Transmission of (solar) radiation through the atmosphere
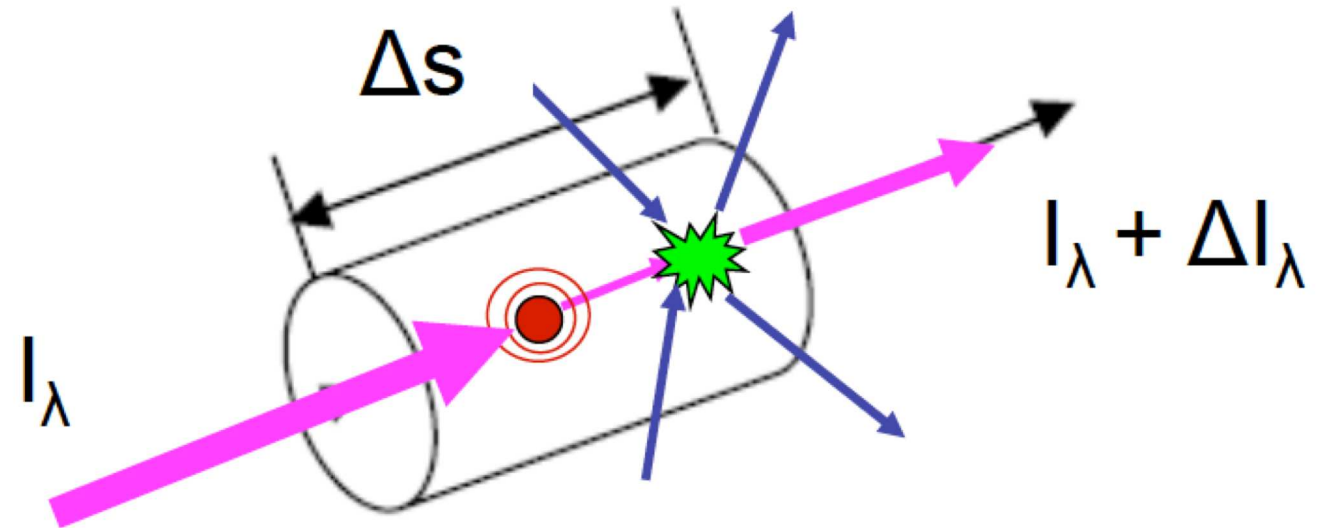
Content

- Basic General Radiative transfer equation
- Shortwave radiative transfer & optical depth
- Scattering
- Infrared absorption
- Atmospheric heating/cooling rates

General radiative transfer

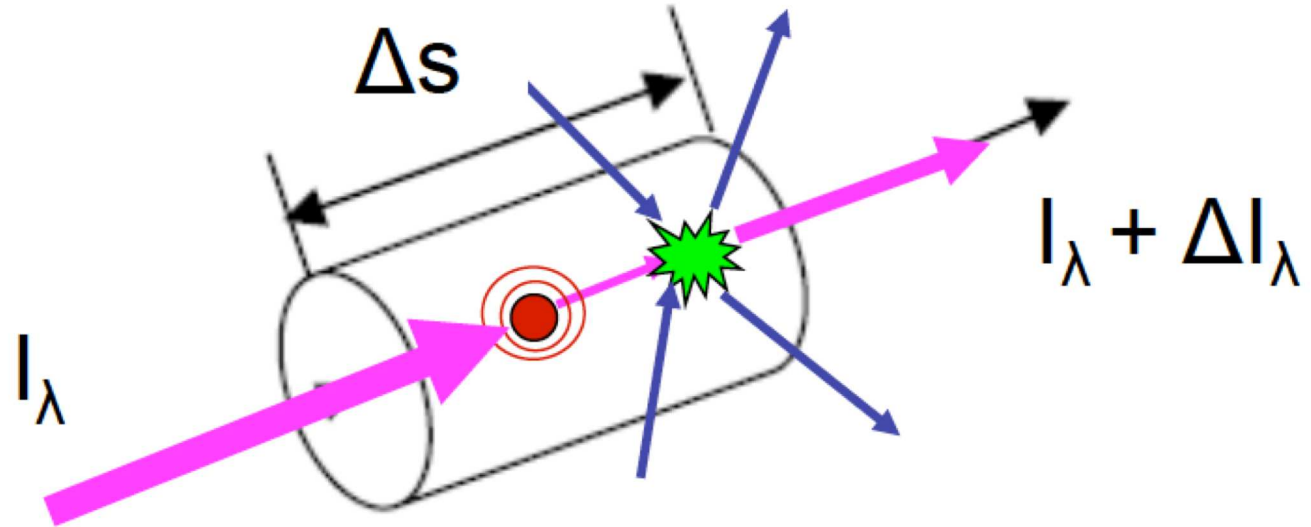Attenuation Processes

Source Processes

Δs

I_λ

$I_\lambda + \Delta I_\lambda$

Propagation of a radiative beam with irradiance I_λ (cf. flux density, Wm^{-2}) through a radiatively active medium of depth Δs

General radiative transfer

Attenuation Processes: loss of radiation along the direction of travel due to absorption or scattering by the intervening matter.

Source Processes: gain of radiation along the direction of travel due to emission or scattering by the intervening matter Energy must thereby be conserved (1. Law of Thermodynamics)


Δs

I_λ

$I_\lambda + \Delta I_\lambda$

Propagation of a radiative beam with irradiance I_λ (flux density, Wm^{-2}) through a radiatively active medium of depth Δs

Attenuation: proportional to the density of the medium, the intensity of the incoming beam, and the pathlength:

$$\Delta I = -k_\lambda \, \rho \, I_\lambda \, \Delta s$$

k_λ: mass extinction coefficient (spectrally and spatially varying, units m^2/kg) or extinction cross-section per unit mass: "virtual area of a completely opaque object, blocking radiation"

Extinction coefficient takes into account absorption & scattering: $k_\lambda = k_{\lambda,abs} + k_{\lambda,scatt}$
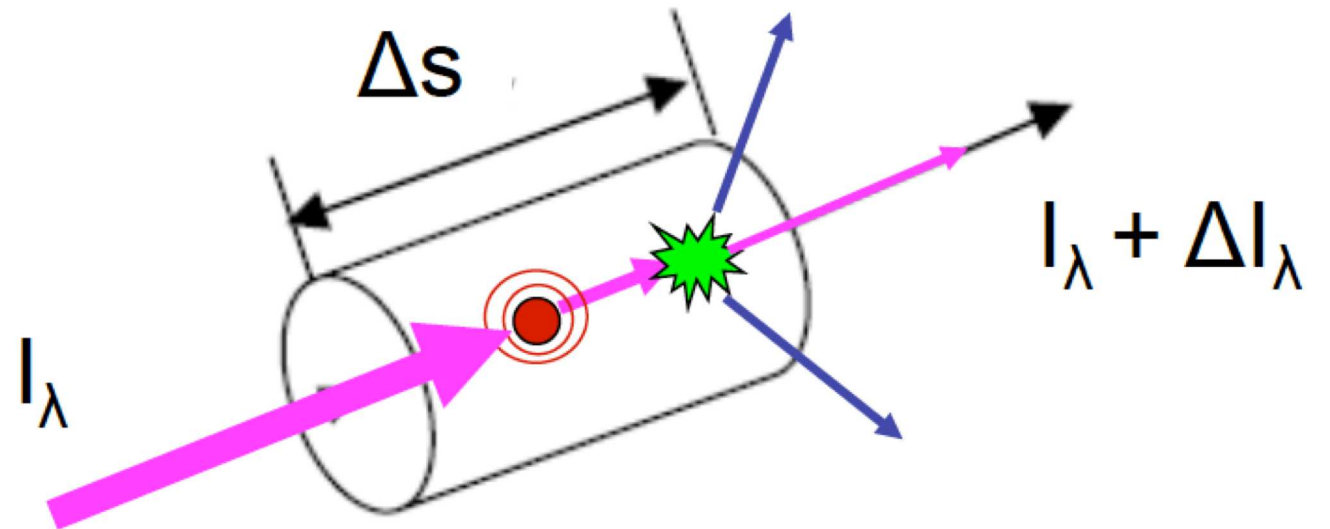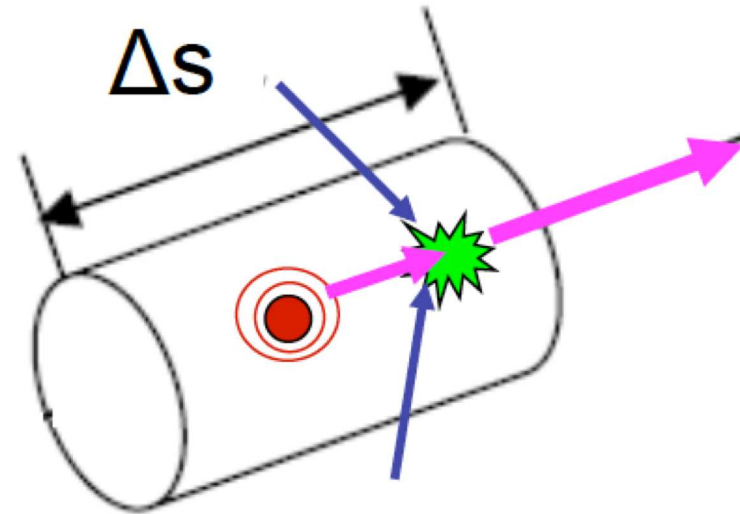
Sources of radiation along the optical path arising from either emission of the medium or scattering from all directions into the direction of the path, are represented by the source function (J_λ)

The incremental addition of radiation is given by:

$$\Delta I = J_\lambda \, \rho \, \Delta s$$

where $J_\lambda = J_{\lambda, \, emit} + J_{\lambda, \, scat}$ (unit $Js^{-1}kg^{-1}$)

(next week's lecture)

Radiative transfer equation in general terms

The alteration of a radiative beam with intensity I_λ when passing through a radiatively active medium of depth Δs can thus be described as:

$$\Delta I_\lambda = \underbrace{-k_\lambda \rho I_\lambda \Delta s}_{\text{Attenuation term}} + \underbrace{\rho J_\lambda \Delta s}_{\text{Source term}}$$

$$\frac{\Delta I_\lambda}{\Delta s} = -k_\lambda \rho I_\lambda + \rho J_\lambda$$

