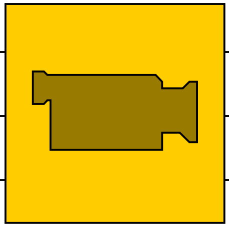
PHY2505S
Atmospheric Radiative Transfer and Remote Sounding

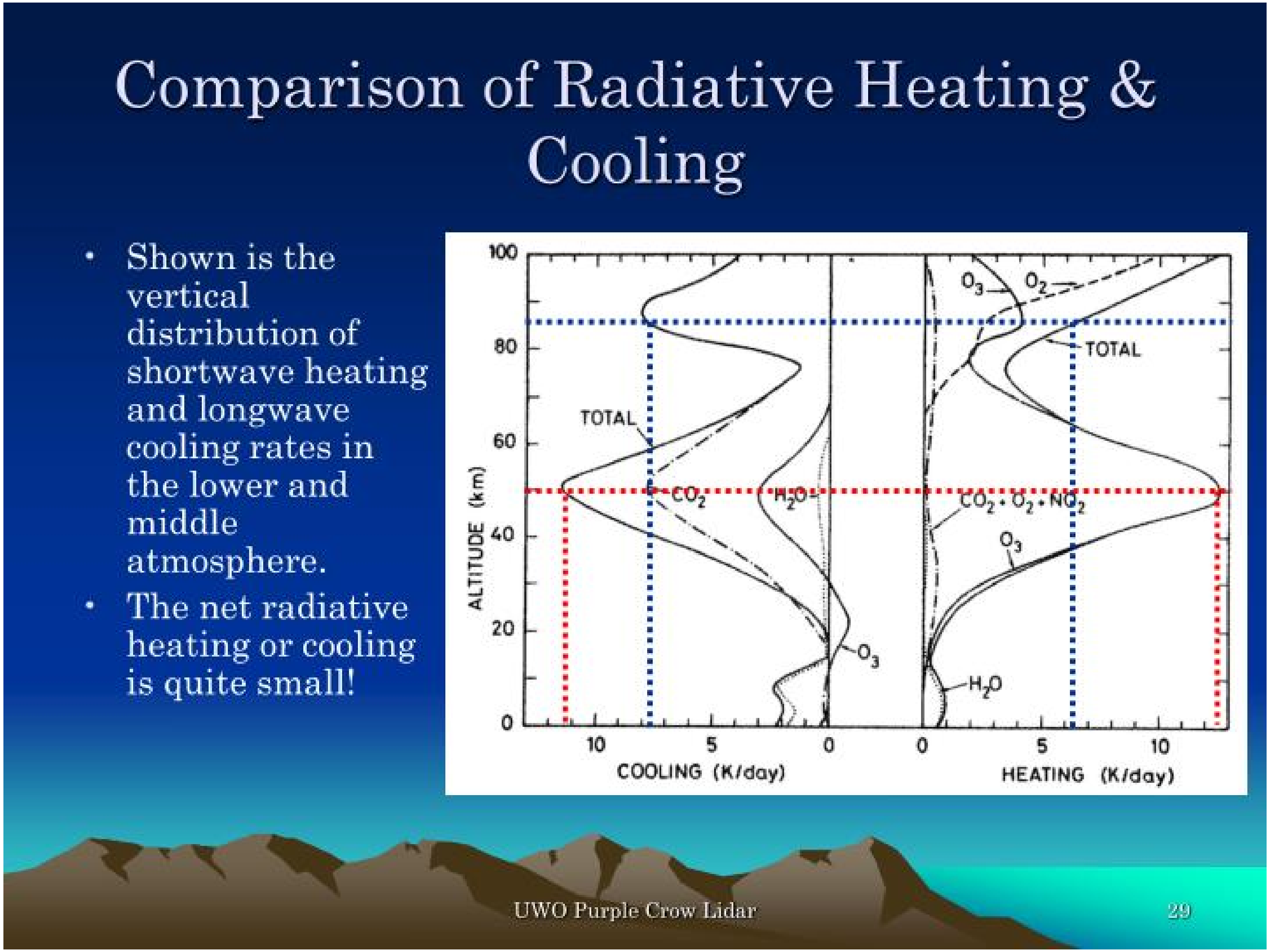
Lecture 11

- Spectral Modelling
- Infrared Cooling Rates
- Atmospheric Scattering

Spectral Modelling & Infrared Cooling Rates

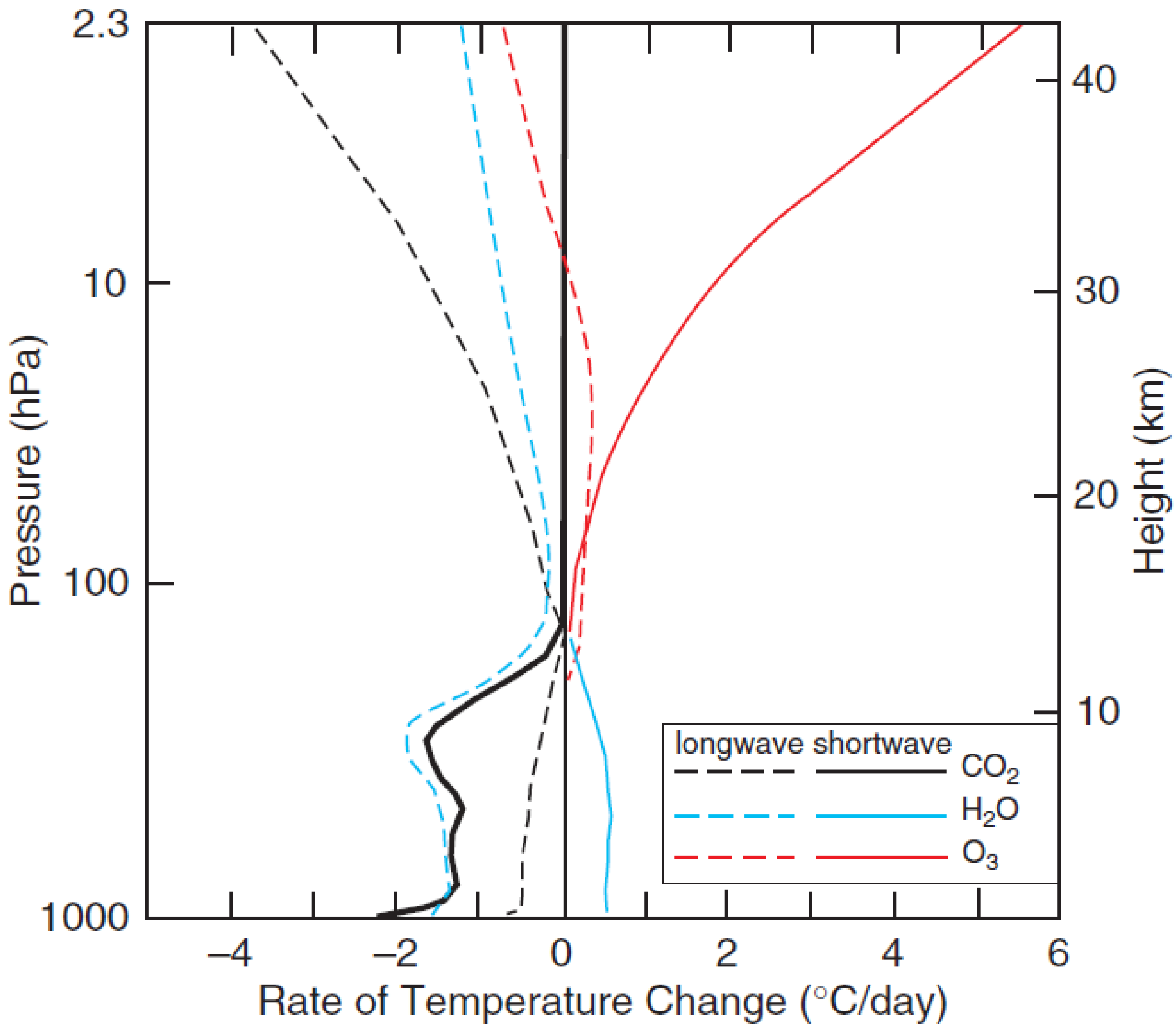


Heating & Cooling Rates (Lecture 6)



