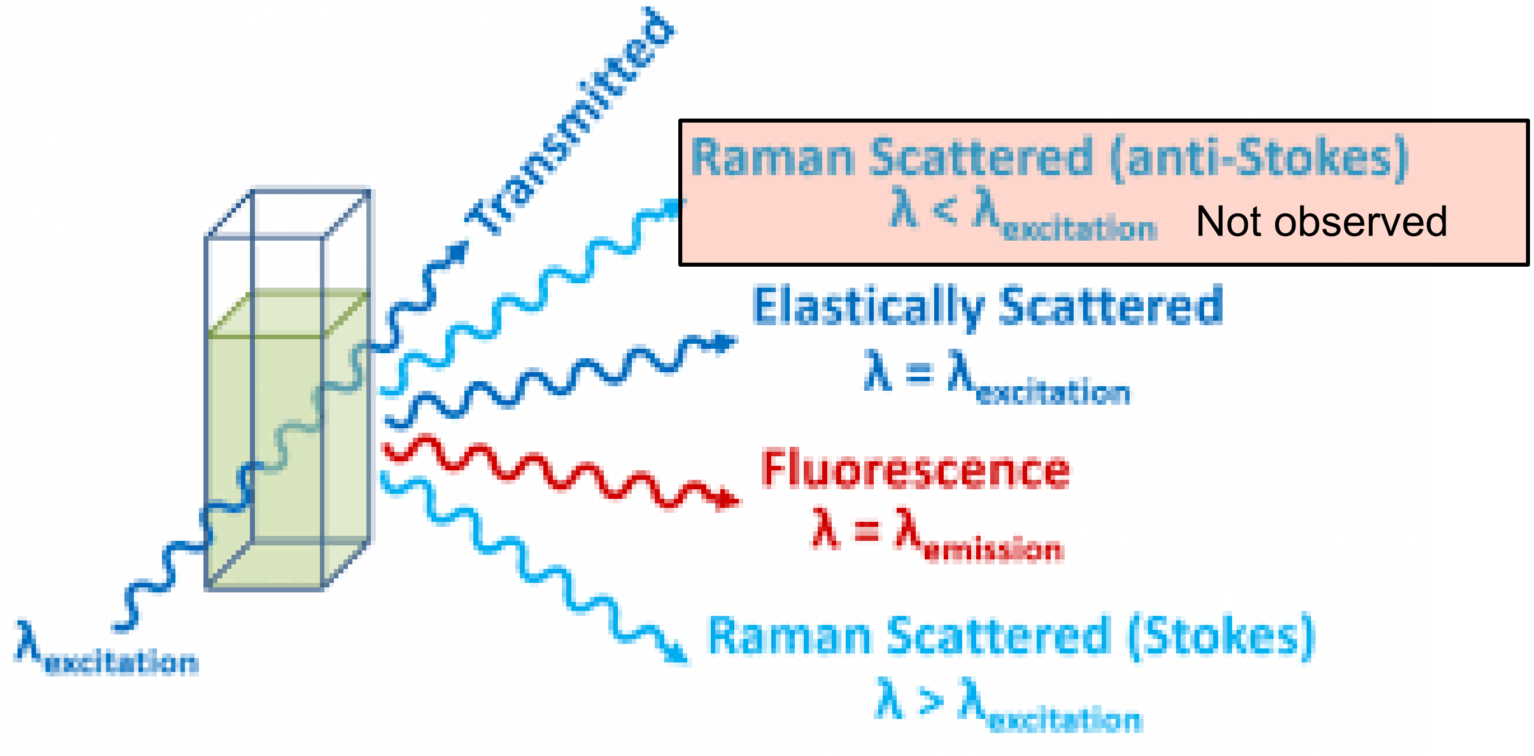


IR absorption

Elastic scattering by water molecules

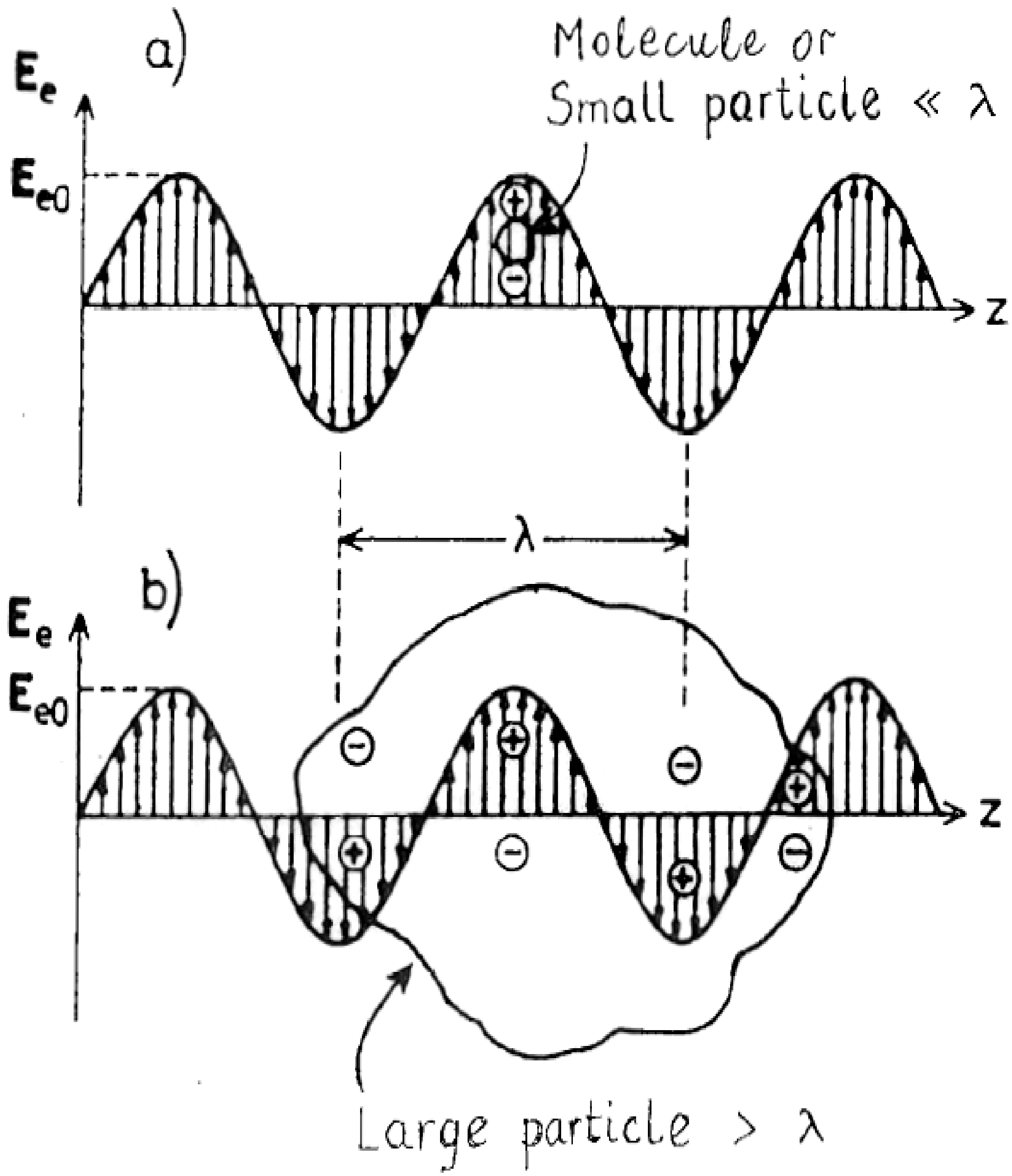
Inelastic Raman scattering by water molecules

