SECOND YEAR: 2604
PLANETARY REMOTE SENSING 4

ELECTROMAGNETIC *RADIATION:*
emission and extinction processes

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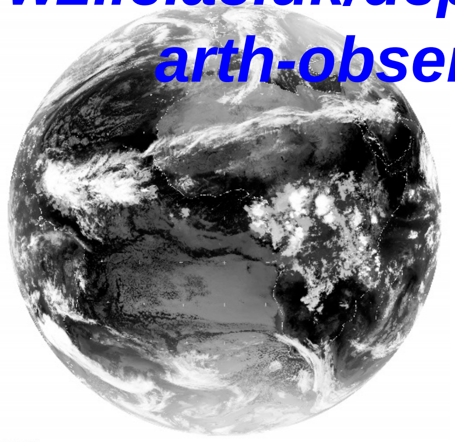
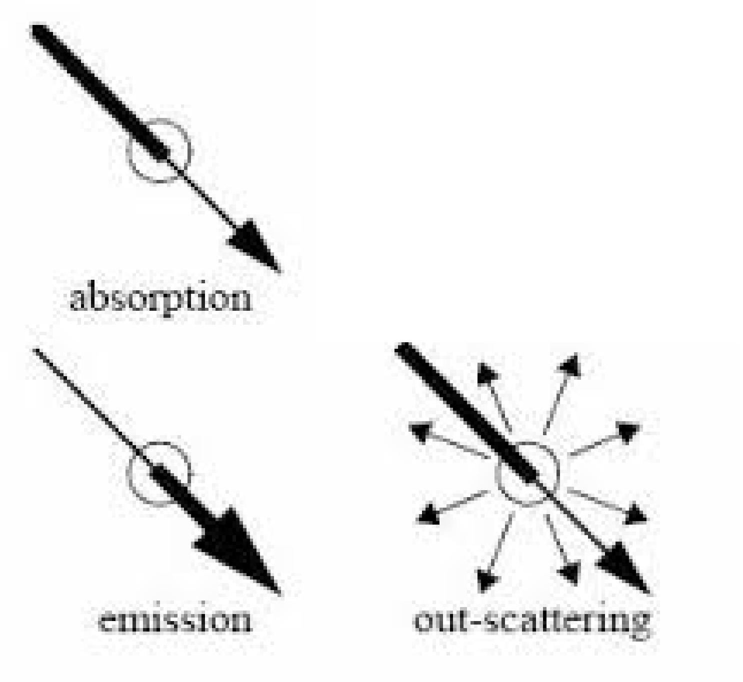


Interaction of Light and Matter

Light (EM radiation) can interact with matter in the following ways:

- **Emission: add (generates) photons**
- **Absorption: removes photons**
- **Scattering: changes direction of photons (and sometimes energy) e.g. when impinging onto a surface, a cloud or an aerosol layer**

In such conditions (the medium is non transparent) radiance is not constant along the ray



BEER-LAMBERT LAW

The Beer-Lambert Law: if a signal of intensity I_λ penetrates a distance, dL, in a homogenous medium with absorption coefficient, k_a (dimensionally L^{-1}):

L

$I_\lambda(0)$ → **GAS: $k_a(\lambda)$, c** → $I_\lambda(L)$

$$dI_\lambda = - k_a(\lambda)\, I_\lambda\, dL$$

Observed experimentally

Radiance is not constant along the ray!

Then if k_a = constant along the path L

$$I_\lambda(L) = I_\lambda(0) \exp\{- k_a(\lambda)\, L\}$$

transmissivity: $\mathcal{T}(\lambda) = I_\lambda(L) / I_\lambda(0) = \exp\{- k_a(\lambda)\, L\} = \exp\{-\tau\}$

with τ = optical depth

Optical thickness: contributors

L

$I_\lambda(0)$ → **GAS: $k_a(\lambda)$, c, T** → $I_\lambda(L)$

$$I_\lambda(L) = I_\lambda(0)\ \exp\{-k_a(\lambda)\,L\} = I_\lambda(0)\ \exp[-\sigma(\lambda)\,c\,L]$$

with c = the density of molecules per unit volume.