Bob Sica, UWO, https://www.slideserve.com/bena/uwo-s-purple-crow-lidar-studies-atmospheric-change-powerpoint-ppt-presentation

Vertical Profiles of Heating & Cooling Rates

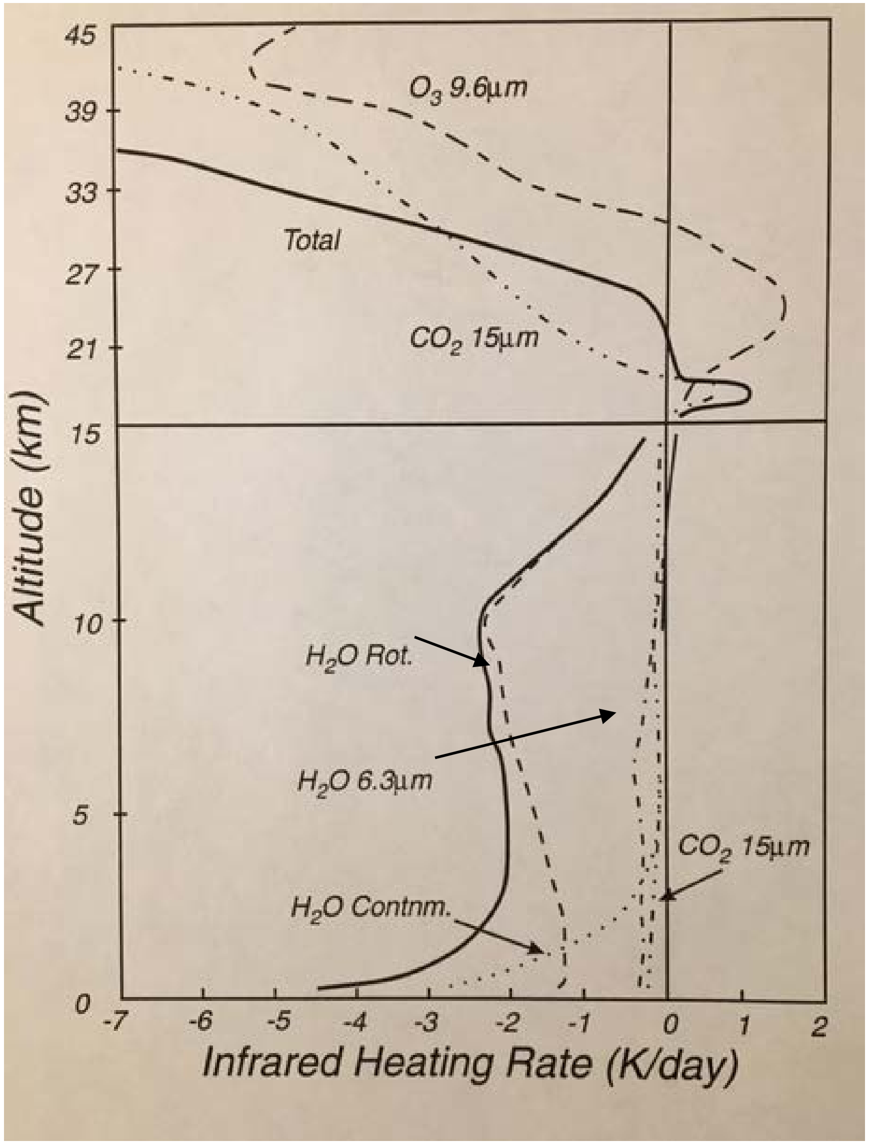


[Adapted from S. Manabe and R. F. Strickler, *J. Atmos. Sci.*, **21**, p. 373 (1964).]

Wallace and Hobbs, Figure 4.29

- In the troposphere, CO_2 and H_2O cool in the longwave, with H_2O dominating until its mixing ratio decreases. This is partly offset by H_2O shortwave absorption.
  Net effect: radiative cooling by GHGs in troposphere.
- The stratosphere is close to radiative equilibrium, with longwave cooling balanced by shortwave heating due to ozone.

Vertical Profiles of IR Cooling Rates



- Calculated using Goody random band model parameters for H_2O, CO_2, and O_3, and the Curtis-Godson approximation (after Liou)
- In the lowest 2 km, the H_2O continuum (8-12 μm) dominates due to rapid increase in T and H_2O partial pressure near the surface
- The 6.3 μm H_2O band contributes little because the atmospheric Planck function has little energy at these λs
- Cooling in the middle and upper troposphere is dominated by the H_2O rotational band (40-900 cm^{-1})
- O_3 has a net heating effect at 18-27 km due to its increase in concentration
- Above 30 km, the cooling rate increases rapidly due to 15 μm CO_2 and 9.6 μm O_3 and cooling to space becomes important