Shortwave radiative transfer

Sun emits radiation roughly as a blackbody of 5777K
With maximum intensity at 0.5 μm (Wien's displacement law)
=> significant amount of solar radiation between 0.2 μm and 4 μm
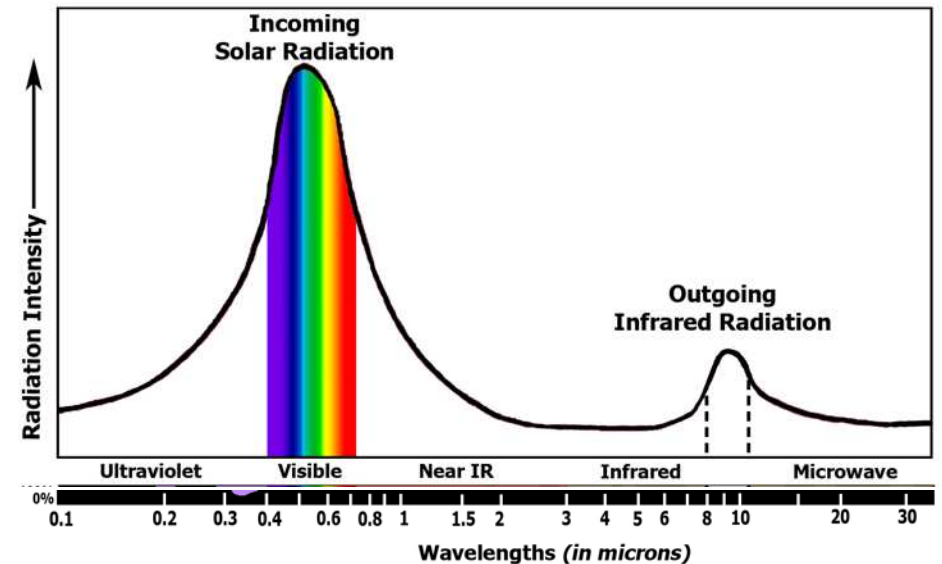Emission of atmosphere and Earth surface (with T ~ 250-300K) in this
spectral range negligible =>**Assumption**: atmosphere a purely absorbing & scattering,
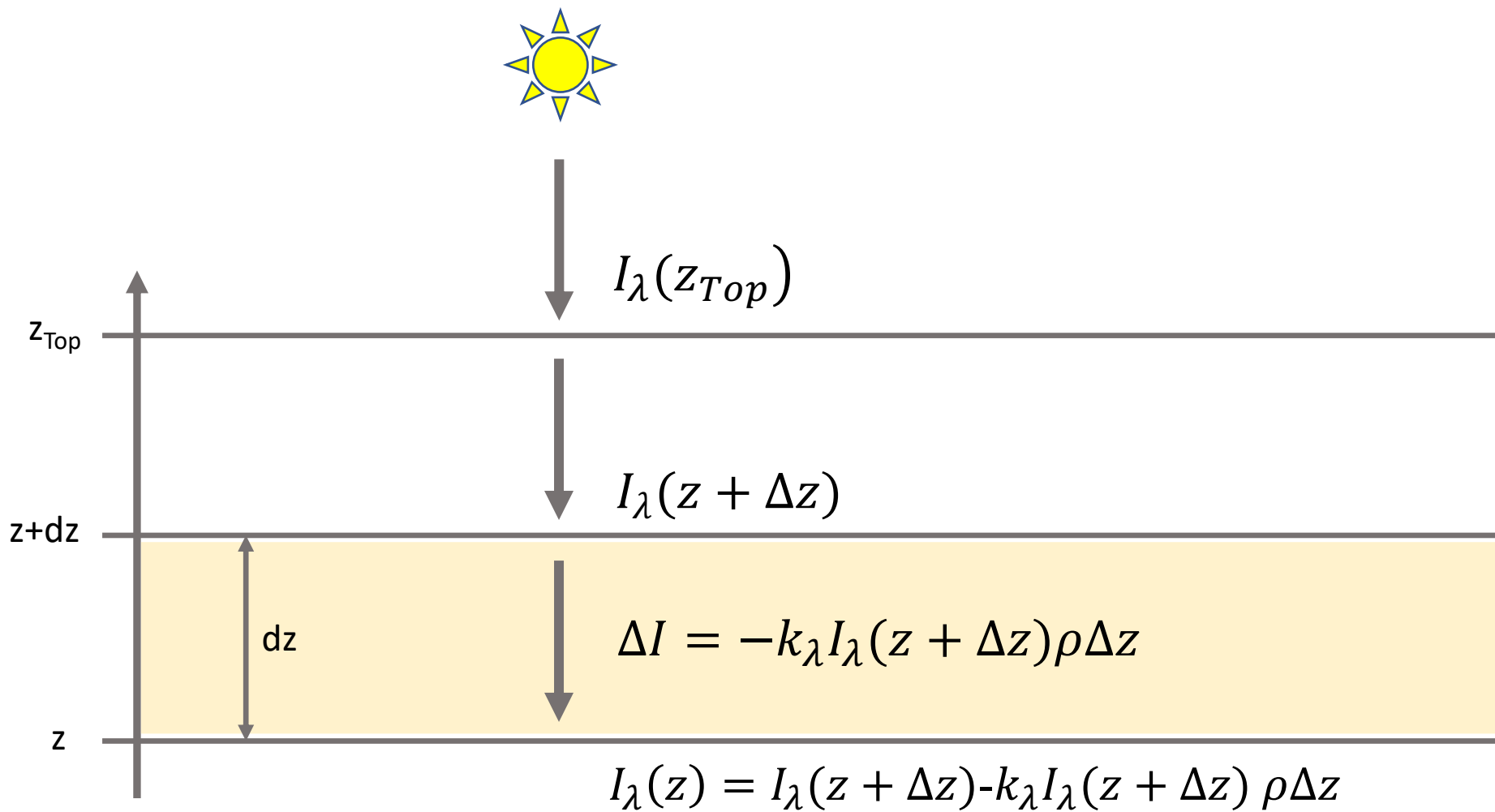but non-emitting medium in the wavelength range of solar radiation

Radiative transfer equation:

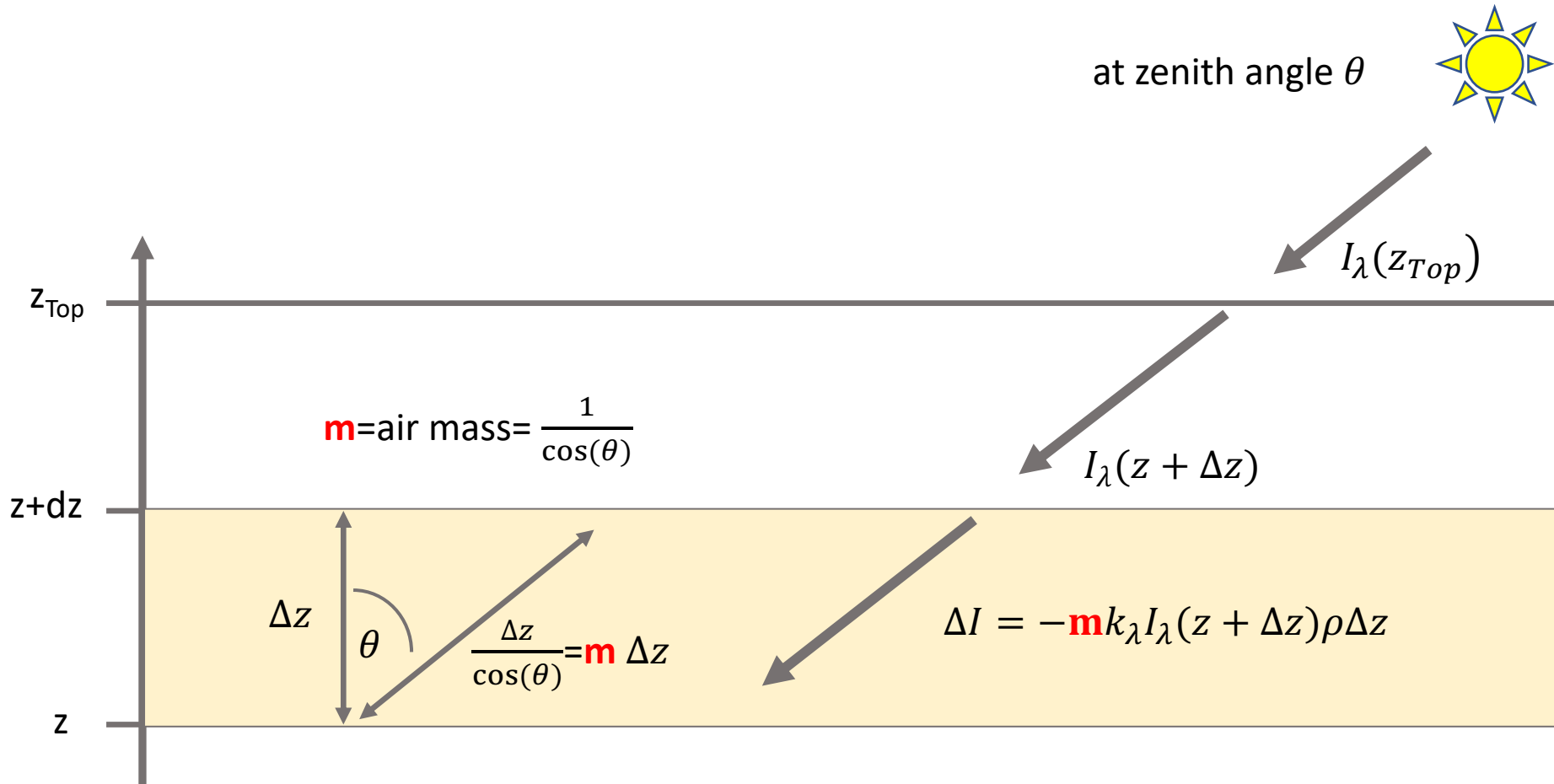$$\frac{\Delta I_\lambda}{\Delta s} = -k_\lambda \rho I_\lambda + \rho J_\lambda$$

Reduces for solar radiation to:

$$\frac{\Delta I_\lambda}{\Delta s} = -k_\lambda \rho I_\lambda$$

$$z_{Top}$$

$$I_\lambda(z_{Top})$$

$$z+dz$$

$$I_\lambda(z + \Delta z)$$

$$dz$$

$$\Delta I = -k_\lambda I_\lambda(z + \Delta z)\rho\Delta z$$

$$z$$

$$I_\lambda(z) = I_\lambda(z + \Delta z) - k_\lambda I_\lambda(z + \Delta z)\,\rho\Delta z$$

$$\Delta I = I_\lambda(z + \Delta z) - I_\lambda(z) = -k_\lambda I_\lambda(z + \Delta z)\,\rho\Delta z$$

at zenith angle θ

$I_\lambda(z_{Top})$

z_{Top}

m=air mass=$\dfrac{1}{\cos(\theta)}$

$I_\lambda(z + \Delta z)$

z+dz

Δz

θ

$\dfrac{\Delta z}{\cos(\theta)}$=$m\,\Delta z$

$\Delta I = -mk_\lambda I_\lambda(z + \Delta z)\rho\Delta z$

z

$\Delta I = I_\lambda(z + \Delta z) - I_\lambda(z) = -mk_\lambda I_\lambda(z + \Delta z)\,\rho\Delta z$

$$\frac{dI_\lambda}{dz} = -mk_\lambda I_\lambda \rho \qquad \text{Beer's law}$$

Solving Beer's Law …

White board:

$$\frac{dI_\lambda}{dz} = -mk_\lambda I_\lambda \rho$$

$$I_\lambda(z) = I_\lambda(z_{Top})e^{-m\int_{zTop}^{z} k_\lambda \rho dz}$$

$$T = \frac{I_\lambda(z)}{I_\lambda(z_{Top})} \quad \text{transmissivity}$$

$$\int_{zTop}^{z} k_\lambda(z)\rho(z)dz = \tau_\lambda \quad \text{optical depth/thickness}$$

$$T = \frac{I_\lambda(z)}{I_\lambda(z_{Top})} = e^{-m\tau_\lambda}$$

Exponential decay in T with path length

optical depth expresses ability of medium to block light and is dimensionless

Examples

Optical depth before and after Pinatubo

SAGE II 1020 nm Optical Depth

91-April-10 to 91-May-13   91-June-15 to 91-July-25

91-August-23 to 91-September-30   93-December-5 to 94-January-16

<10⁻³   10⁻²   >10⁻¹
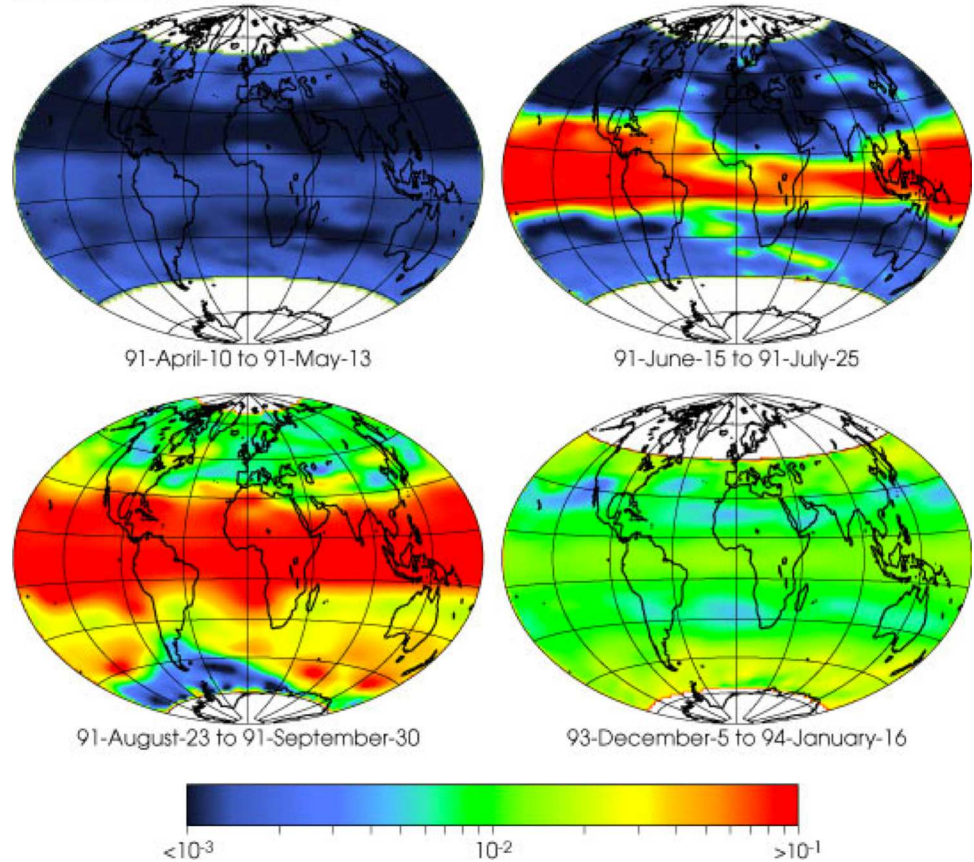
"... hazy layer of aerosol particles composed primarily of sulfuric acid droplets. Over the course of the next two years strong stratospheric winds spread these aerosol particles around the globe." SAGE II data