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

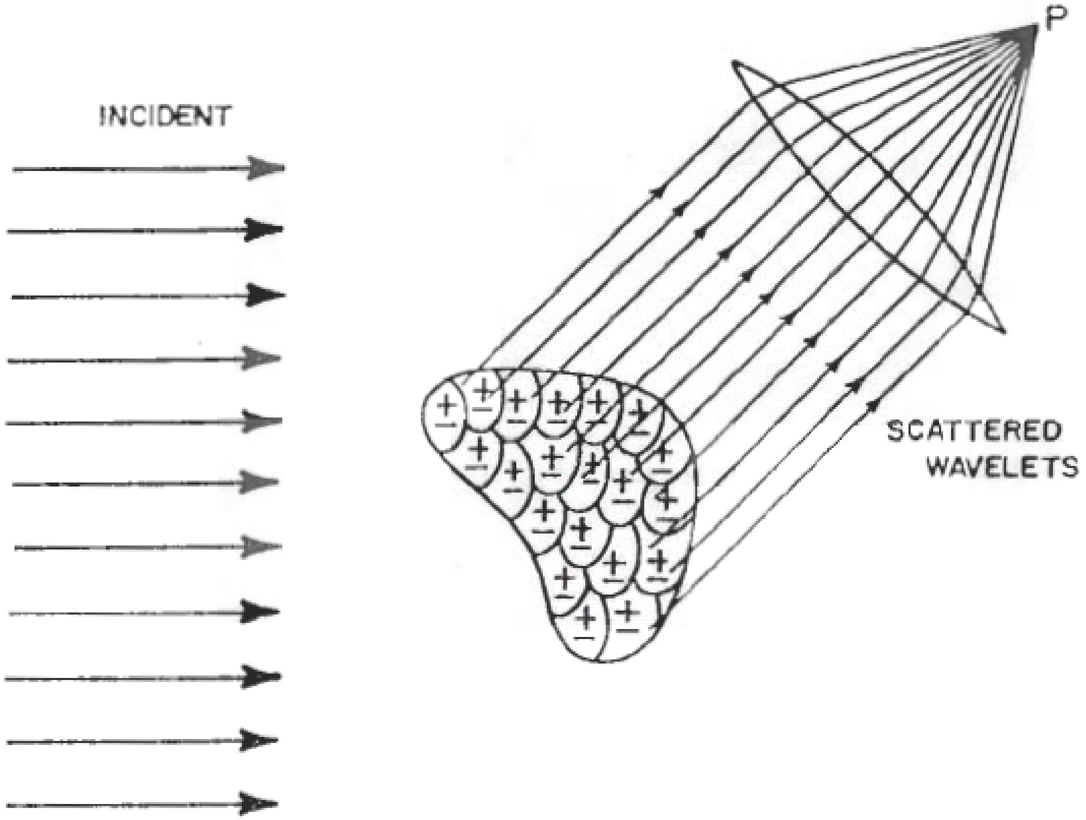


Not observed

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

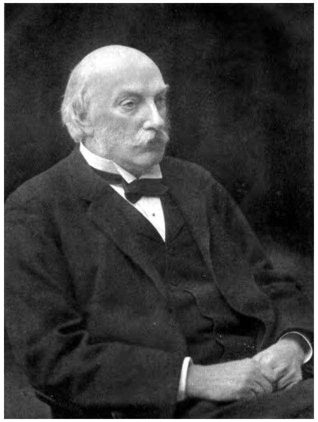


A single particle subdivided into oscillating dipoles



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.

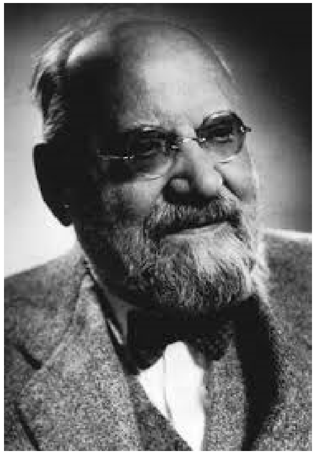
Computations of light scattering: From Rayleigh and Mie theory to geometric ray tracing



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

Particle size ≪ λ

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.



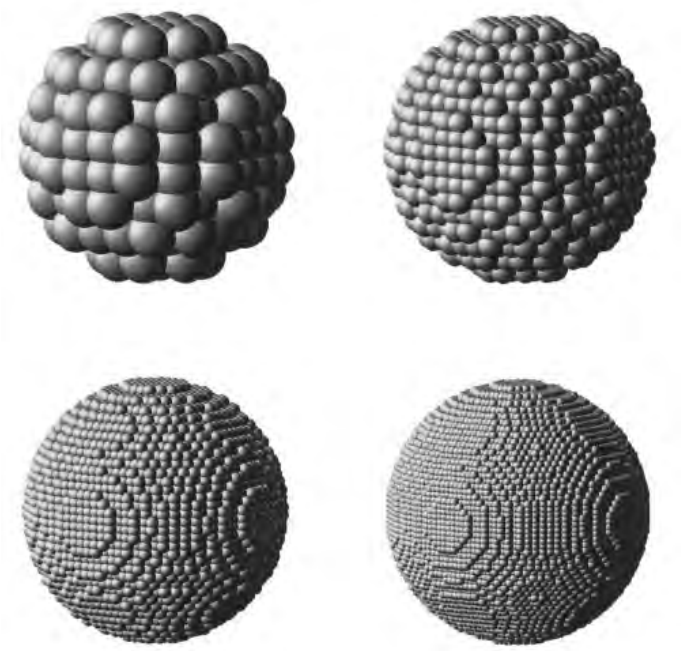
Gustav Mie (1868 - 1957)