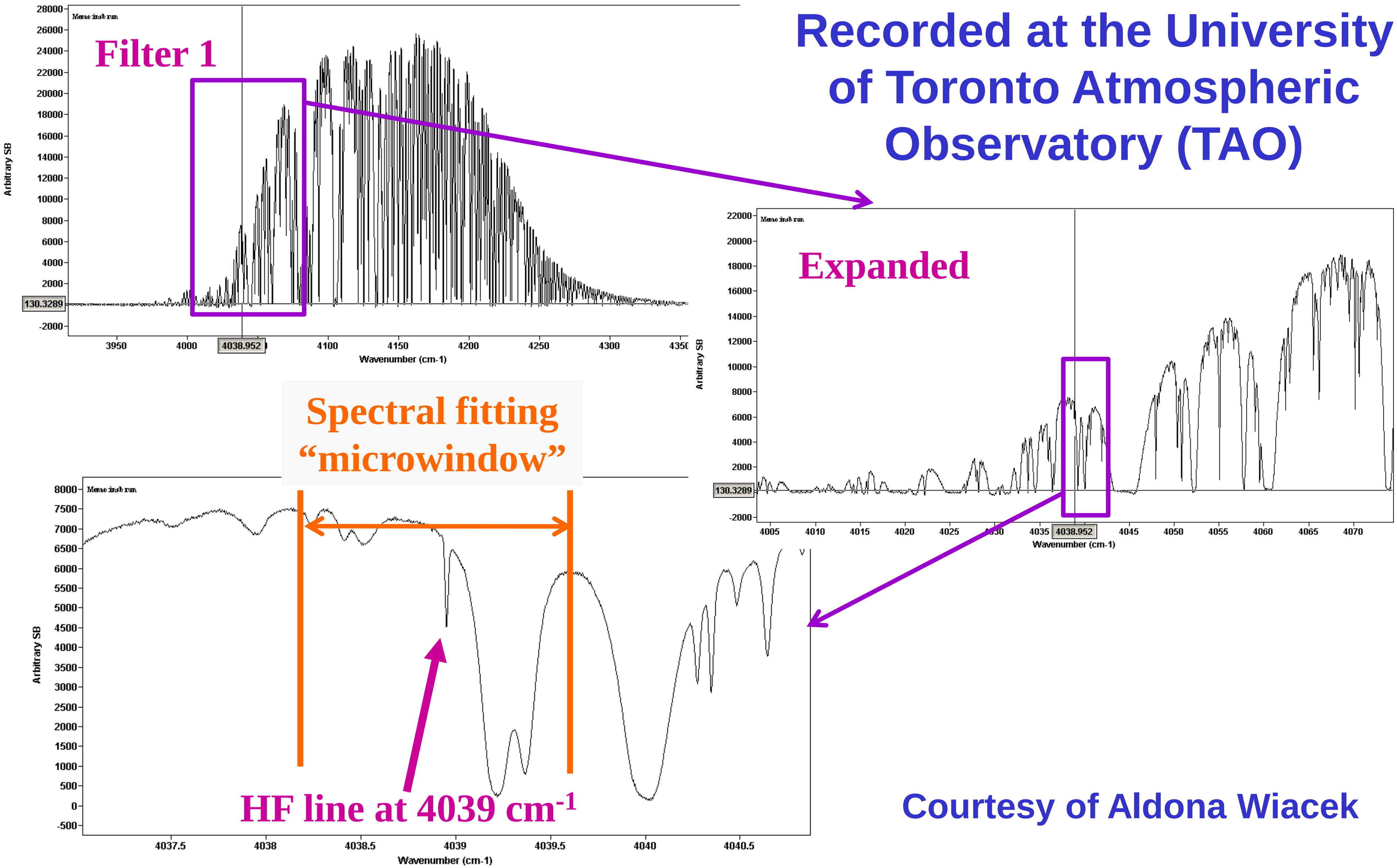
Atmospheric Spectroscopy: A Practical Application

- Using an appropriate line shape function, the absorption coefficient can be calculated at any point in spectral space.

- This can then be used to derive the total absorption of the line, the atmospheric transmission, etc.

- Calculation of the line shape function requires knowledge of the relevant spectral line parameters.
  - → HITRAN is the most widely used spectroscopic database with information (intensity, half-width, and so on) for more than 1,000,000 spectral lines for about 36 different molecules.

Example: Solar IR Absorption Spectra



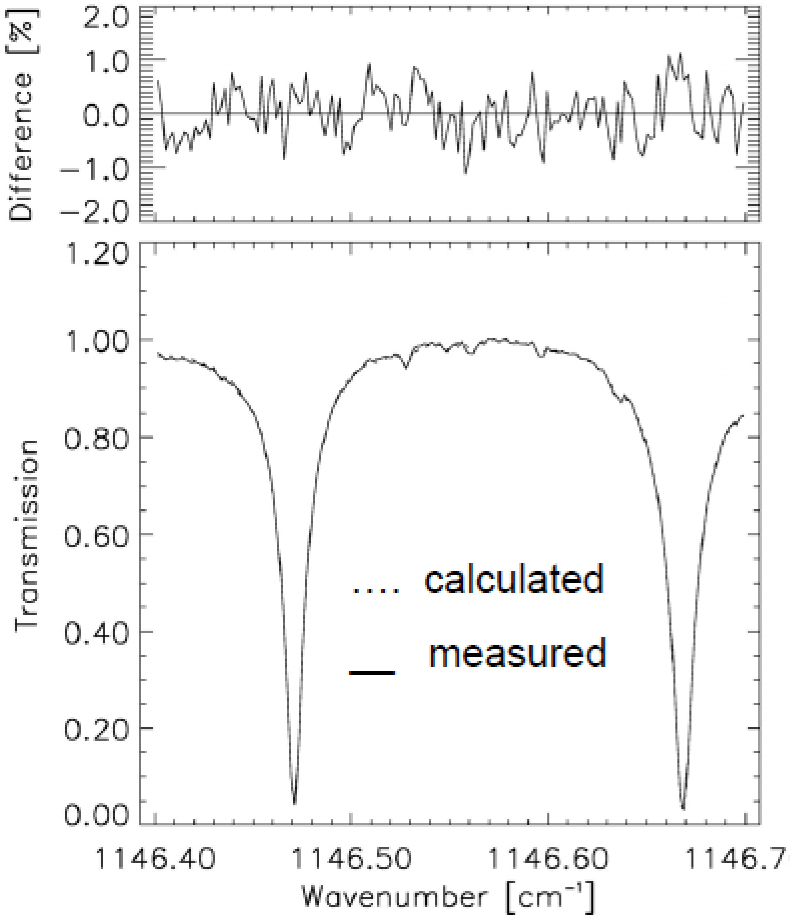
Recorded at the University of Toronto Atmospheric Observatory (TAO)

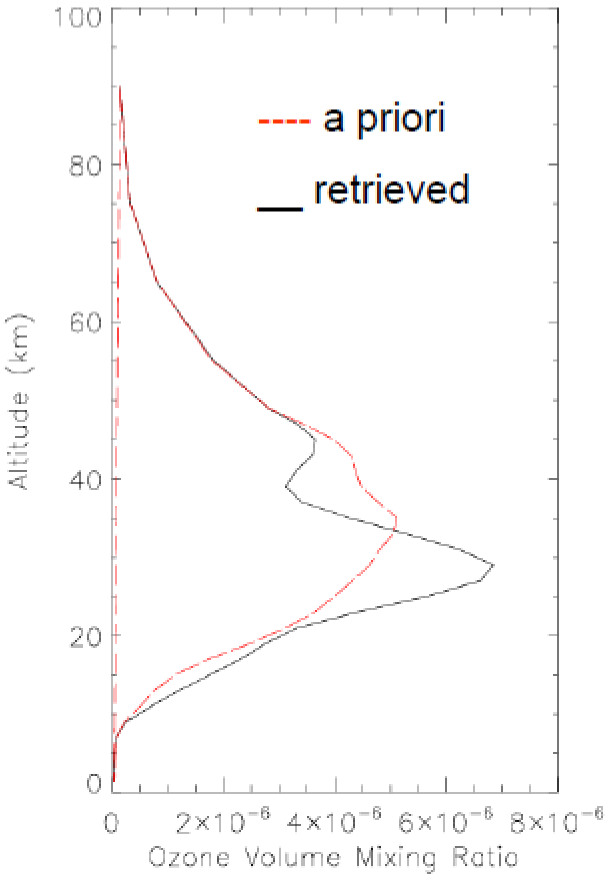
Courtesy of Aldona Wiacek

Example: Solar IR Absorption Spectra

From CANDAC/PEARL Fourier Transform IR Spectrometer

Sample fit for O3, the measurement is from March 4, 2007





Courtesy of Rodica Lindenmaier

Atmospheric Extinction Processes

- There are three atmospheric processes that can cause extinction of radiation.

Extinction of the beam:
- Absorption (k_a)
- Simple scattering (k_s)
- Resonant scattering (k_r)

$$k = k_a + k_s + k_r$$

total extinction coefficient,
Note: each term has spectral dependence, not indicated here

Simple Scattering

- Simple scattering is the deflection of energy from its current direction into another direction (recall intensity has direction).
- The energy is redirected rather than lost.
- There is usually very little interaction with the kinetic energy reservoir and so little heating or cooling is associated with simple scattering.