Beijing before and after big parade

Extend observational records from 1980s to present
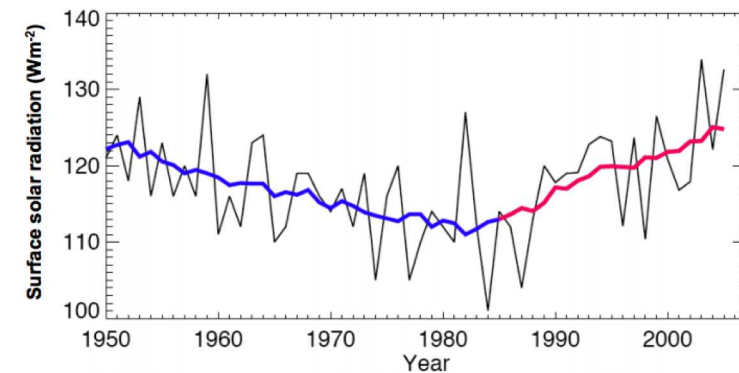
Surface Solar Radiation at Potsdam   Wild et al. 2005:

Extinction coefficient k_λ

$$\tau_\lambda = \int_{zTop}^{z} k_\lambda \rho dz$$

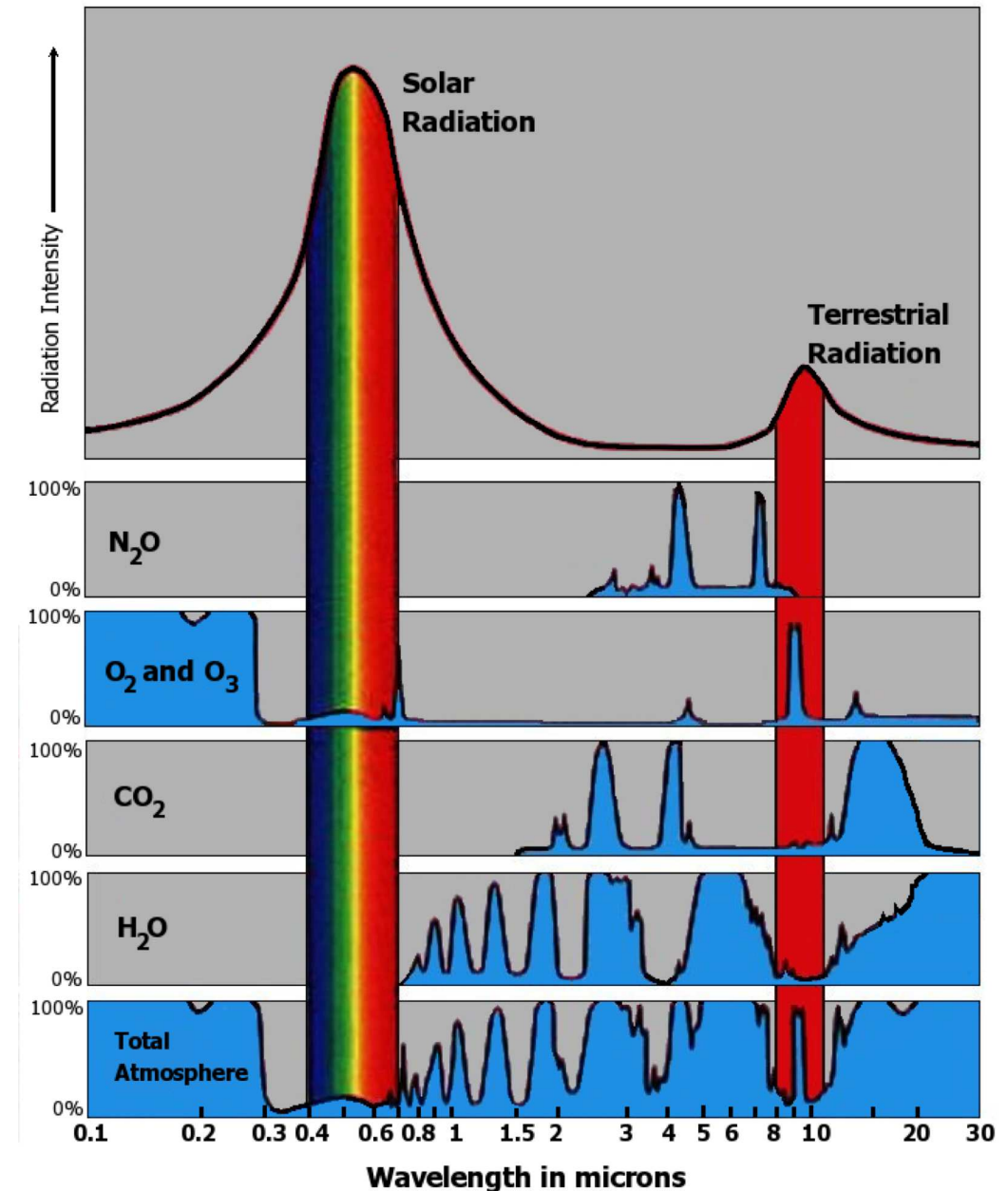$$k_\lambda = k_{\lambda,absorption} + k_{\lambda,scattering}$$

Under cloud free conditions:

$$k_{ext} = k_A + k_R + k_M$$

k_A = gas absorption (H_2O, CO_2, O_3, O_2, …)

k_R = Rayleigh scattering (molecular)

k_A = Mie scattering (aerosols)

Absorption processes

- **Electron transitions:** Absorption of EM radiation by electron transition from lower to higher energy level enabled by photon energy.

- Only possible of energy level difference matches with amount of energy of photon; wavelength dependent ("selective absorption")

- Gamma rays, X-Rays, UV, visible

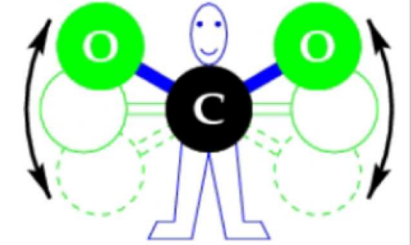$$hv = E_2 - E_1$$
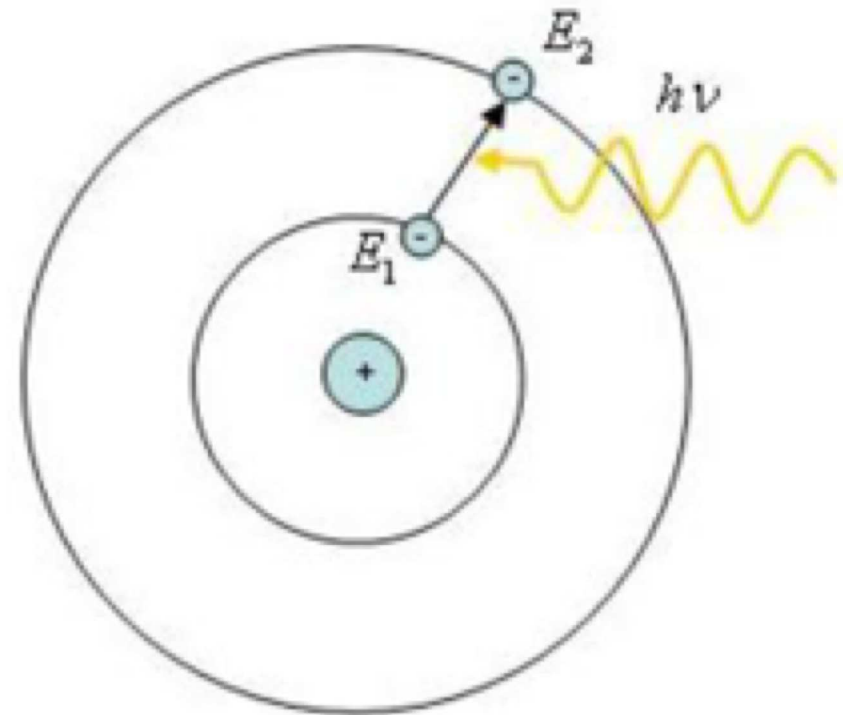
Absorption processes

Vibrational & rotational transitions covered last time!

- Vibrational transitions
  - near IR, thermal IR:1 μm $\lesssim \lambda \lesssim$ 20 μm
  - three modes (symmetric/antisymmetric stretch, bend) for triatomic molecules