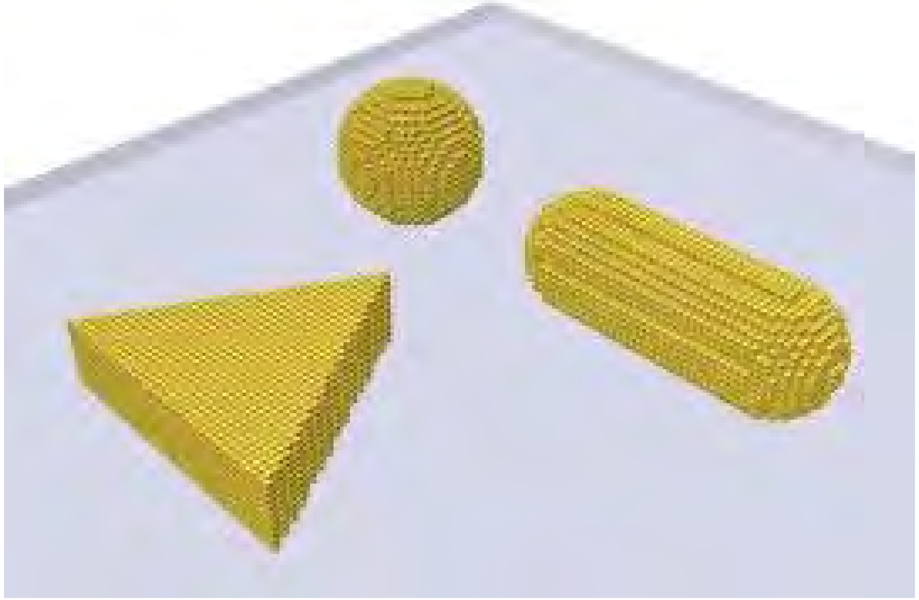
Arbitrary size of spherical particles

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

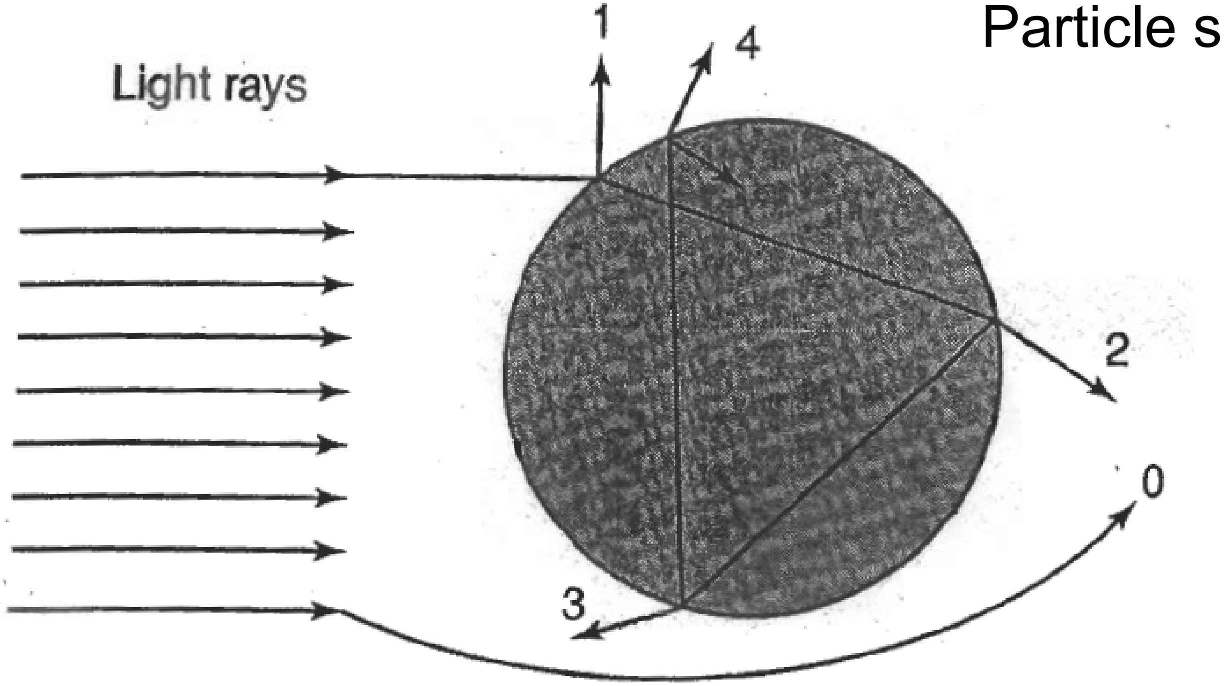




In the discrete dipole approximation, an object of arbitrary shape (e.g., a particle) is approximated in terms of a finite array of small electric dipoles. These dipoles acquire dipole moments in response to the local (incident) electric field and produce scattered field.