Consequences:

- Need to pay attention to the angular properties of the energy redistribution
- Energy is also scattered into the beam from other directions

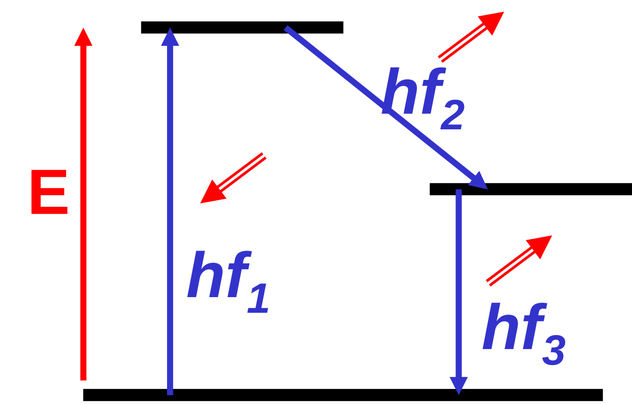
Resonant Scattering

- Resonant scattering combines some of the properties of both absorption and single scattering.
- Energy is first absorbed by the molecule, and then re-emitted some time later.

The re-emission may be at:
- same
- nearly the same
- very different

depending upon the quantum levels involved

- The re-radiation is usually isotropic.
- Some degree of interaction between the process and the kinetic energy field.
- The only atmospheric process by which radiation may be directly changed in frequency.
- It is less important in the lower atmosphere.

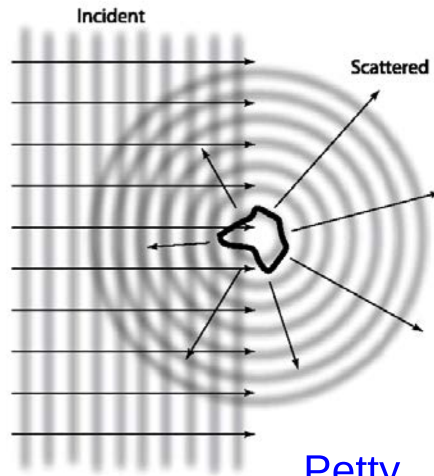


$hf_1 \sim hf_2 + hf_3$

(f = frequency)

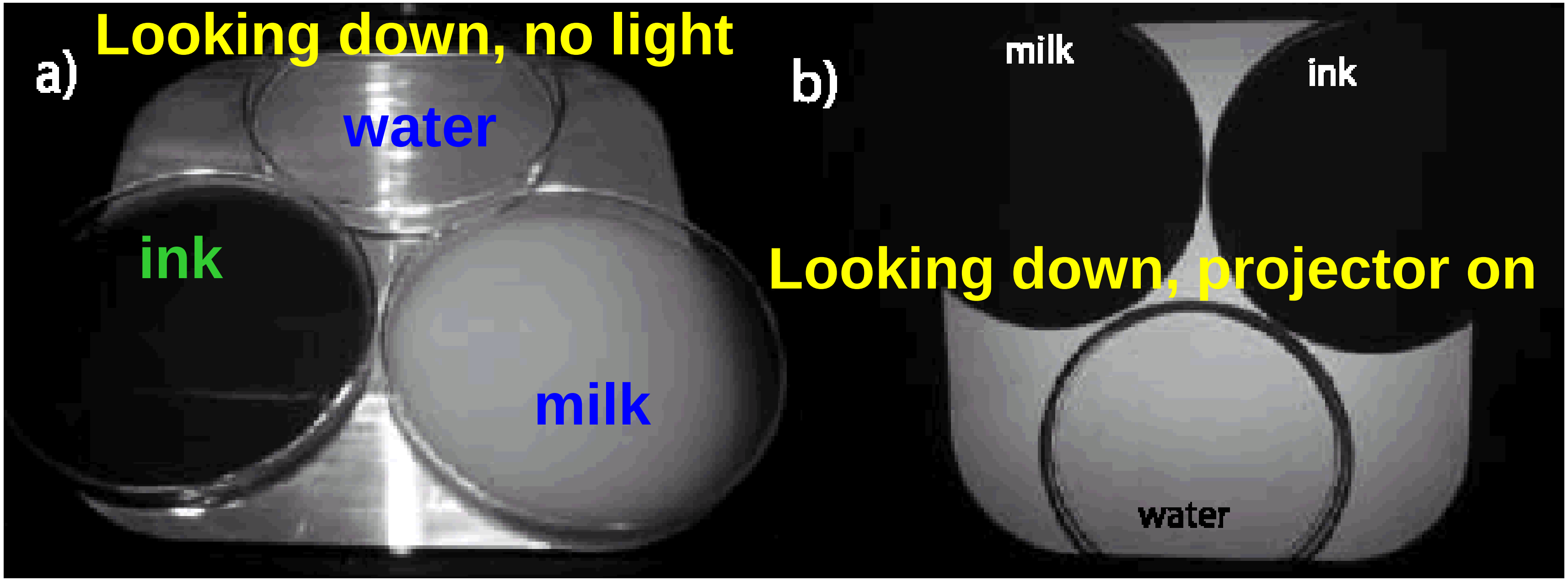
Scattering in Planetary Atmospheres

Scattering is the redirection of radiation out of (or into) the original direction of propagation, usually due to interactions with particles.



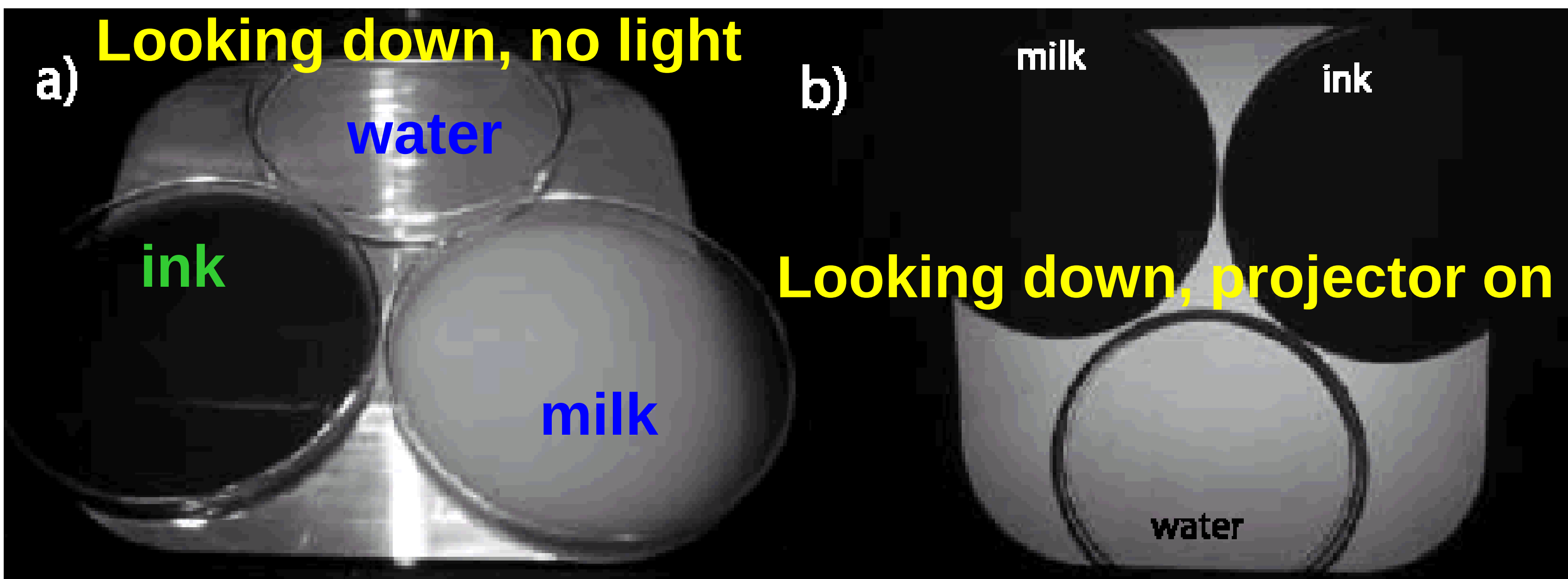
Scattering of incident light wave by a particle