- Rotational transitions
  - far IR, microwave: $\lambda \gtrsim$ 20 μm
  - bending vibrational motions in CO2, CH4 break symmetry and lead to oscillating dipole moment
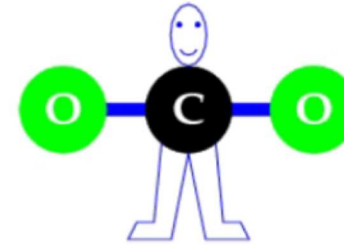
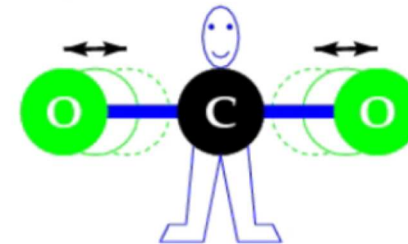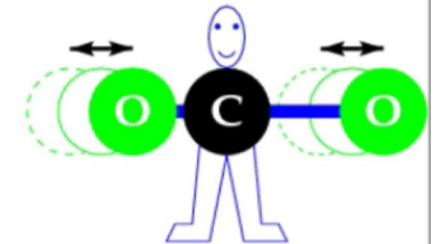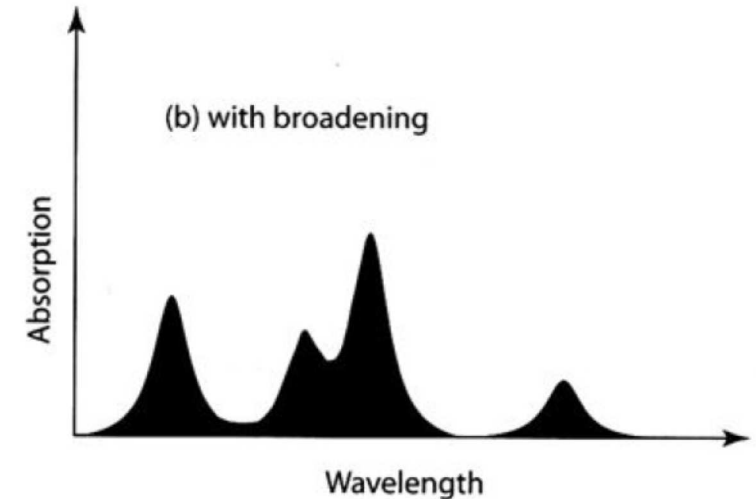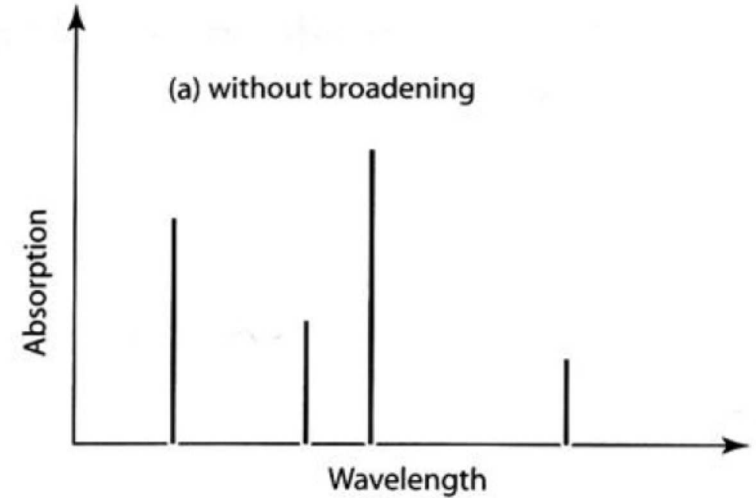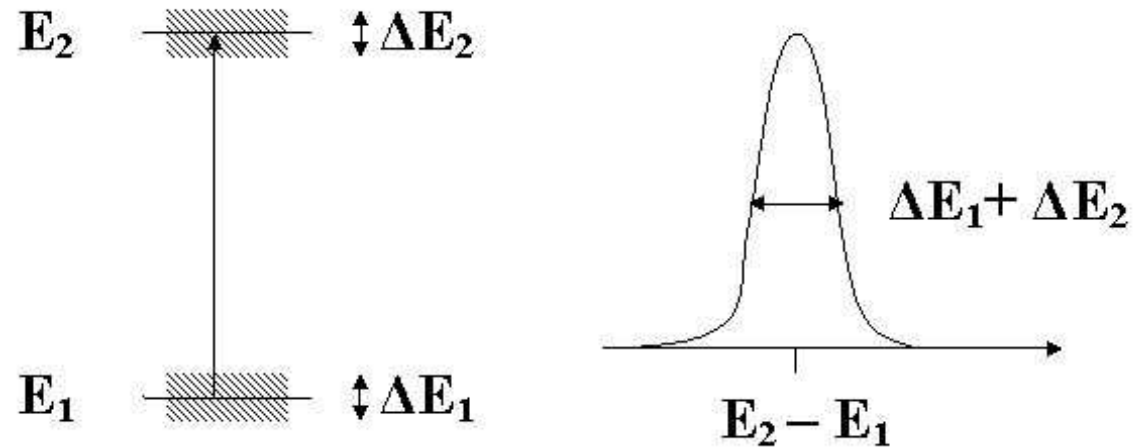# Absorption line broadening

- Above processes are quantized, selective but monochromatic emission (almost) never observed!

- Energy levels change due to external influences & loss of energy in emission

- Radiation emitted is nonmonochromatic: spectral lines of finite width instead of discrete lines

- Broadening closes gaps between closely spaced absorption lines, so that the atmosphere becomes opaque over a continuous range of wavelengths.

- Spectrum is "smeared", but note: energy & intensity is conserved

Intrinsic or Natural broadening

- Excited quantum state has intrinsic lifetime before it decays to lower energy state.
- Transitions between states will not result in monochromatic absorption/emission
- Because of *quantum mechanical uncertainty* (Heisenberg's Uncertainty Principle) in the energy of states due to uncertainty in lifetime (dt) of system; short-lived states have large uncertainties in the energy; and a range of frequencies is possible (frequency width dv)

$$\Delta v \sim \frac{\Delta E}{h} \sim \frac{1}{2\pi\Delta t}$$

Pressure broadening

- Collisions between absorbing molecules and between absorbing and no-absorbing molecules; dominates in lower atmosphere (<20km)

- Disrupt natural transitions between energy states

- Absorption/emission occur at wavelength that deviate from natural line position

- Shape of spectral lines is given by *Lorentz profile*

$$k_\nu = Sf(\nu - \nu_0) \text{ (generic shape)}$$

k_ν=absorption cross-section of molecule at frequency ν, S=line strength/intensity, $f(\nu - \nu_0) =$ lineshape function, ν_0= center frequency, α_L = Lorentz halfwidth at half maximum, proportional to number of collisions

$$f(\nu - \nu_0) = \frac{\alpha_L/\pi}{(\nu-\nu_0)^2 + \alpha_L{}^2} \text{ (Lorentz shape)}$$

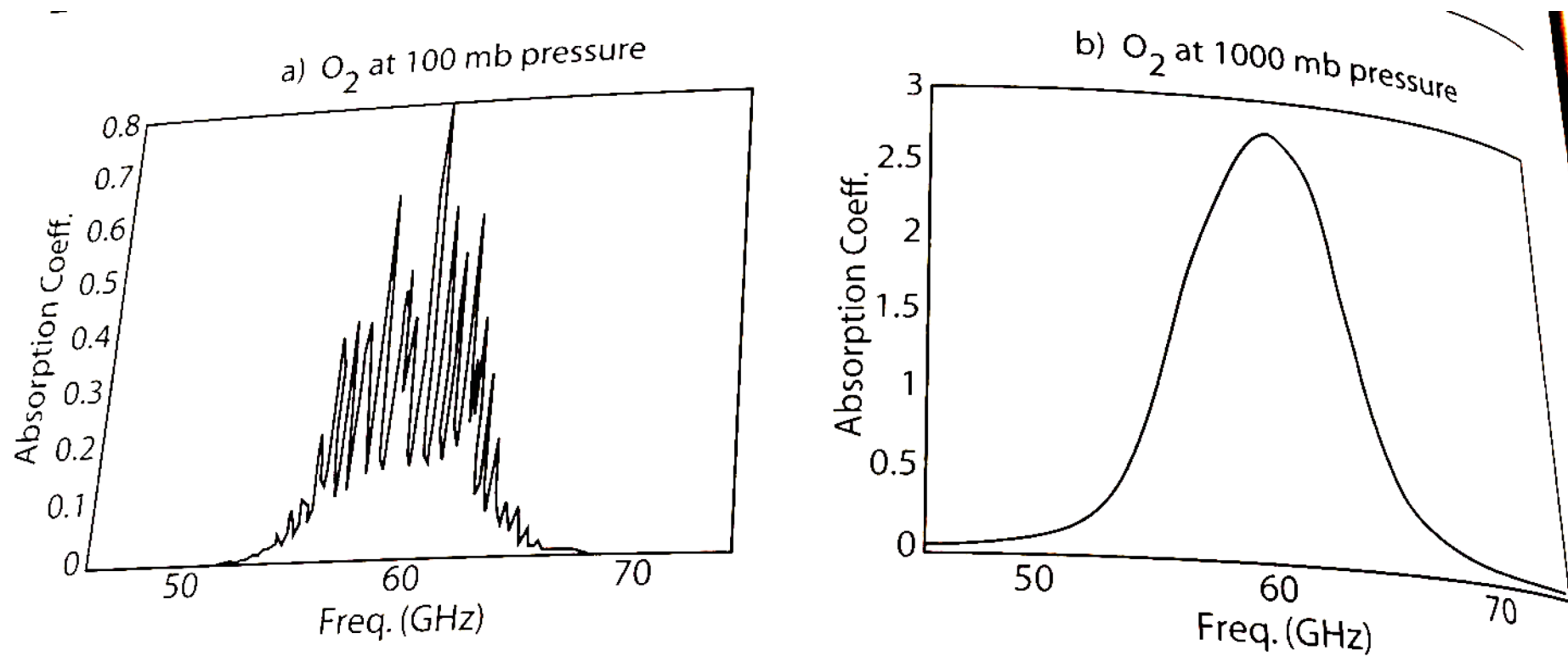$$\alpha_L \sim p/\sqrt{T}$$

Pressure broadening

Fig. 9.8: Absorption coefficient of oxygen in the microwave band near 60 GHz, (a) at 100 mb pressure, revealing the individual lines making up the absorption band; (b) at 1000 mb, for which pressure broadening obliterates the line structure.
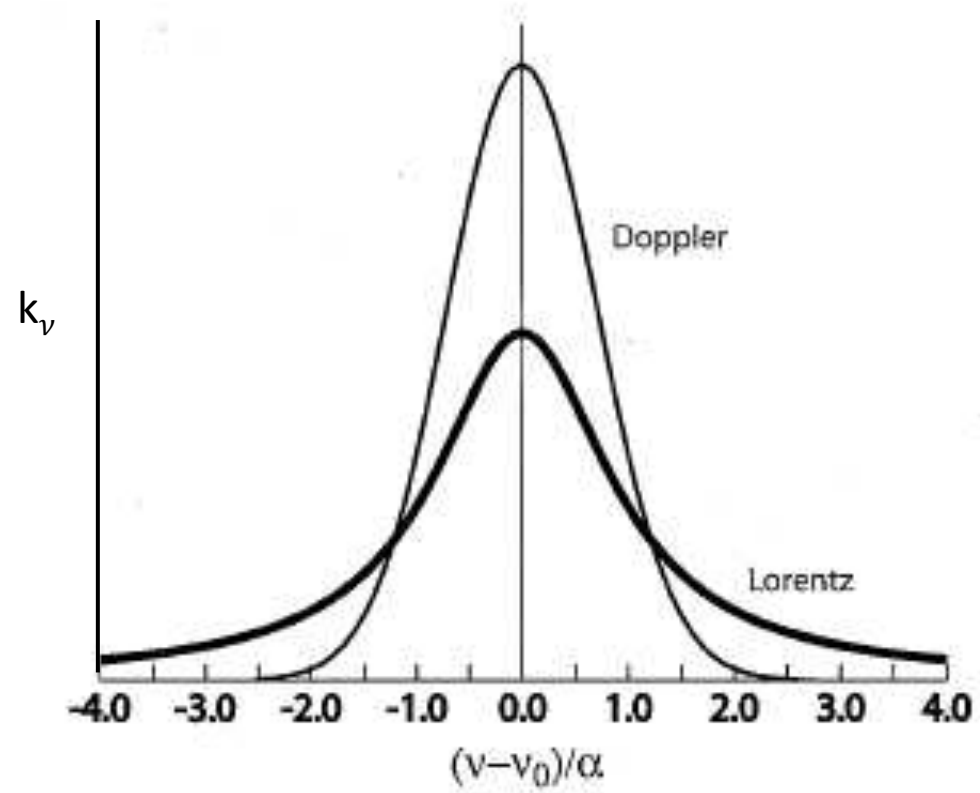
Doppler broadening

- Random translational (thermal) motions of molecules; dominates in upper atmosphere

- Motion of molecule along line-of-sight introduces shift into frequency of photons

- **Doppler shift frequency: $\nu' = \nu(1 - vel/c)$**

  - ν =frequency measured by stationary observer; ν' measured by observer moving with *vel*

- frequencies that do not coincide with ν_0 line are absorbed if molecule has right relative velocity. frequency equal to ν_0 are only absorbed by molecules with relative velocity close to zero.

- Net effect is decrease in absorption by molecule at ν_0 (line center) and increase in absorption of nearby frequencies.