Geometrical optics approximation for light scattering

Particle size ≫ λ



0 Exterior Diffraction

1 External Reflection

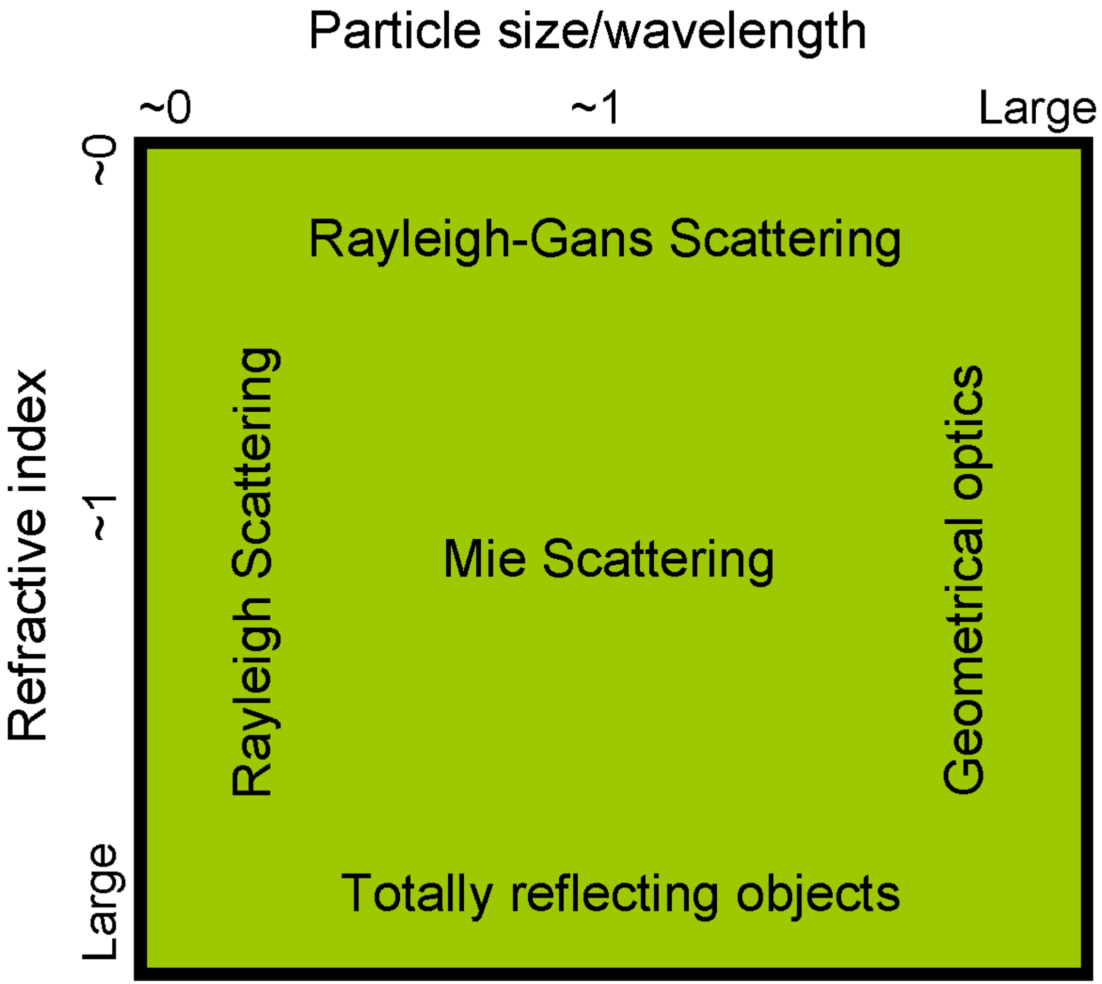
2 Two Refractions

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/wavelength

~0

~1

Large

Refractive index

~0

~1

Large

Rayleigh-Gans Scattering

Rayleigh Scattering

Mie Scattering

Geometrical optics

Totally reflecting objects

Particle size parameter

α (or x) = $2 \pi r / \lambda$ =

$\pi D / \lambda$

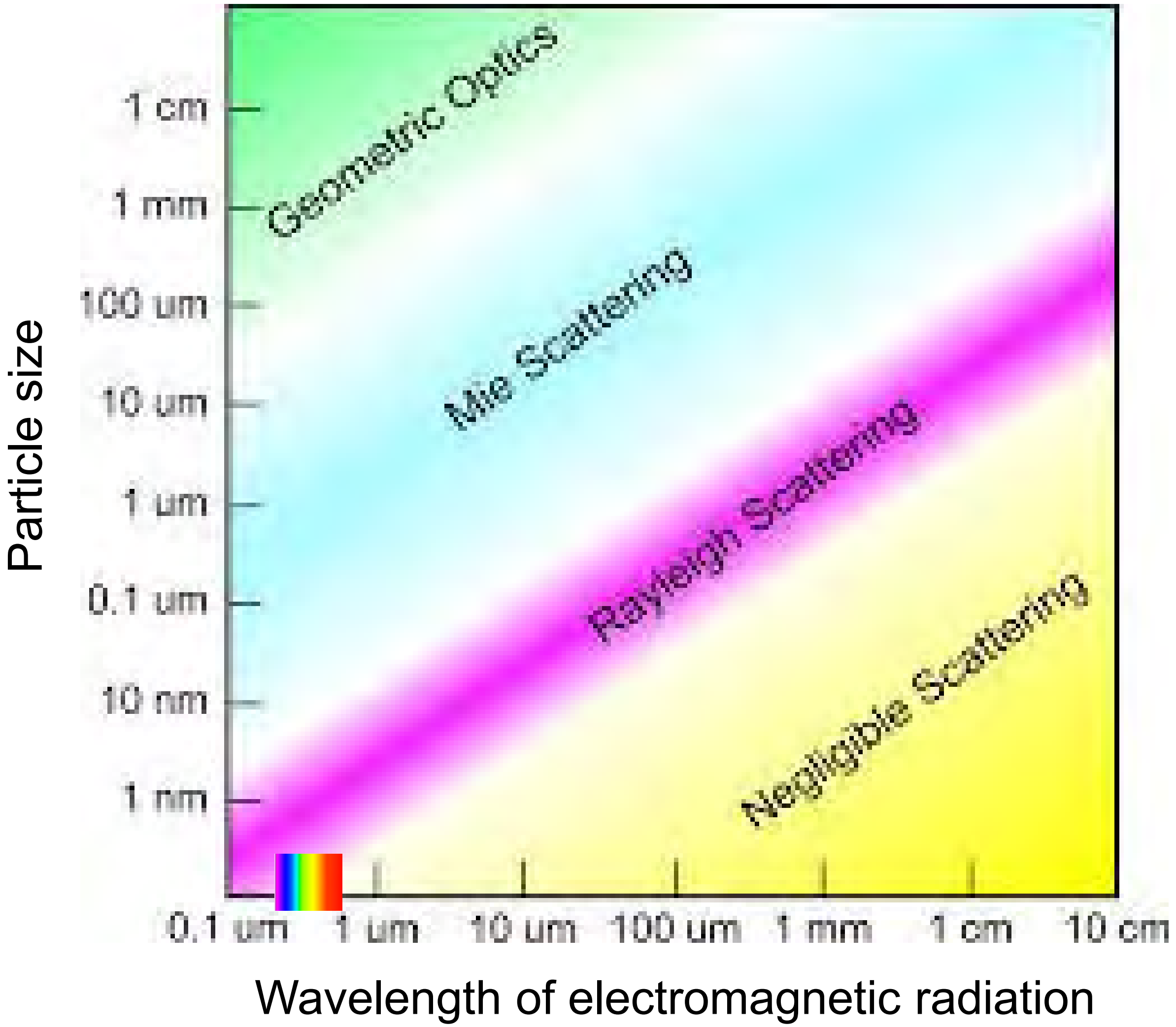
where *r* is particle radius and *D* particle diameter