Petty, Figures 7.1, 7.2



Scattering in Planetary Atmospheres

- Looking down, projector off: only the ink looks black
- When the projector is turned on:
  - → Both milk and ink extinguish the beam – absorption and scattering
  - → Black ink absorbs light – will warm up with time
  - → Milk scatters the light out of its original direction into other directions
  - → Proof: Look sideways – (1) ink is dark, milk lights up;
    (2) measure temperature as ink heats up



Petty, Figure 7.2

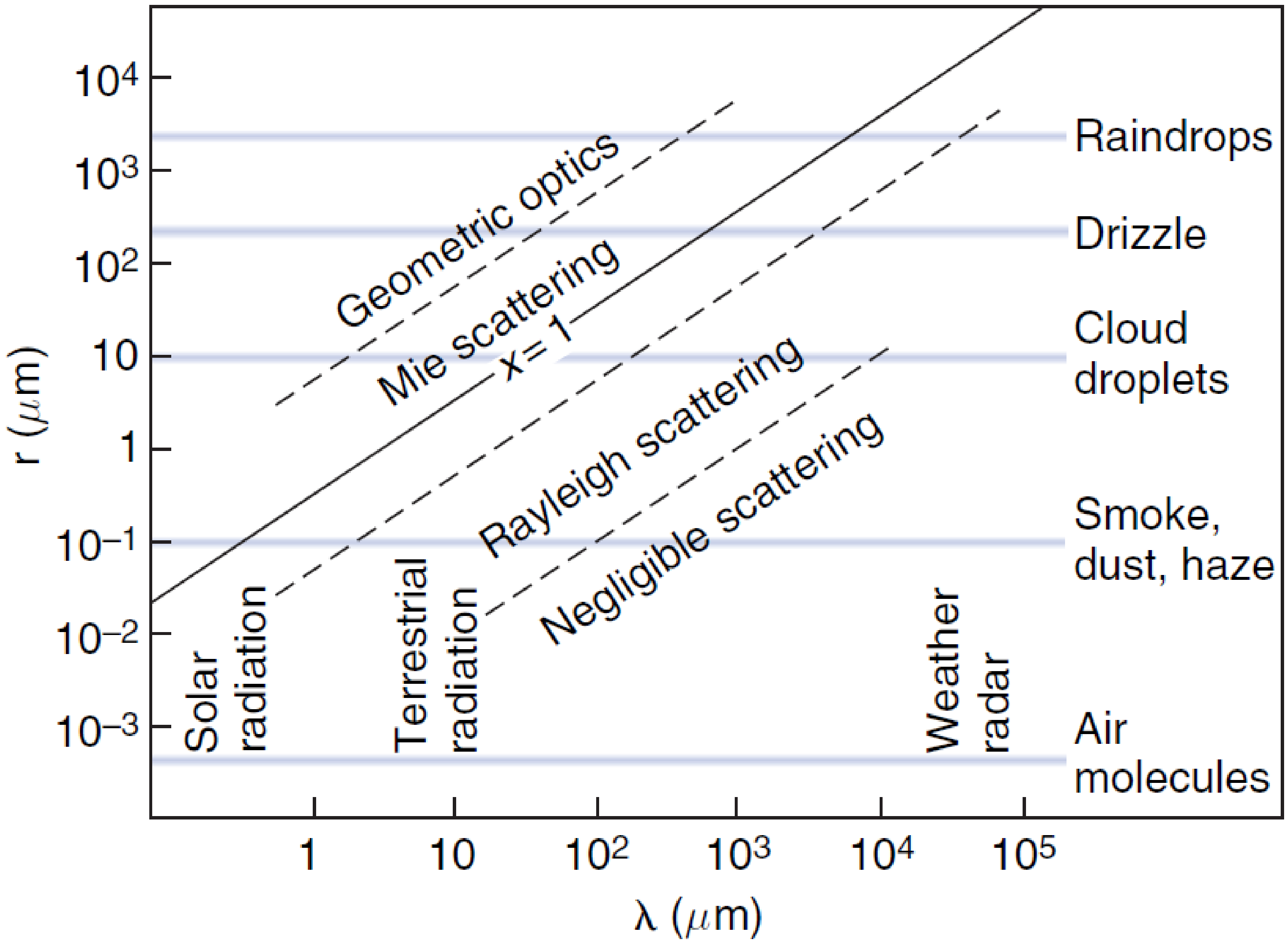
Scattering in Planetary Atmospheres

Scattering in the atmosphere generally occurs in three forms, by:

- Molecules
- Aerosols
- Clouds

And there are three regimes determined by the particle size and scattering wavelength:

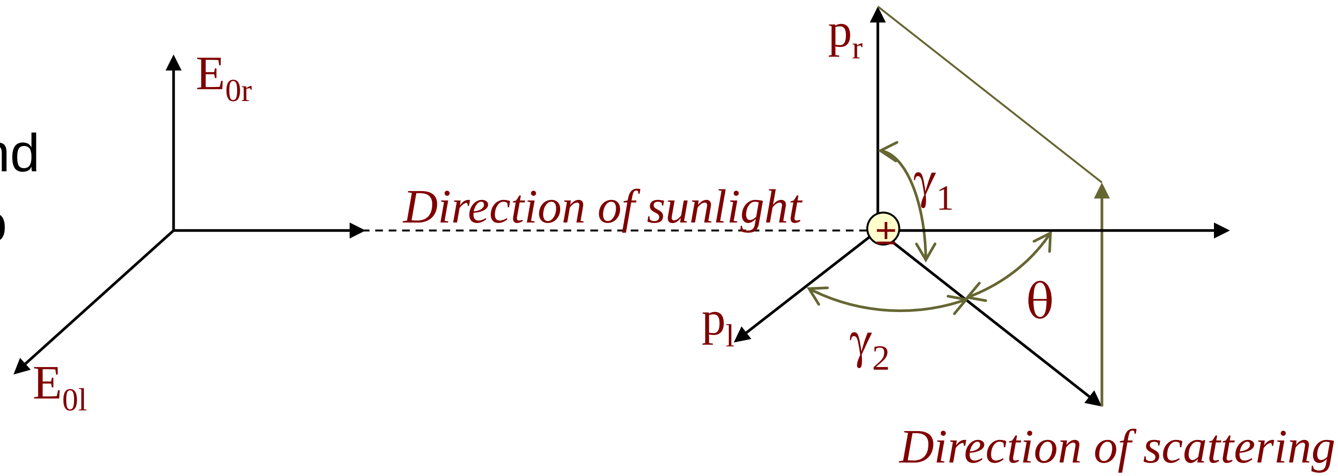
- Rayleigh
- Mie
- Geometric



Wallace and Hobbs, Figure 4.11

Rayleigh Scattering - 1

Interaction between the incoming light and the molecules – also known as Rayleigh scattering (1871).