- Gaussian distribution of molecular speeds, hence Gaussian line shape for Doppler broadening:

$$f_D(\nu - \nu_0) = \frac{1}{\alpha_D \sqrt{\pi}} exp\left[-\frac{(\nu-\nu_0)^2}{\alpha_D^2}\right]$$

$$\alpha_D = \nu_0 \sqrt{\frac{2k_B T}{mc^2}} \; ; \text{Doppler line width}$$
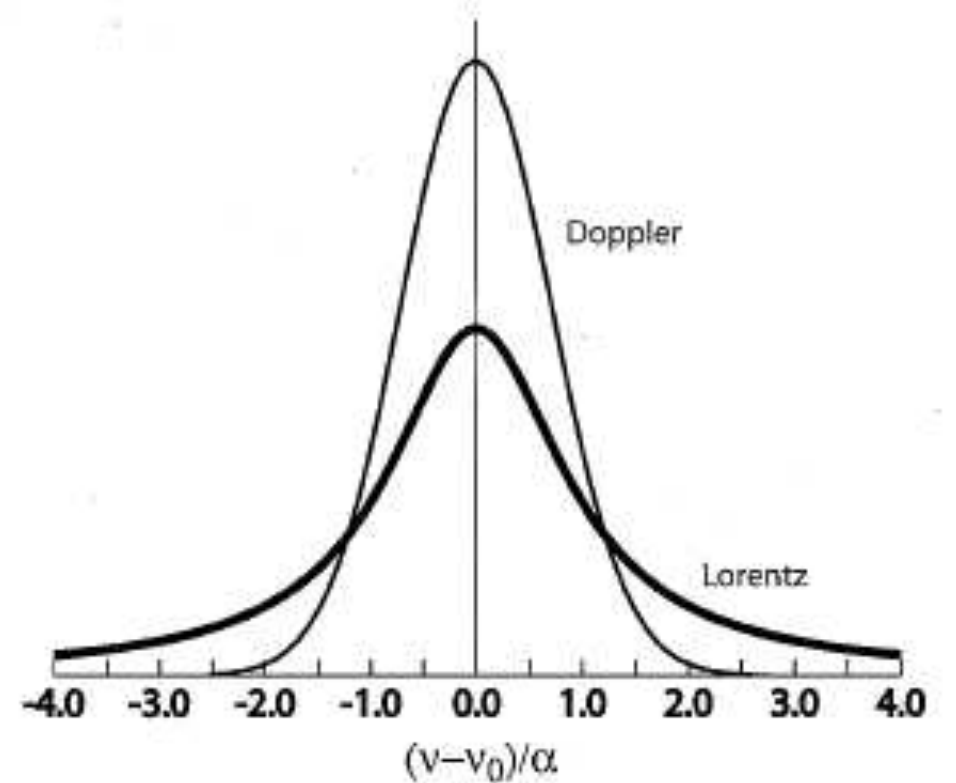
- Mean speed of molecules and therefore line width increases with temperature and decreases with molecular mass
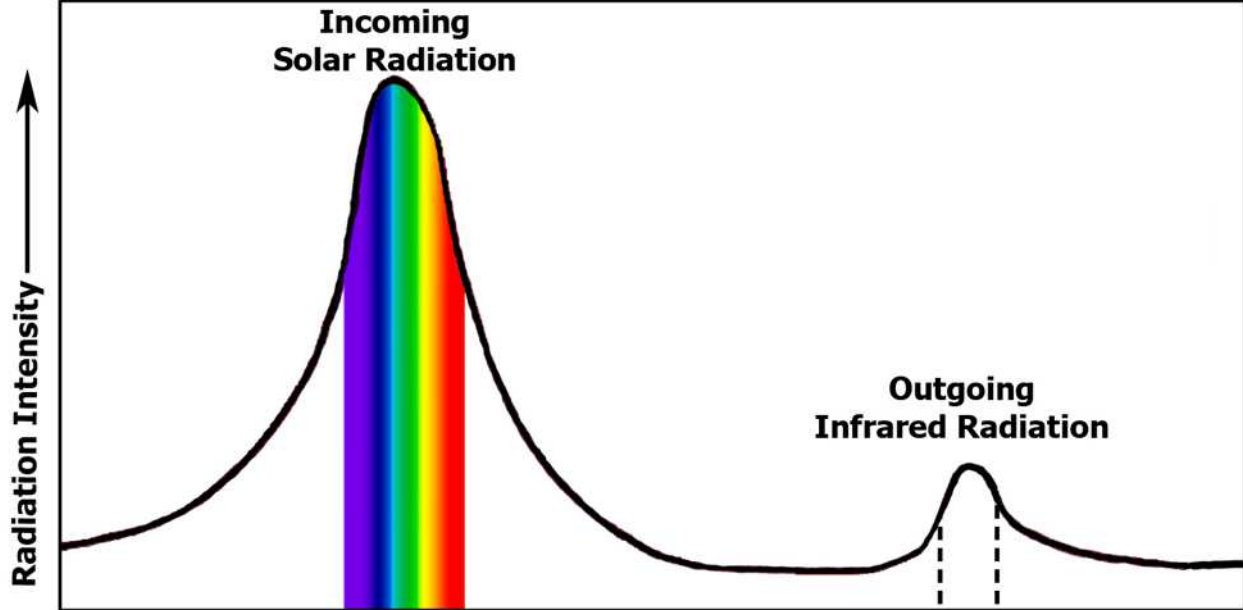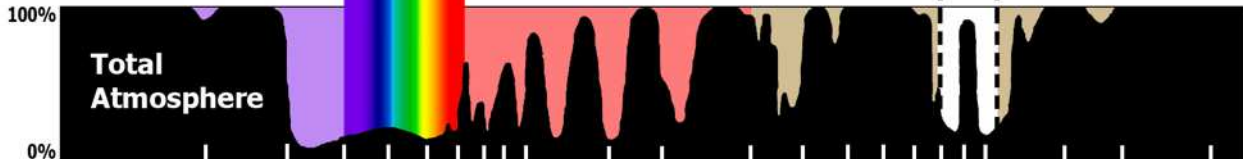
Pressure vs. Doppler
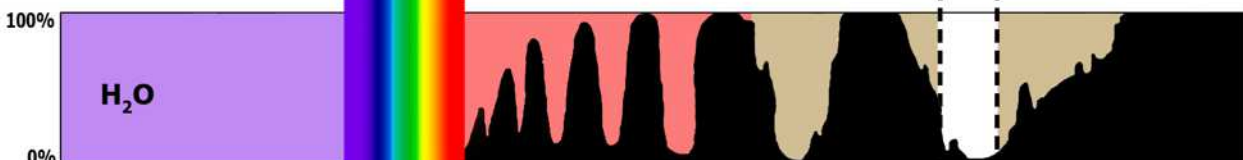
Pressure vs. Doppler

- Shape
- Altitude – pressure effect
- Wings (Pressure more absorption in far wings)
- 20-50km both broadening effects become equally important: Voigt profile, convolution of Lorentz and Doppler line shapes.
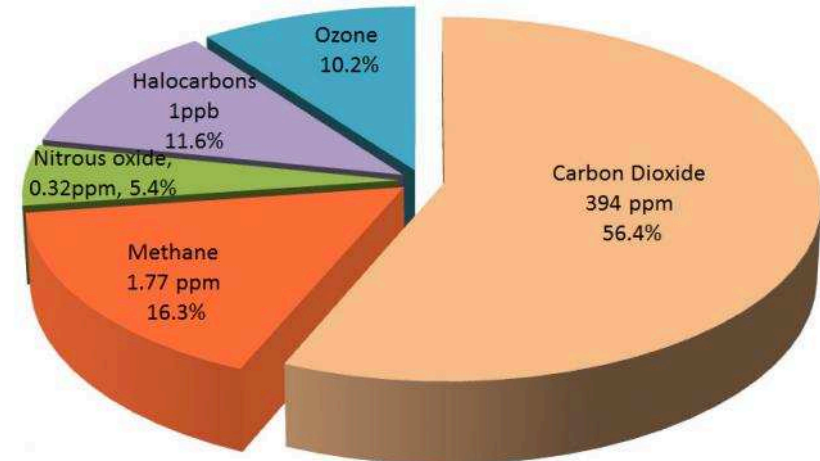
Incoming Solar Radiation

Outgoing Infrared Radiation

Radiation Intensity

Ultraviolet   Visible   Near IR   Infrared   Microwave

Absorption (%)

O_2 and O_3

CO_2

H_2O

Total Atmosphere

100% 0% 100% 0% 100% 0% 100% 0%

0.1 0.2 0.3 0.4 0.6 0.8 1 1.5 2 3 4 5 6 8 10 20 30

Ozone 10.2%

Halocarbons 1ppb 11.6%

Nitrous oxide, 0.32ppm, 5.4%

Methane 1.77 ppm 16.3%

Carbon Dioxide 394 ppm 56.4%

Carbon Dioxide   Methane   Nitrous oxide   Halocarbons   Ozone

H_2O: 4%
CO_2: 0.04%

Rayleigh scattering or: why is the sky blue?

- Homogenous, spherical particle with radius much smaller than incident radiation ($< 0.1\ \lambda$) (atoms, molecules)

- Parametric process = elastic scattering = no change in energetic state of particle or frequency of scattered wave

- Oscillating electric field acts on charges of particle inducing oscillating electric dipole that produces scattered wave (or modifies applied field)

dipole oscillation

γ

γ

elastic Rayleigh scattering
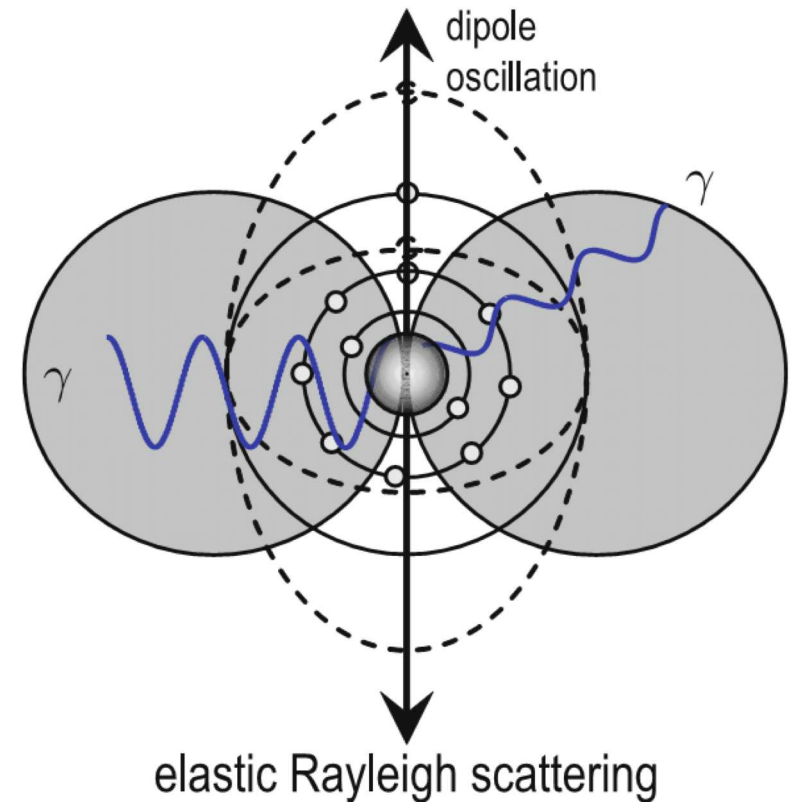
Rayleigh scattering or: why is the sky blue?