Rayleigh scattering approximation

$\alpha \ll 1$

Geometrical optics approximation

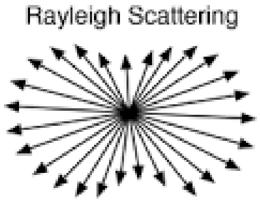
$\alpha \gg 1$


Particle size
1 cm
1 mm
100 um
10 um
1 um
0.1 um
10 nm
1 nm
Geometric Optics
Mie Scattering
Rayleigh Scattering
Negligible Scattering
0.1 um
1 um
10 um
100 um
1 mm
1 cm
10 cm
Wavelength of electromagnetic radiation

Angular patterns of scattered intensity from particles of different sizes

Very small particles

Size: smaller than one-tenth the wavelength of light
Description: symmetric

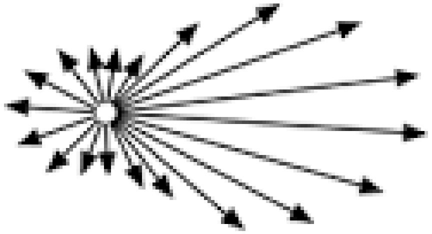


Molecular scattering as a function of scattering angle ψ:

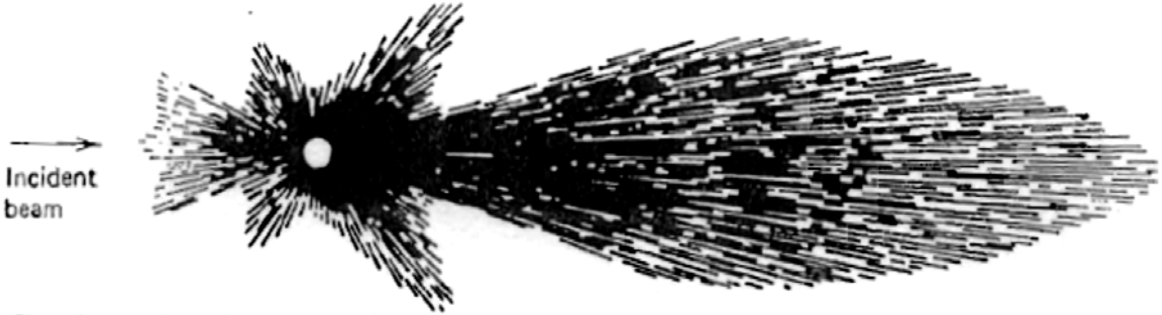
Scattered intensity $\sim (1 + \cos^2\psi)$ for unpolarized incident light

Larger particles (still smaller than the light wavelength)

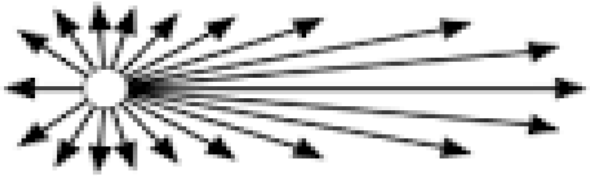
Size: approximately one-fourth the wavelength of light
Description: scattering concentrated in forward direction



Very large particles (larger than the light wavelength)