Three factors affects the optical thickness:

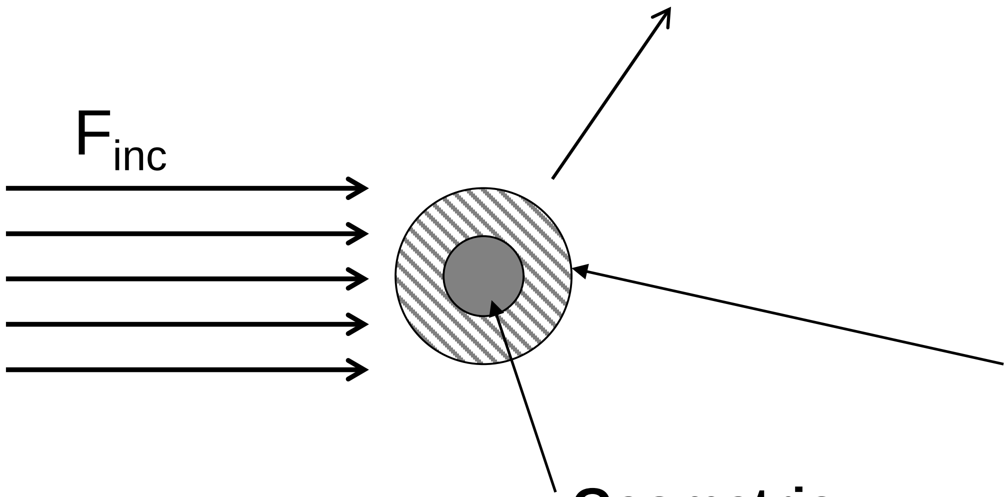
- **Spectroscopy: absorption cross section $\sigma(\lambda)$** [cm^2/molecule]
- **Composition/density: $c = \chi\, c_{air}$** [molecules/cm^3]
- **Photon path-length: geometrical distance = L** [km]

mixing ratio of the gas

General form with k_a changing in space: $I_\lambda(L) = I_\lambda(0)\,e^{-\int_0^L \sigma(\lambda,p,T)\,c(p,T)\,dL}$

Interaction of Particle with E/M Radiation: cross sections

Sphere, radius r,
complex refractive index m=$m_r + i m_i$



Geometric cross-section πr^2

Particle scattering/absorption is defined in terms of cross-sectional areas σ & efficiency factors Q

σ_a = effective area projected by the particle that determines absorption

Similarly σ_s, σ_e

The particles is absorbing and/or scattering some of the incident radiation ➔absorbed/scattered power

$$\sigma_{e,s,a} = \frac{P_{e,s,a}}{F_{inc}}$$

The **efficiency factor** **then follows**

$$\boxed{Q_{e,s,a} = \frac{\sigma_{e,s,a}}{\pi r^2} = f(x,m)}$$

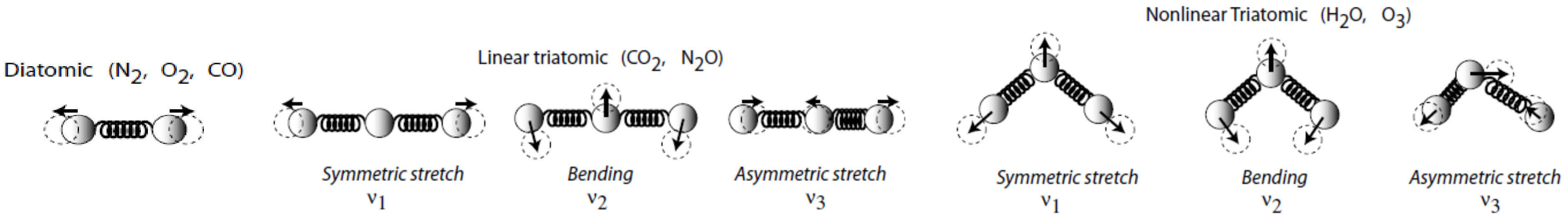
N.B.: Q can be larger than 1!!!

Spectroscopy

The study of the interaction of a medium with radiation is known as ***spectroscopy***. The spectral properties of gases, liquids and solids are determined fundamentally by quantum mechanics.

Hence $\sigma_a(\nu)$ is fundamentally due to quantised transitions between energy levels in molecules.

In the infra-red, the transitions occur as distinct *bands* unique to each gas (specifically due to the vibration and rotation of each molecule).