Consider a small homogeneous, isotropic, spherical particle (radius r < λ incident).

The incident radiation produces a homogeneous electric field $\mathbf{E_0}$ – applied field.

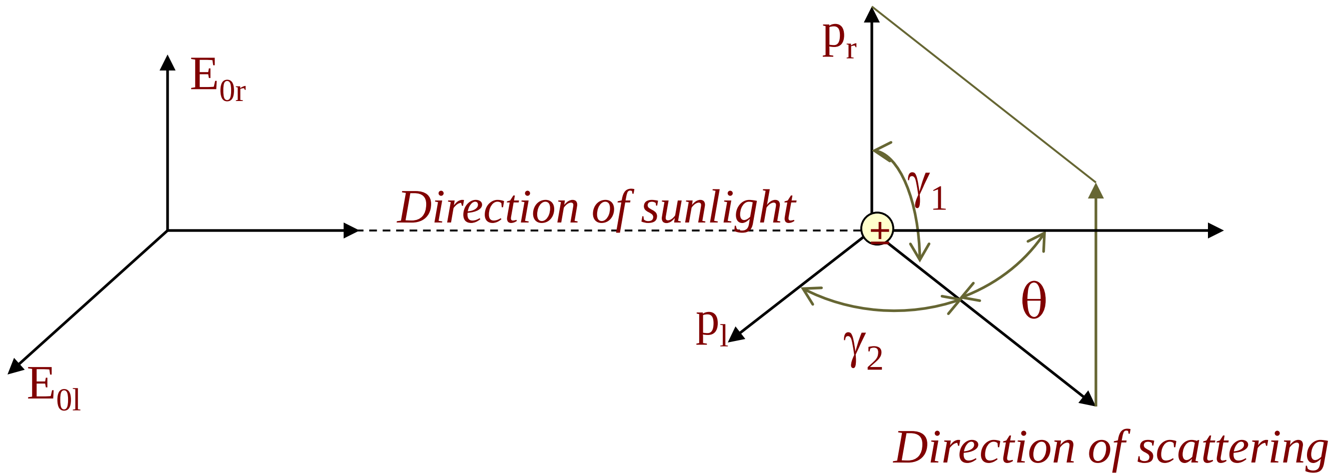
Because r << λ, E_0 generates a dipole configuration on it – the electric field of the particle (caused by the electric dipole) modifies the applied field inside and near the particle. ***E*** *→ applied field + particle's own field.*

p_0 *→ induced dipole moment:*

$p_0 = \alpha E_0$ *→ defines the polarizability α of a small particle.*

E_0 generates oscillation of an electric dipole in a fixed direction. The oscillating dipole produces, in turn, a plane-polarized electromagnetic wave – the scattered wave.

Rayleigh Scattering - 2



The scattering function for molecular scattering is given by $\cos^2\theta$ for the parallel vector and 1 for the perpendicular vector: $\mathbf{P(\theta) = \frac{3}{4}(1 + \cos^2\theta)}$

$\rightarrow$ *Even if the incoming beam is unpolarized, the outgoing beam is polarized.*

If we concentrate on the **extinction coefficient** we find that it is given by:

$$\frac{8\pi^3}{3\lambda^4}\frac{(m^2-1)^2}{N^2} \text{ per molecule.}$$

N = number density
m = refractive index (depends on λ and composition of the particle; real part governs speed of propagation of wave, imaginary part governs absorption)

Rayleigh Scattering - 3

Mass scatttering coefficient (cm^2/molecule or m^2/kg):

$$k_s = \frac{8\pi^3}{3\lambda^4} \frac{(m^2-1)^2}{N^2} f(\delta)$$

Blue light is scattered more efficiently than red light – hence the blue sky

A correction factor f(δ) is normally added in the equation above to take into consideration the anisotropic property of molecules ($f(\delta) = (6+3\delta)/(6-7\delta)$ with the anisotropic factor δ of 0.035).

Anisotropy implies that the refractive index of the molecules varies along the x, y, and z directions → is a vector

The real part of the refractive indices of air molecules (m) in the solar spectrum range are very close to 1, but they depend on the wavelength of the incident radiation. Because of this dependence, white light may be dispersed into component colors by molecules that function like prisms.
The real part of m may be approximated by:

$$(m_r - 1)\times 10^8 = 6432.8 + 2949810/(146 - \lambda^{-2}) + 25540/(41 - \lambda^{-2})$$ *(λ in μm)*

Scattering by Larger Particles

- As particles becomes larger, the assumptions of Rayleigh scattering become less justifiable
  - → Lorentz-Mie scattering (Lorentz 1890 and Mie 1908)
  - → this requires solving Maxwell's equations in all their glory!

- Mie applied Maxwell's EM equations to the case of a plane EM wave incident on a sphere, and showed that the scattered radiation for a sphere depends only on:
  - → viewing angle
  - → complex index of refraction **$m = m_r + i\, m_i$**
  - → size parameter **$\chi \equiv 2\pi r / \lambda$** , where r = radius of the sphere

- Rayleigh scattering: $\chi < 0.1$
- Mie scattering: $0.1 < \chi < 50$
- Geometric (optics) scattering: $\chi > 50$

Scattering Efficiency - 1

Scattering efficiency: Q_s = total scattered radiation / incident radiation = scattering coefficient (cm^2 $molec^{-1}$) / cross-sectional area of particle

$$Q_s = \frac{k_s}{\pi r^2} \;(= K_\lambda \text{ in textbook})$$

- So $\sigma_s = k_s N = \pi r^2 Q_s N \quad (cm^{-1})$
- A plot of the scattering efficiency shows a series of maxima and minima, with smaller ripples superimposed.
- The maxima and minima are caused by interference between the light diffracted and transmitted by the sphere, and the ripple is due to rays that graze the sphere and deflect energy in all directions.