- Phase function P describes probability of direction of scattered photon ("peanut shape") $P(\phi) \propto 1 + cos2(\phi)$

$$I(\phi) = I_0 \frac{k_R}{r^2} \frac{P(\phi)}{4\pi}$$ Scattered intensity

- In case of molecular scattering, **mass extinction coefficient** k_R (m²/kg) $\propto \sum_i \sigma_i$ = sum of all individual particles' extinction cross-sections, is independent of "particle" radius **a** (although $\sigma_i \propto \frac{a^6}{\lambda^4}$), only # in volume important
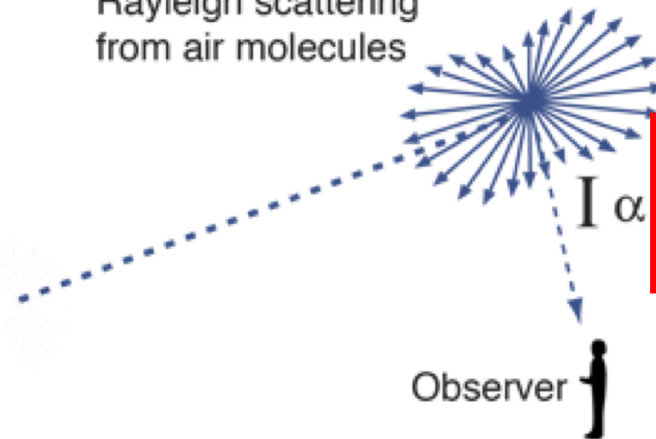
$$k_R = \frac{8\pi^3(m^2 - 1)^2}{3\lambda^4 N^2}$$ $$k_R \ \alpha \ \frac{1}{\lambda^4}$$

m = refractive index ("deflection of light")
N = # of molecules in volume, a=radius
r= distance between particle and observer

refractive index
n₁   n₂

normal
θ₁
θ₂
interface
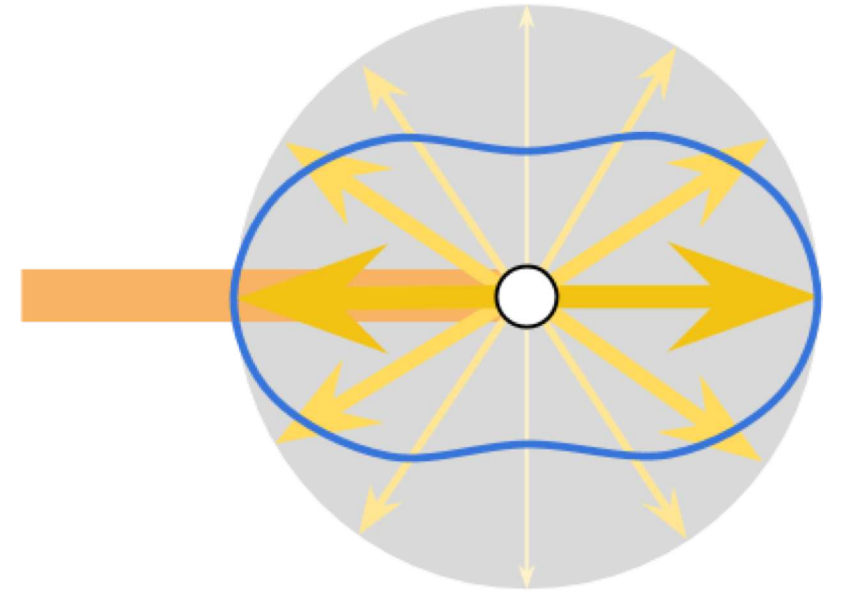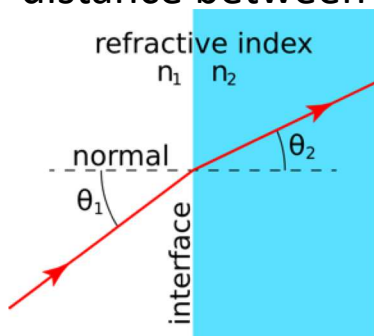
Rayleigh scattering
from air molecules

$I \ \alpha \ \frac{1}{\lambda^4}$

Observer

The strong wavelength dependence of Rayleigh scattering enhances the short wavelengths, giving us the blue sky.

The scattering at 400 nm is 9.4 times as great as that at 700 nm for equal incident intensity.

Mie scattering (also elastic)

- Homogenous, isotropic, spherical particle with radius at similar size or larger then incident radiation λ (aerosol, smoke, dust, haze)

- Interaction of radiation represents fine-scale scattering from microstructures integrated over larger structure (infinite series of electric multipoles). Rayleigh and geometric scattering are in essence approximations under certain conditions.

- For aerosols in atmosphere, k_M cannot neglect size distribution of particles with different radii (as opposed to #distribution for gas):

$$k_M = \sum_i \frac{\sigma_i}{M_i}; \quad M_i = \text{mass of individual particle}$$

assuming Rayleigh theory applies: $k_M \propto \dfrac{a^6}{\lambda^4}$

- Size matters with Mie! and governs scattering intensity, almost no wavelength dependence for very large particles (see next slide)

- Radiation tends to be mostly scattered forward, even more so the larger the particle is with respect to wavelength of incident radiation
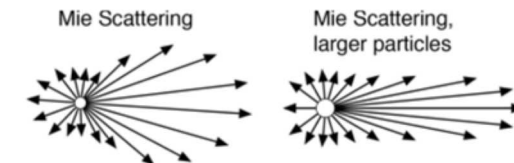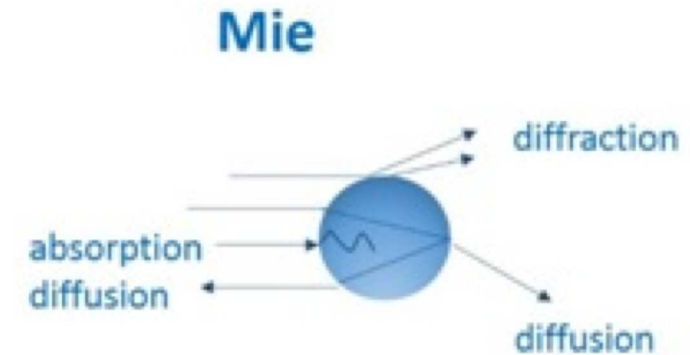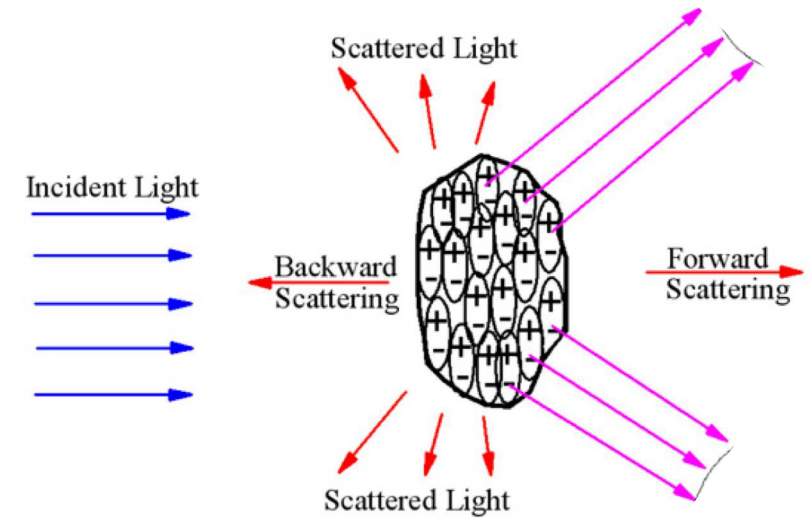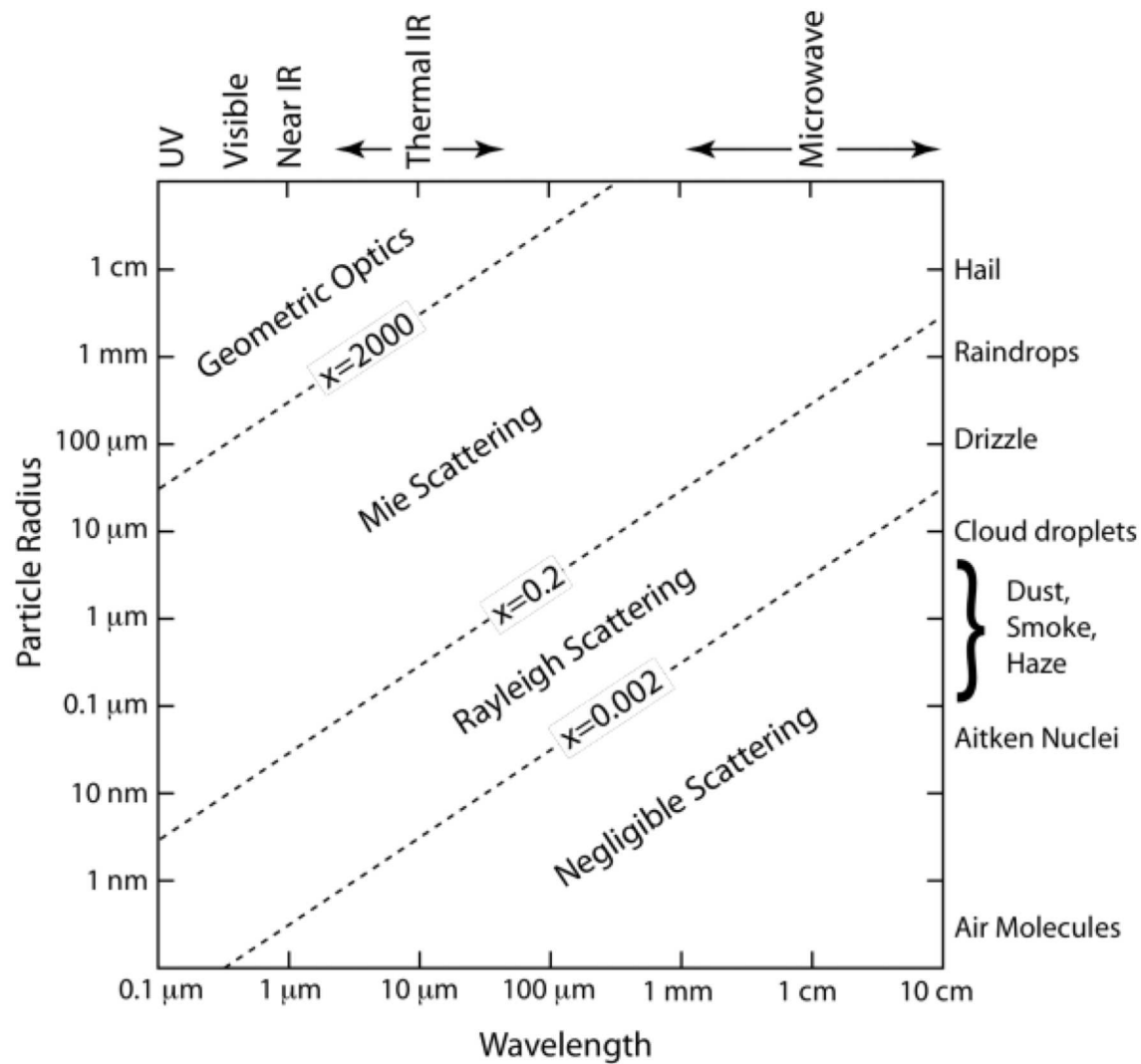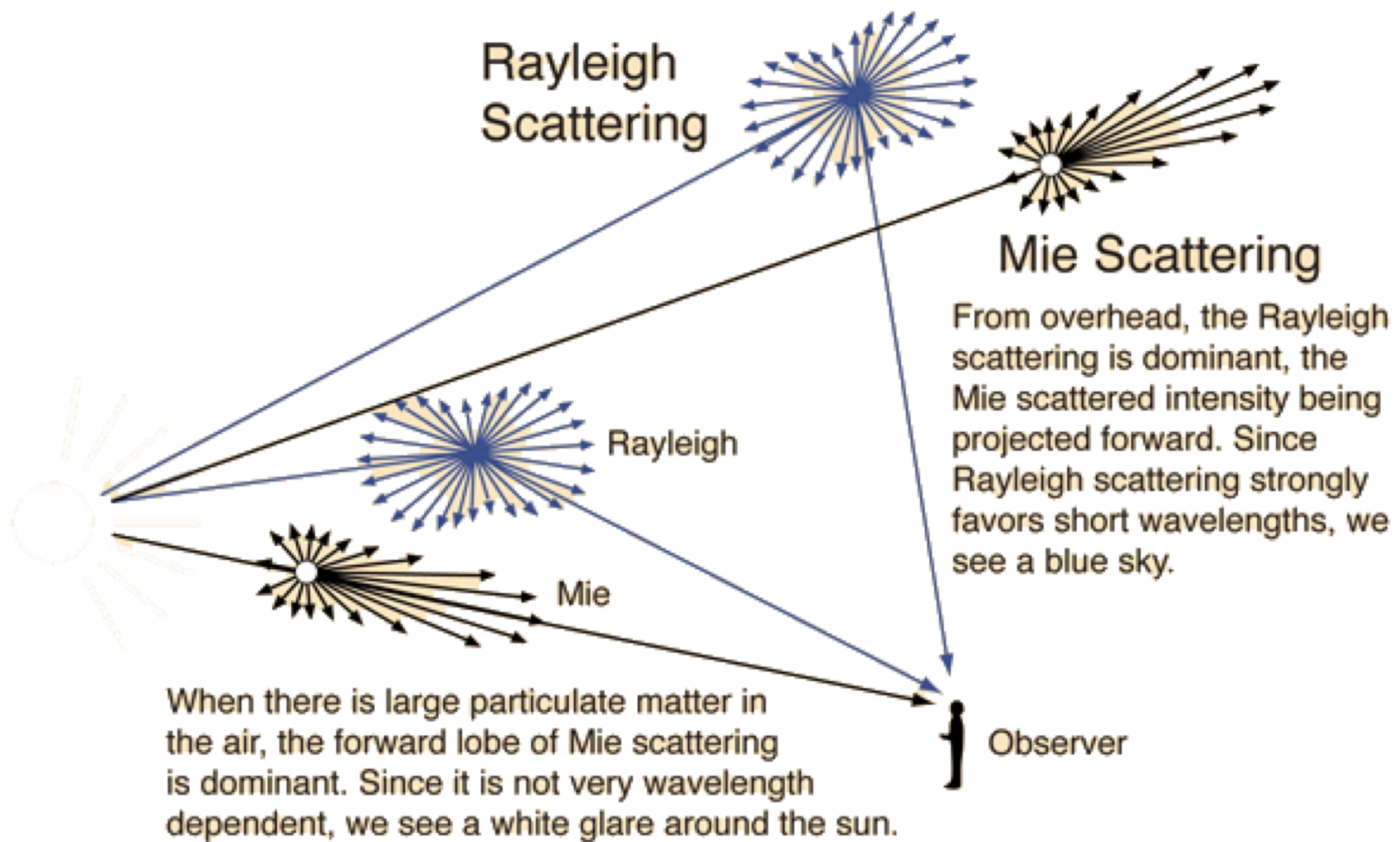
Q=extinction efficiency=$\frac{\sigma}{A}$