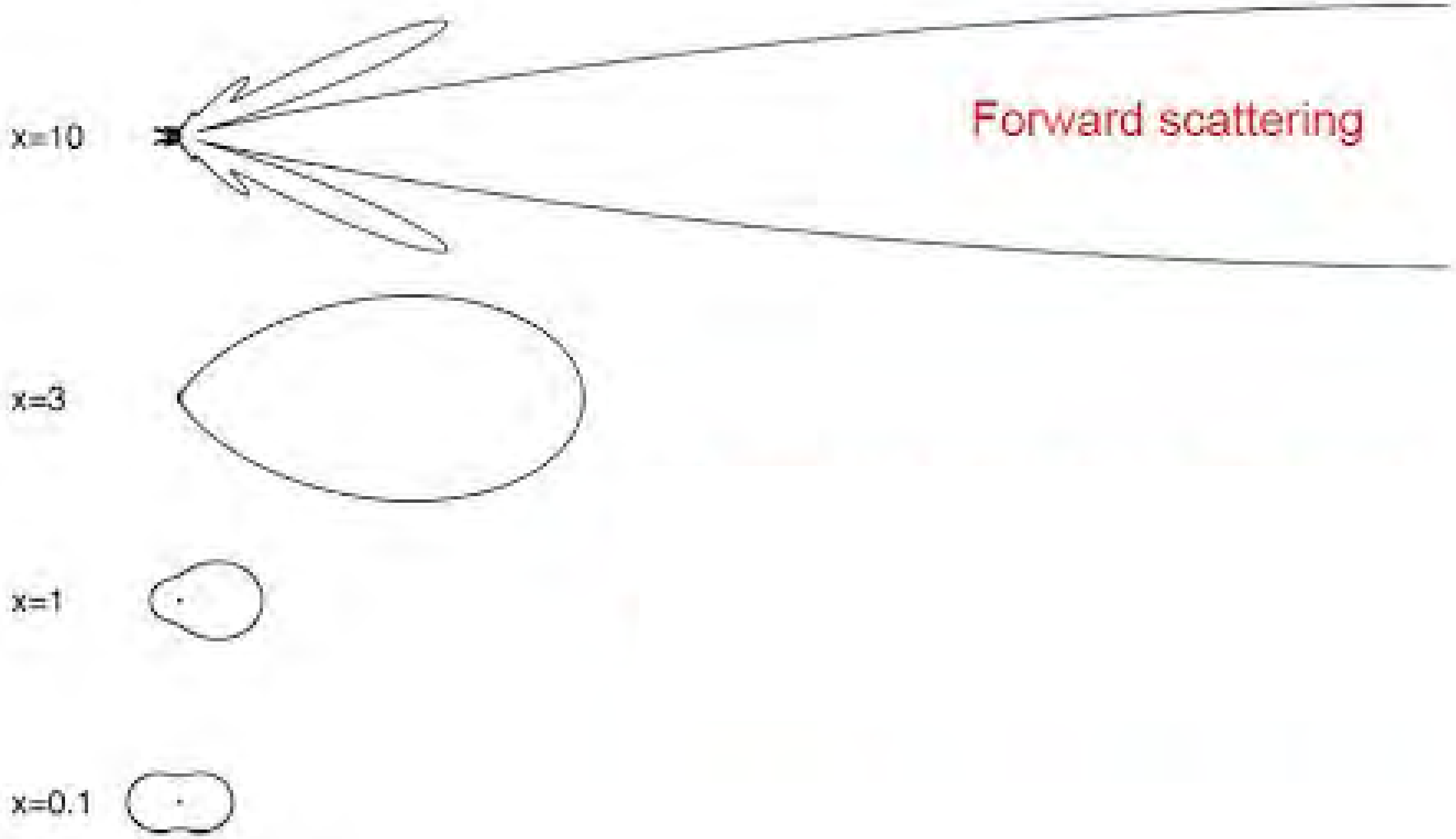


Size: larger than the wavelength of light
Description: extreme concentration of scattering in forward direction; development of maxima and minima of scattering at wider angles



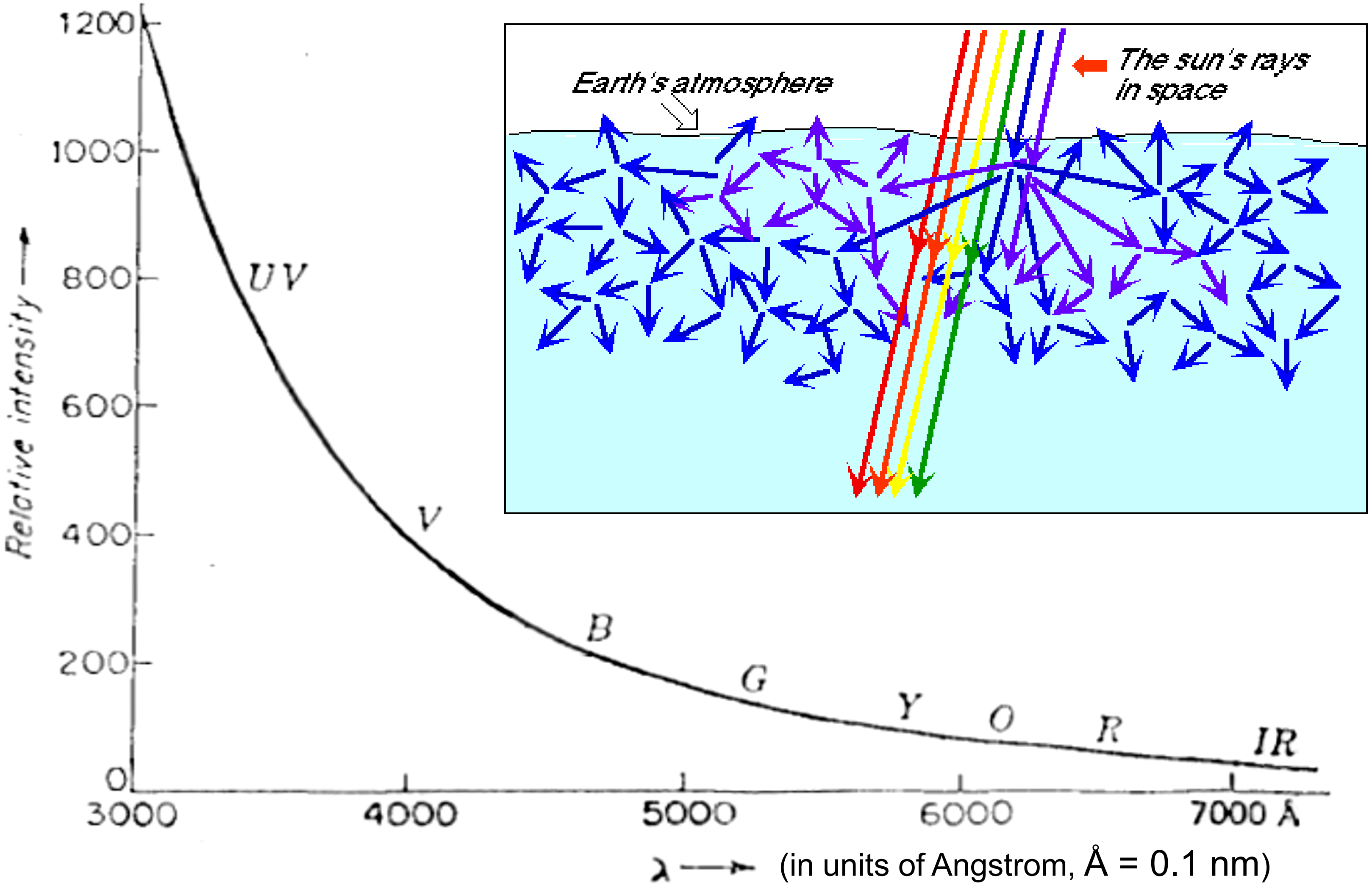
The angular distribution of light intensity scattered by a particle for a given size parameter *x* (≡ α)

(results derived from Mie theory for spherical particles)