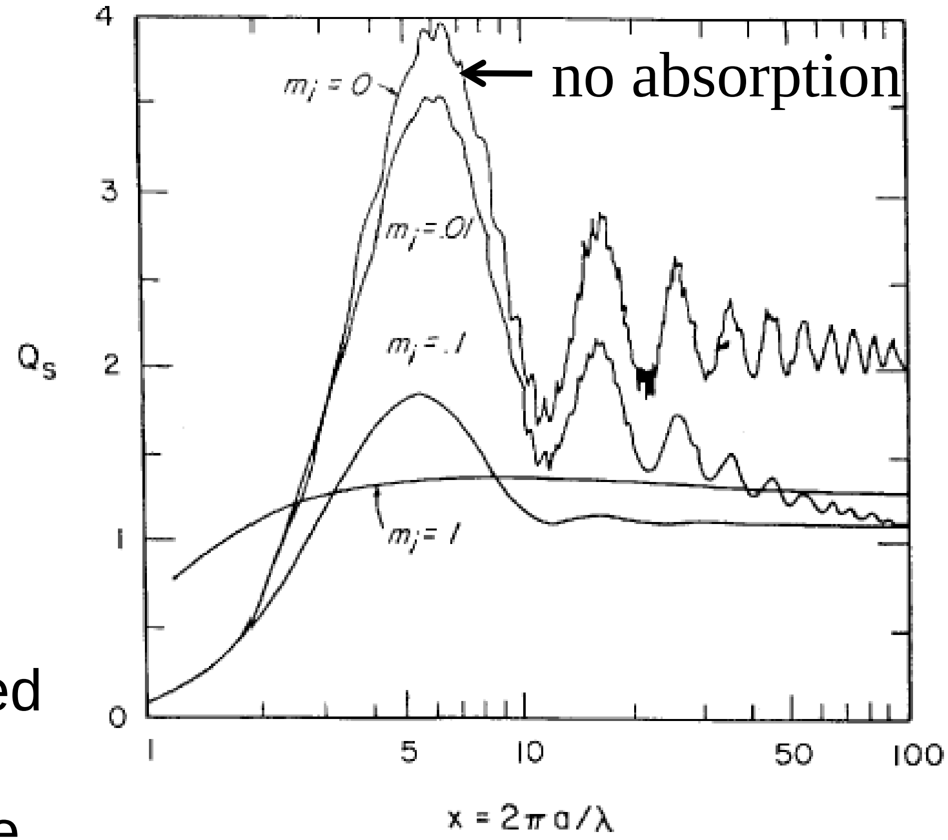


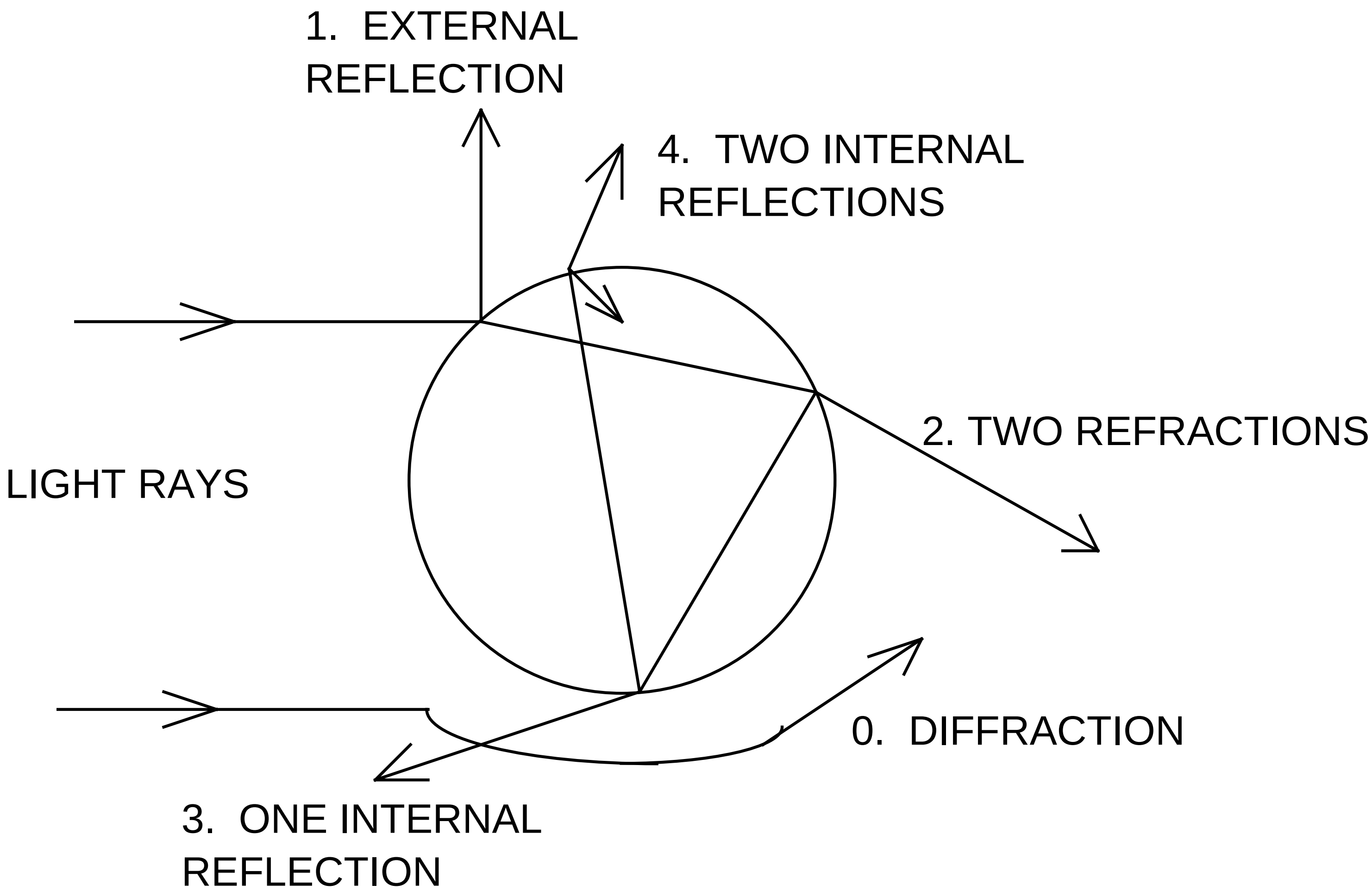
Figure 50: Typical Mie Scattering Diagram

Scattering Efficiency - 2

- Note that the scattering efficiency can be greater than one, and that it tends to oscillate about a value of 2 as $\chi \rightarrow \infty$.
  - → This is called the extinction paradox.

- $Q_s = 2$ means that a large particle removes twice as much light from the incident beam as it intercepts.
  - → A purely geometrical consideration of extinction would suggest a limiting value of 1 determined by the amount of radiation blocked by the cross-sectional area of the particle.
  - → The edge of the particle causes diffraction which is concentrated in a narrow lobe about the forward direction and contains an equal amount of energy to that incident on the cross section of the particle.
  - → The light removed from the forward direction of the incident beam thus consists of a diffracted component that passes by the particle, and a scattered (or blocked) component that undergoes reflection and refraction inside the particle.

Scattering Efficiency - 3



LIGHT RAYS SCATTERED BY A SPHERE

An Aside: Diffraction - 1

- **Diffraction** refers to various phenomena associated with wave propagation, such as the bending, spreading and interference of waves passing by an object or aperture that disrupts the wave.
- While diffraction always occurs, its effects are generally most noticeable for waves where the wavelength is on the order of the feature size of the diffracting objects or apertures.