Geometric scattering:
$\boldsymbol{k_M}$=2A;
A=actual cross-section
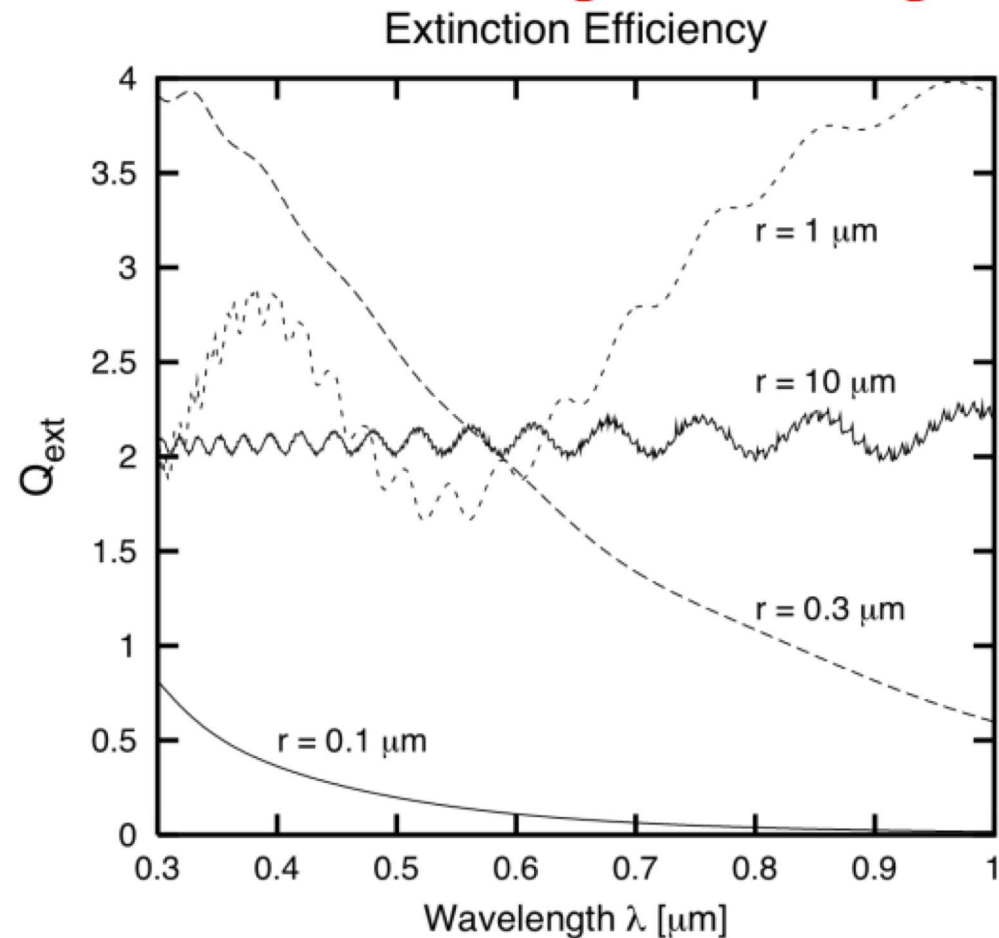
Rayleigh Scattering

Mie Scattering

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

Rayleigh

Mie

When there is large particulate matter in the air, the forward lobe of Mie scattering is dominant. Since it is not very wavelength dependent, we see a white glare around the sun.

Observer

Remote sensing makes intensive use of Rayleigh scattering at different wavelengths! Backscatter intensity & travel time at specific wavelength relate to particle size, amount, and location
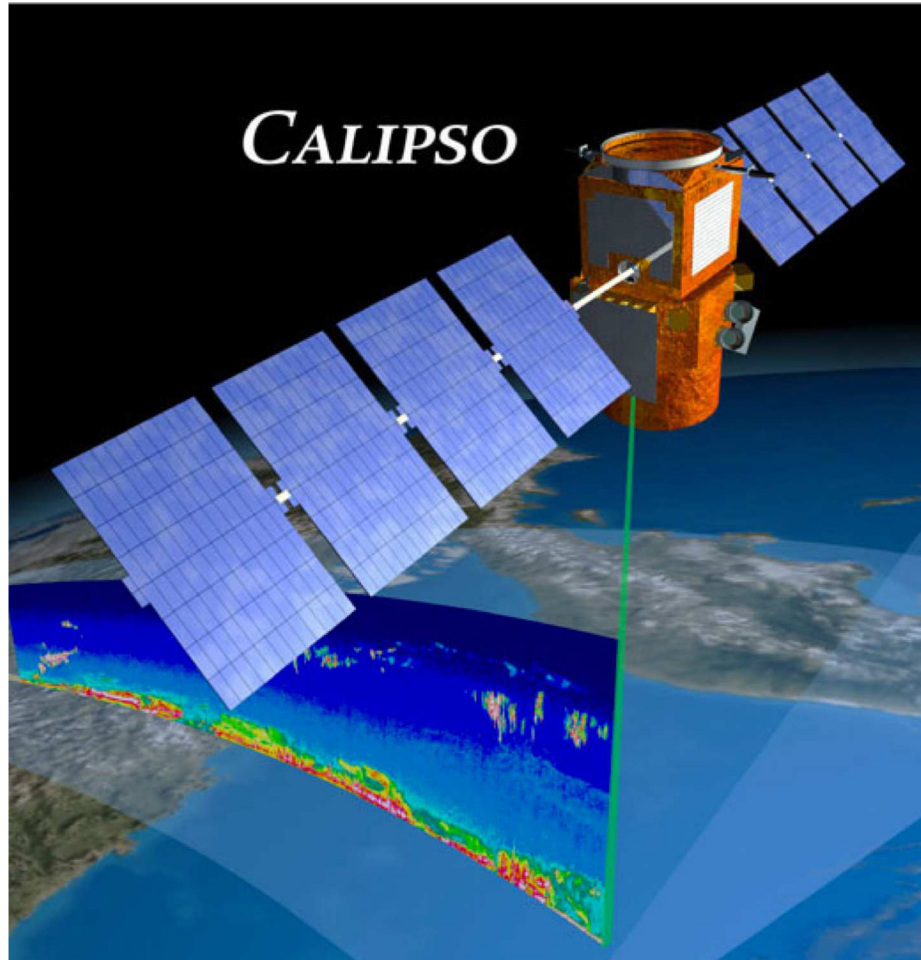
Lidar (visible/near IR laser pulse)
Light Detection and Ranging
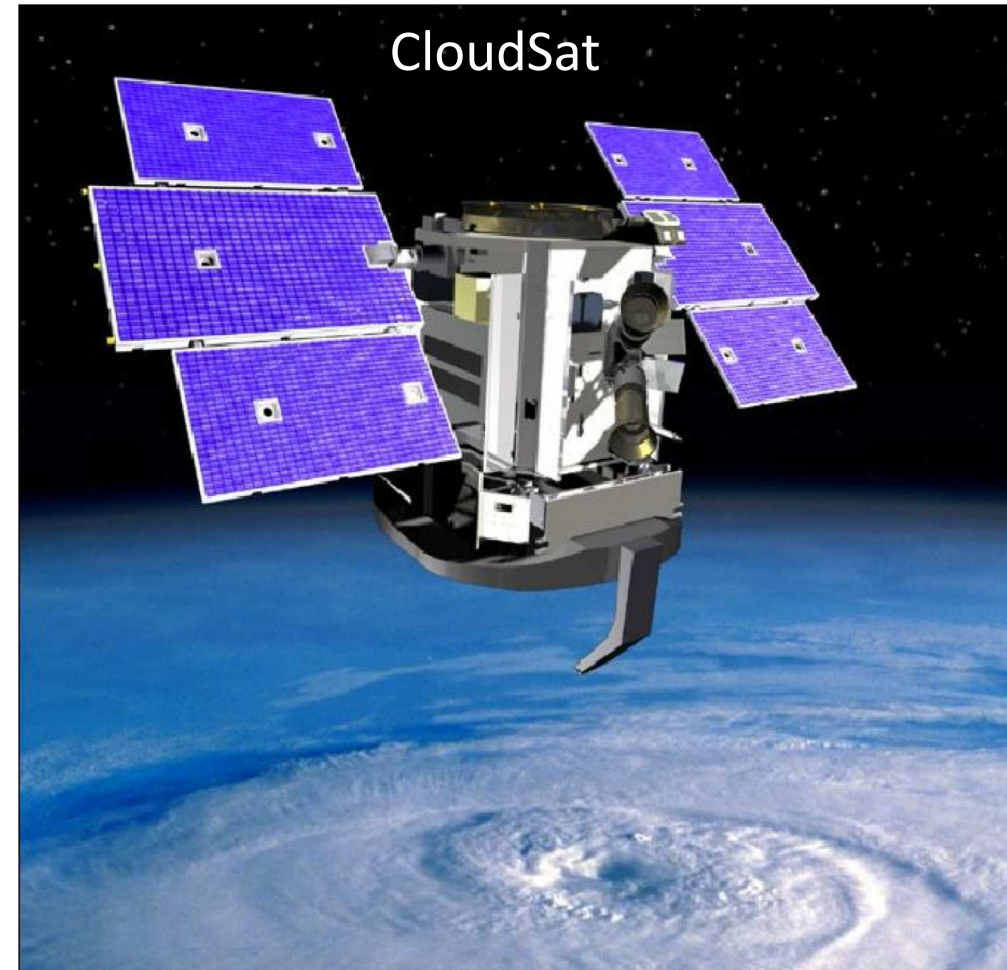
RADAR (microwave impulses)
Radio Detection And Ranging

Heating rates

It follows that the *radiative heating rate* at level z is given by

$$\mathcal{H} \equiv -\frac{1}{\rho(z)C_p}\frac{\partial F^{net}}{\partial z}(z) , \qquad (10.54)$$

where $\rho(z)$ is the air density at level z and $C_p = 1005\,\text{J}/(\text{kg K})$ is the specific heat capacity of air at constant pressure. The minus sign is needed because an *increase* in F^{net} with height implies a net *loss* of energy from level z. Traditionally, $\mathcal{H}$ is expressed in units of °C/day. When the value of $\mathcal{H}$ is negative (as it is more often than not), one might prefer to speak instead of positive *radiative cooling rate*.