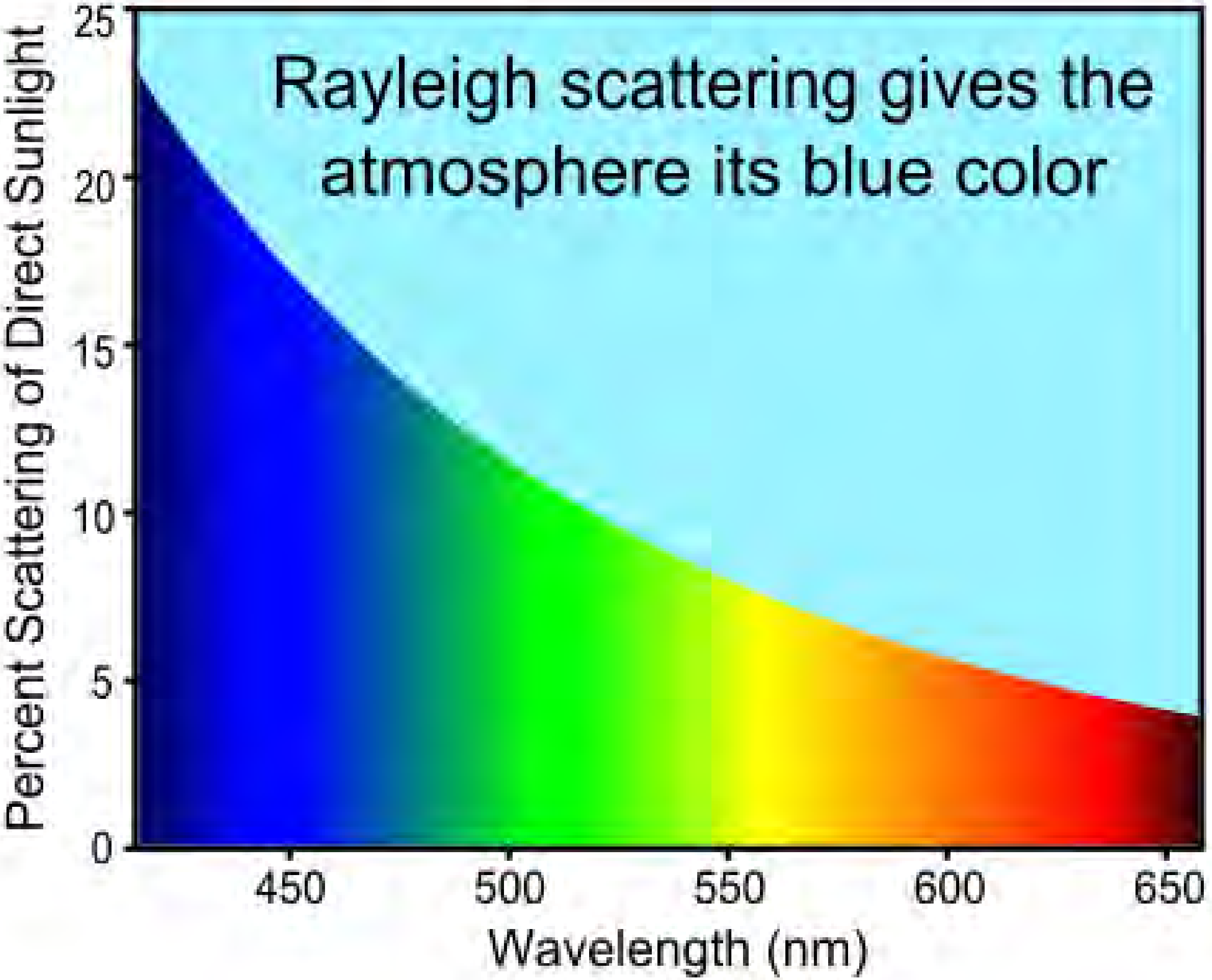


Molecular scattering as a function of light wavelength

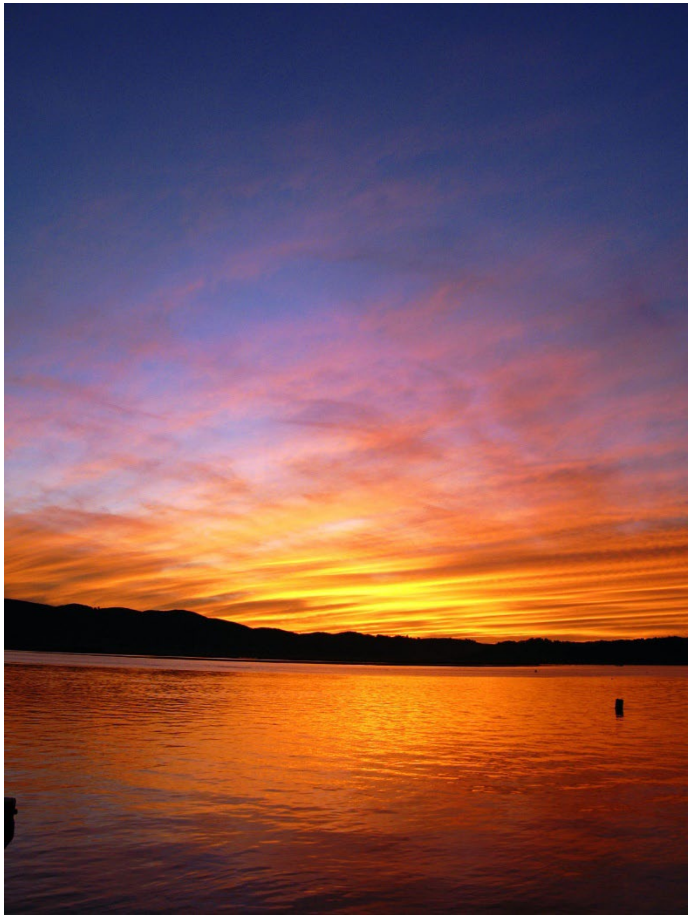
Scattered intensity ~ λ^{-4}



(in units of Angstrom, Å = 0.1 nm)


Rayleigh scattering gives the atmosphere its blue color
Percent Scattering of Direct Sunlight
25
20
15
10
5
0
450
500
550
600
650
Wavelength (nm)

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.