- Vibration of electric charges in the surface with some phase relation
- Spherical wavefronts interfere to produce new wave fronts
- Edges are not sharply bounded

An Aside: Diffraction - 2

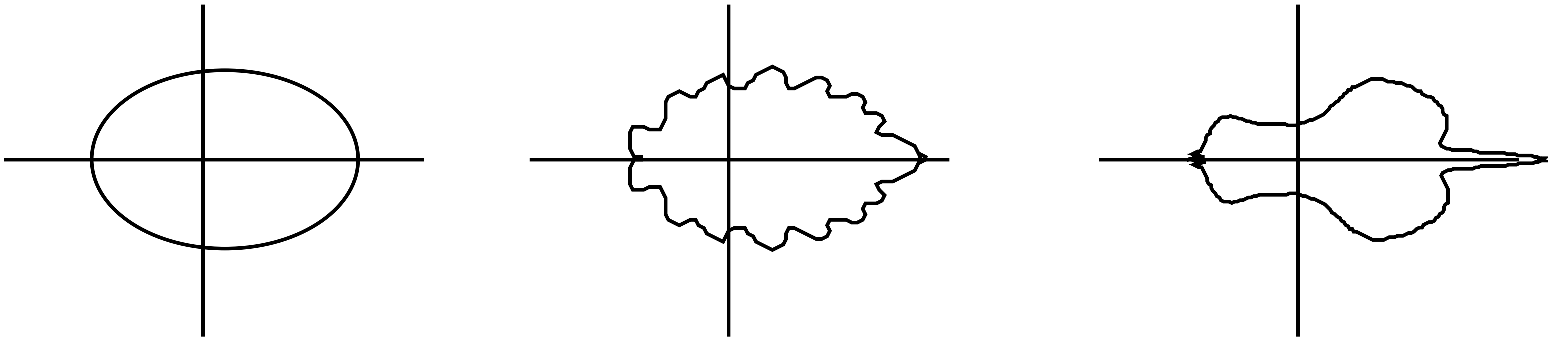
Diffraction Around An Object

- Waves can 'spread' in a rather unusual way when they reach the edge of an object - this is called diffraction.
- The amount of diffraction ('spreading' or 'bending' of the wave) depends on the wavelength and the size of the object.
- Diffraction can be clearly demonstrated using water waves in a ripple tank. Have a look at this a simulation of a ripple tank containing an object which obstructs the propagation of a wave:

Scattering Phase Function

Scattering phase function, P(θ)

- determines the direction in which the radiation is scattered
- peaks in the forward direction as χ increases
- larger particles generally show more structured scattering patterns with lobes
- for most particles, P(θ) has stronger forward and backward peaks, indicating strong forward and back scattering



$\chi = 1$ $\chi = 10$ $\chi = 100$

Scattering Phase Function

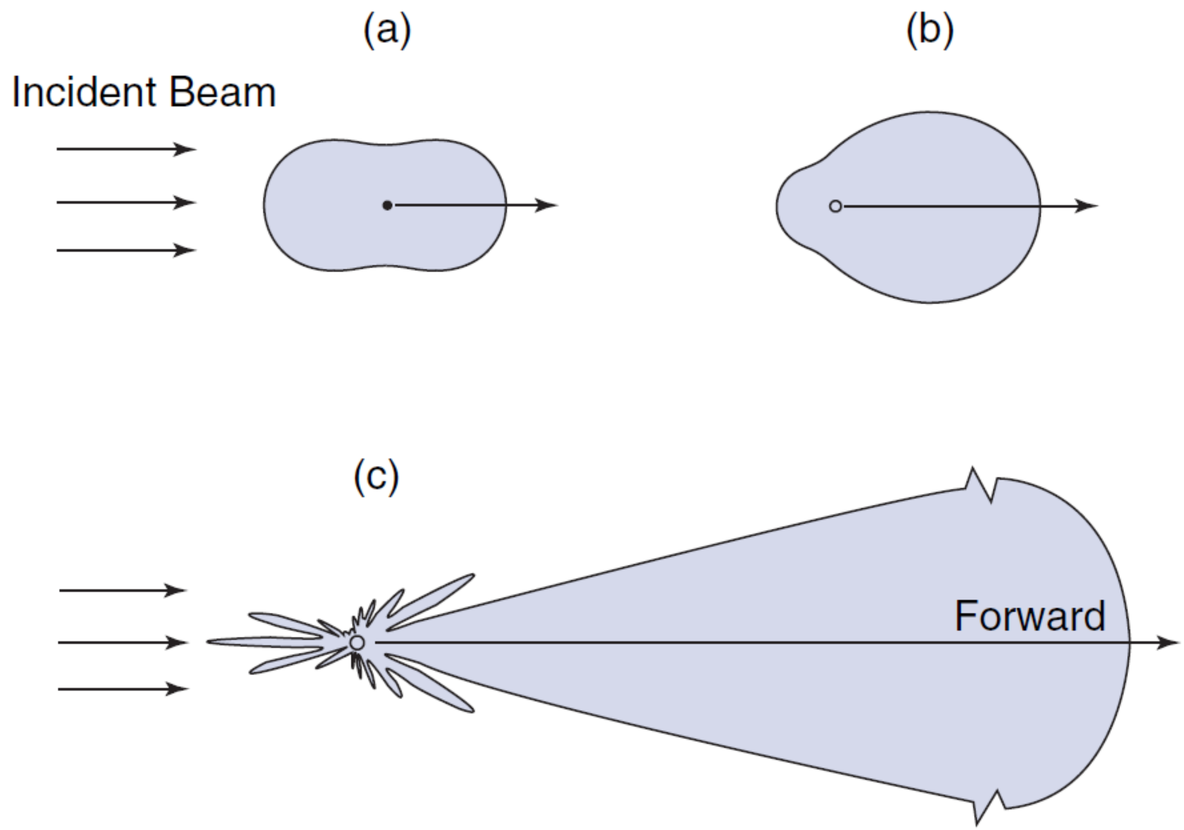
For visible radiation at $\lambda = 0.5\ \mu m$:

$\chi \equiv 2\pi r / \lambda$

(a) $r = 10^{-4}\ \mu m$, $\chi = 0.0013$

(b) $r = 0.1\ \mu m$, $\chi = 1.3$

(c) $r = 1\ \mu m$, $\chi = 13$



Wallace and Hobbs, Figure 4.12

Atmospheric Effects of Scattering

- Weak scattering just redirects the incoming solar beam slightly, allowing it to still reach the surface.
- Stronger scattering increases the atmospheric pathlength, which
  - → increases the atmospheric absorption
    - * e.g., Mars - dust storms fed by increased solar energy absorption
  - → increases the back-scattering to space which therefore increases the atmospheric albedo
    - * e.g., Venus - clouds reflect (back-scatter) about 75% of solar radiation
- Light that arrives at the top of the atmosphere from the Sun is unpolarized – this means that just as many photons have their planes of polarization in one direction as in any other direction.
  - → The degree of polarization of the light reaching the surface of the Earth – or reaching some satellite instrument in space – is due to Rayleigh scattering in the atmosphere.
  - → You can observe this by looking at the sky at 90° to the solar beam – rotate a polarizer and see how the transmitted light changes.

Why Is the Sky Blue?

- We have seen that the intensity of Rayleigh-scattered light depends on the wavelength of the incident light and on the index of refraction of air molecules.
- The intensity scattered by air molecules in a specific direction is proportional to $1/\lambda^4$.
- A large portion of the solar energy lies between the blue and red regions of the visible spectrum.
- λ_{blue} (~0.425 μm) < λ_{red} (~0.650 μm)
- Blue light scatters about 5.5 times more intensity than red light.

The sky appears blue, when viewed away from the Sun's disk.

Why Does Twilight Look Red?

- As the Sun approaches the horizon (at sunset or sunrise), the sunlight travels through a longer atmospheric pathlength, thus encountering more air molecules.
- Therefore more and more blue light – and light of shorter wavelengths – is scattered out of the beam of light.
- The Sun shows a deeper red color than at its zenith.

The Sun is a deeper red color than at its zenith.

Since violet light ($\lambda \sim 0.405\ \mu$m) has a shorter wavelength than blue, why doesn't the sky appear violet?

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Since violet light (λ ~ 0.405 μm) has a shorter wavelength than blue, why doesn't the sky appear violet?

- Some of this violet light is absorbed by the upper atmosphere
- There is more blue than violet in sunlight
- Our eyes are slightly more sensitive to blue than to violet