Heating Rate Due to Absorption (positive) and emission (negative) by gases in the atmosphere. Cloud free atmosphere. (Wallace and Hobbs pg 139.)
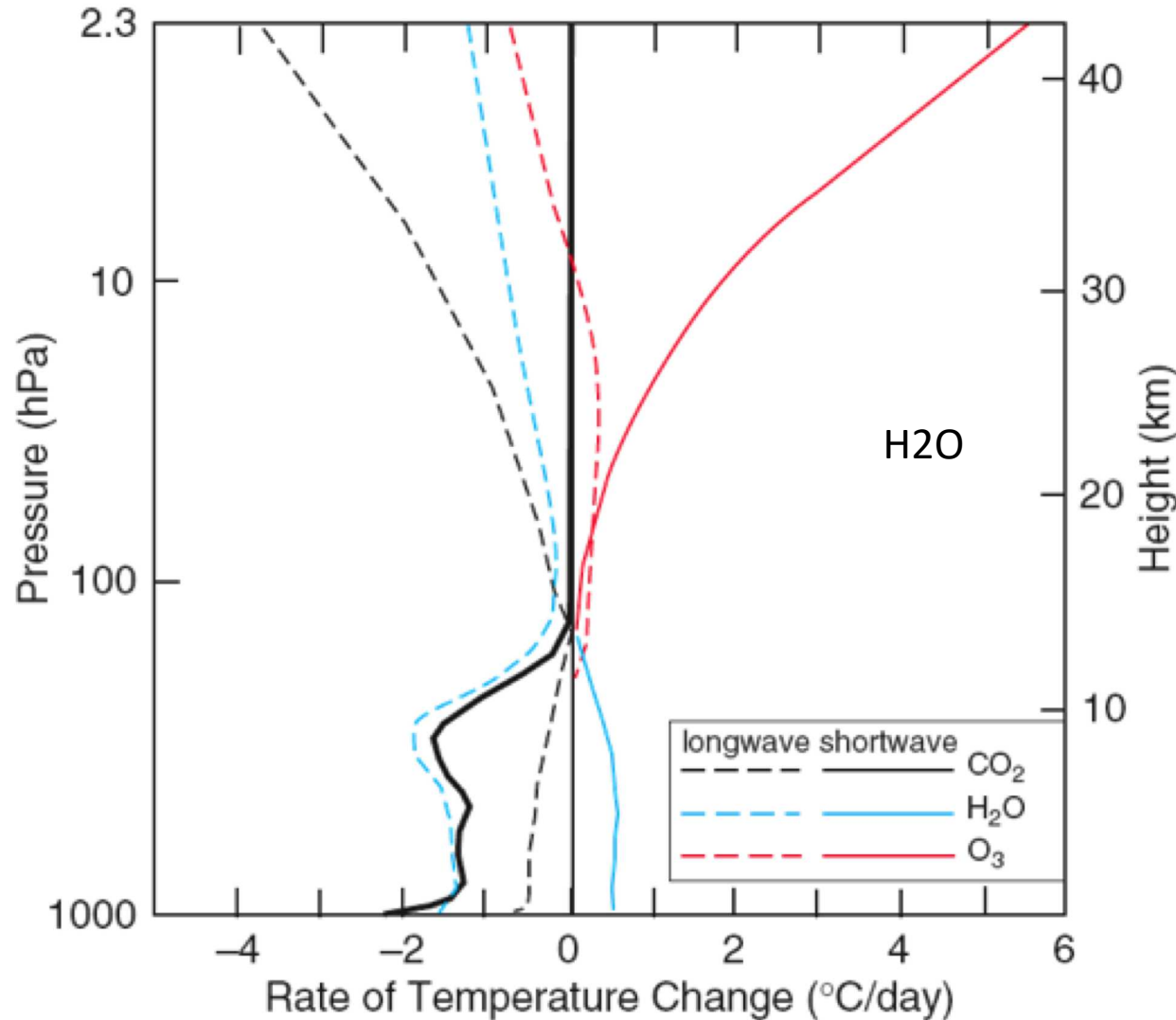
Solar radiation: Solid curves.

Terrestrial radiation: Dashed curves.

Heavy Black: Combined effect of solar and terrestrial radiation.

Notes:

Stratosphere near balance. CO_2 cooling, O_3 heating.

Troposphere, water vapor dominates, with mostly IR cooling and some solar heating.

Heat goes from warm to cold, one way is through radiation transfer (emission/absorption). Emission cools, while absorption is associated with heating. Adding IR absorbers reduces cooling/emission to space

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

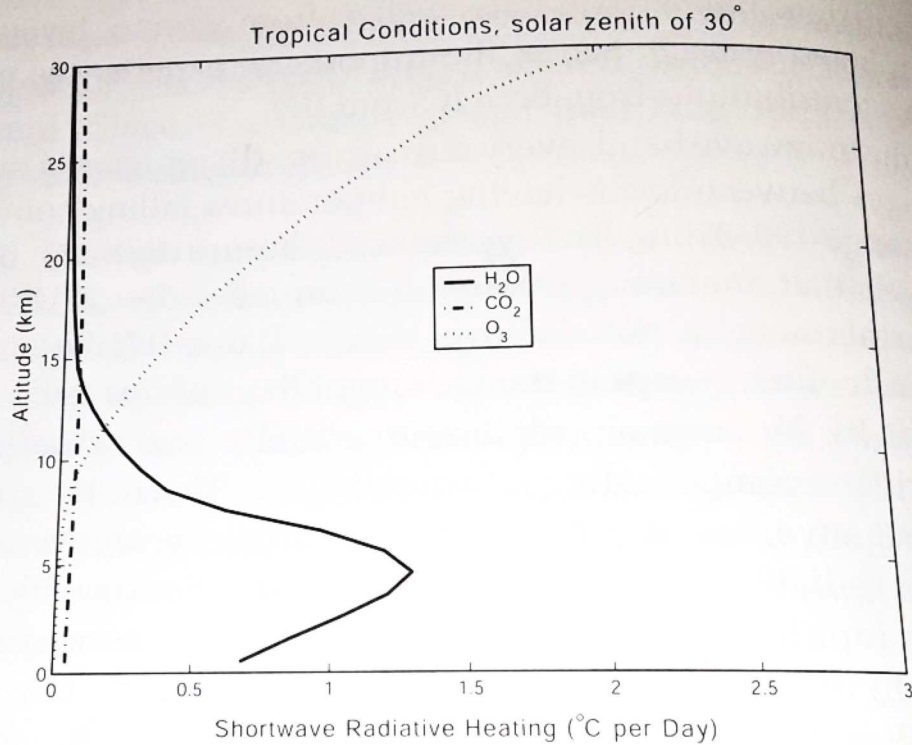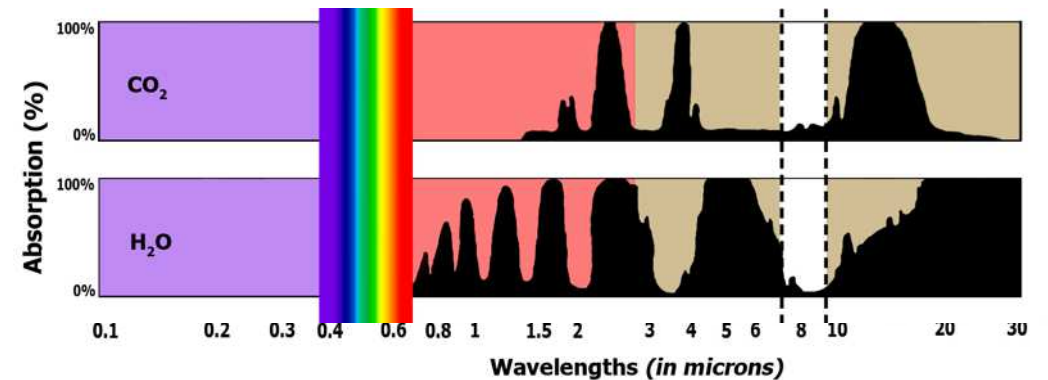# Shortwave radiative heating in tropical conditions

Fig. 10.6: Typical heating profiles due to solar absorption in a cloud-free tropical atmosphere, segregated according to the responsible atmospheric constituents ozone (O_3), carbon dioxide (CO_2), and water vapor (H_2O). (*Figure courtesy of S. Ackerman.*)

- H_2O: bulk absorption in troposphere (near IR), where it is abundant at warm altitudes. higher up condensation leads to removal

- O_3: dominates absorption in stratosphere, created by UV-C and O_2 reaction

- CO_2: evenly mixed throughout atmosphere; some absorption in near IR (2-3 micron)

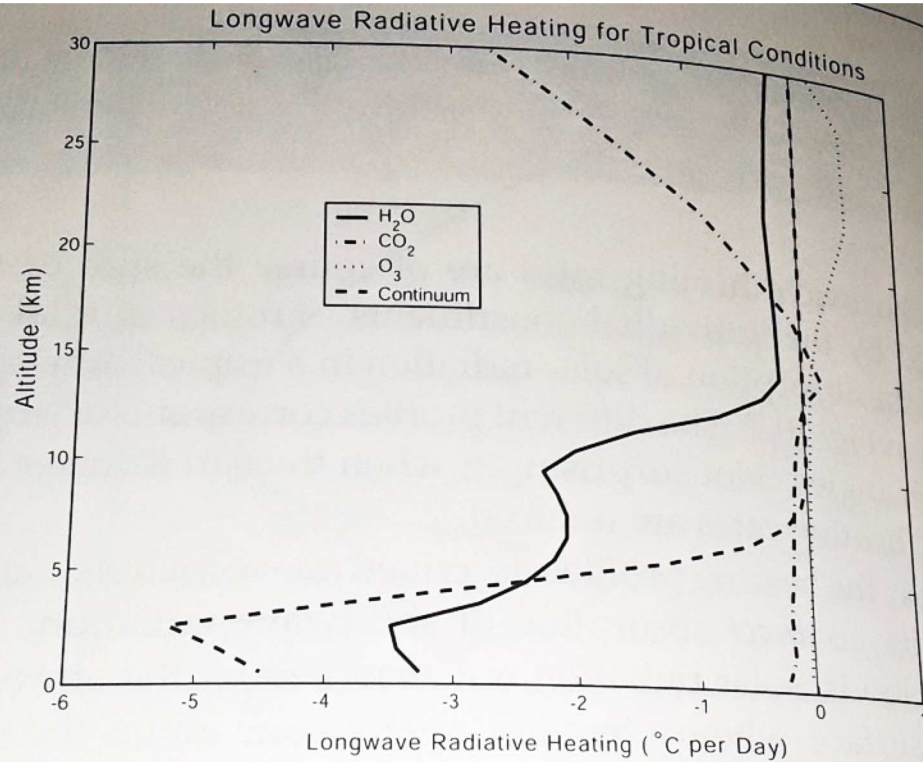# Longwave radiative cooling in tropical conditions

Fig. 10.8: Typical heating rate profiles due to longwave (thermal IR) radiative transfer in a cloud-free tropical atmosphere, segregated according to the responsible atmospheric constituents ozone (O_3), carbon dioxide (CO_2), water vapor resonant absorption (H_2O), and water vapor continuum. Negative values represent cooling. *(Figure courtesy of S. Ackerman, with modifications.)*

- CO_2: only little cooling until 15km (small heating) due to high opacity of pressure broadened 15 micron band: radiation emitted at one level is reabsorbed at nearby level at almost same temperature. Above 15km, pressure broadening much weaker and band breaks open: effective cooling to space

- H_2O: not as well mixed as CO_2 and concentrated in lower troposphere; cooling to space is more effective and peaks twice in troposphere; less opaque than CO_2 around 15 micron, more opaque at around 3 and 5 micron; cooling (emission) modest >15km where there is very little H2O

- H_2O continuum: very sensitive to pressure, mass absorption coefficient drops rapidly with height.