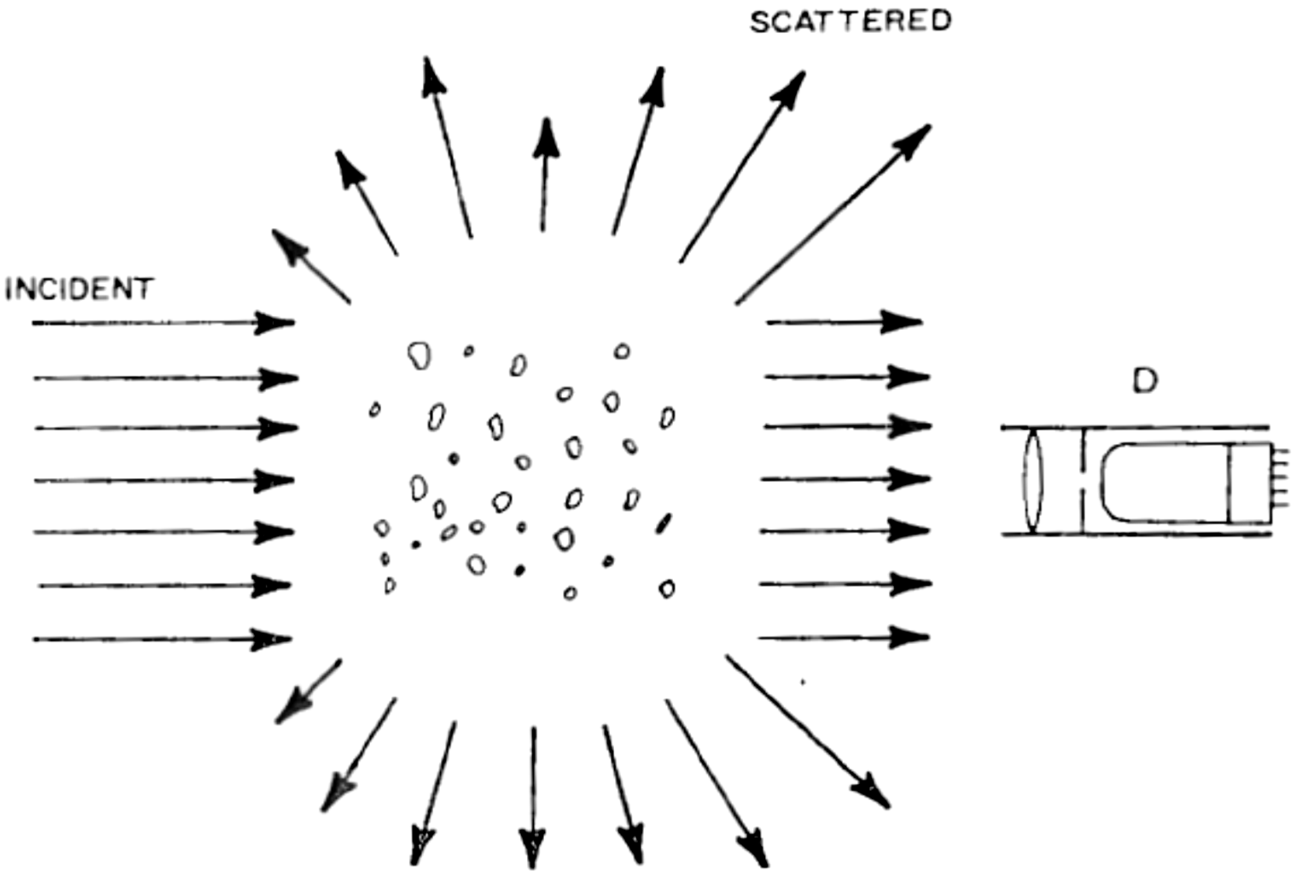


Chandrasekhara Venkata Raman
(1988 -1970)
Nobel Prize 1930

"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

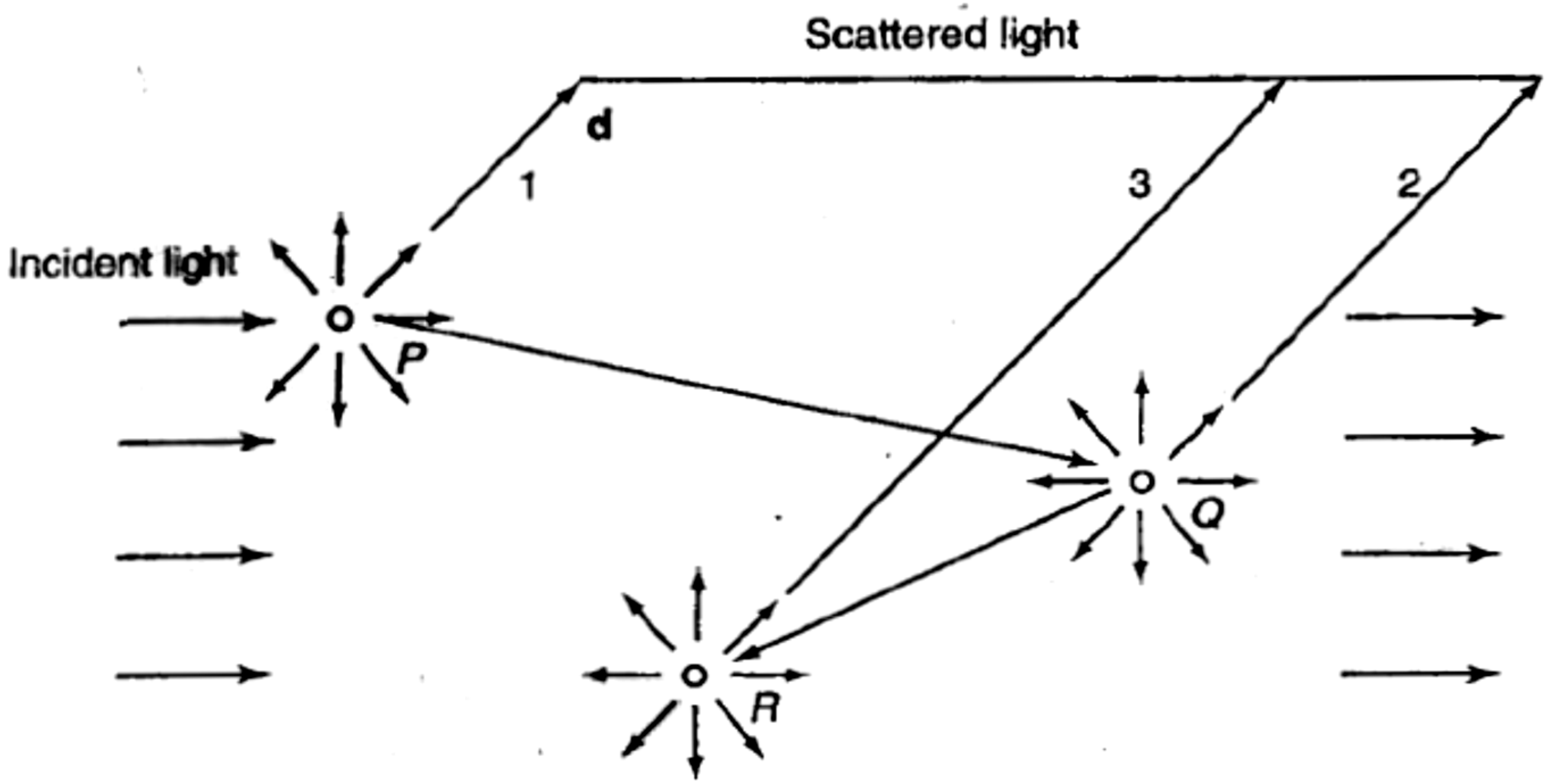


Figure 1.5 Multiple scattering process involving first (P), second (Q), and third (R) order scattering in the direction denoted by **d**.

(Liou 2002)