Light gas molecules **– distinct line structure grouped in bands e.g. CO, CO_2, H_2O, CH_4**

Heavy gas molecules **– densely structured bands that appear apparently smooth (e.g.CFCs)**

Liquids **– simple broad features (droplets, aerosols, surface)**

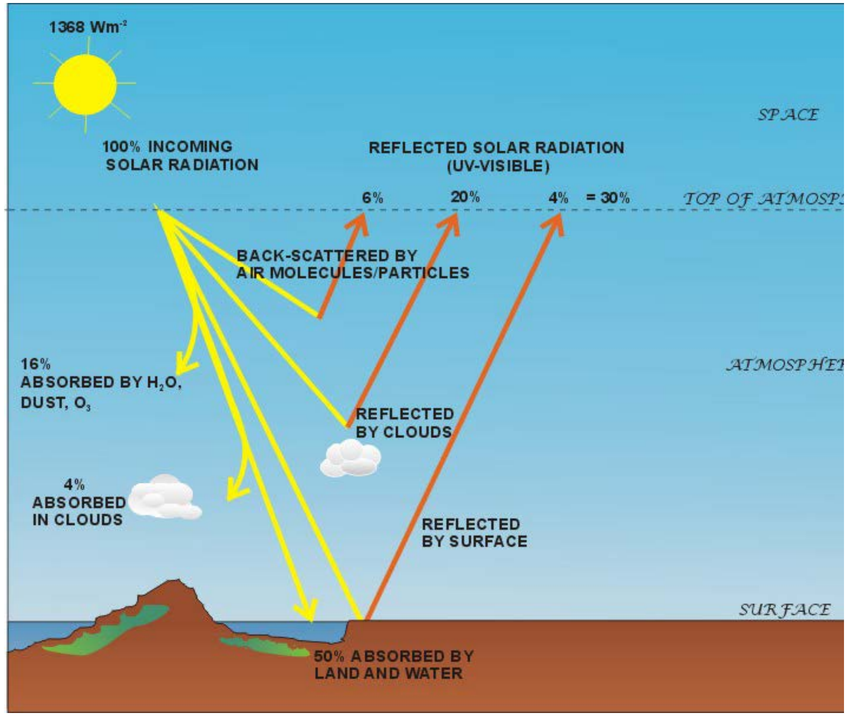
Solids **– simple,broad features (ice, aerosols, surface)**

Scattering theory

Gas absorption in the Earth's atmosphere

Main Visible and near-IR absorption bands of atmospheric gases

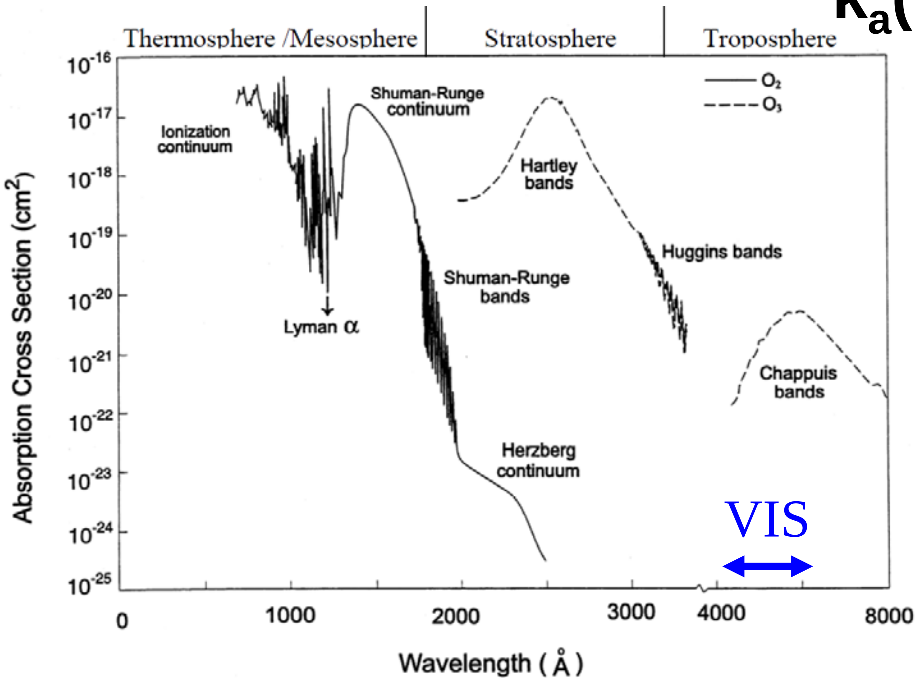
Gas	Center ν (cm^{-1}) (λ(μm))	Band interval (cm^{-1})
H_2O	3703 (2.7)	2500-4500
	5348 (1.87)	4800-6200
	7246 (1.38)	6400-7600
	9090 (1.1)	8200-9400
	10638 (0.94)	10100-11300
	12195 (0.82)	11700-12700
	13888 (0.72)	13400-14600
	visible	15000-22600
CO_2	2526 (4.3)	2000-2400
	3703 (2.7)	3400-3850
	5000 (2.0)	4700-5200
	6250 (1.6)	6100-6450
	7143 (1.4)	6850-7000
O_3	2110 (4.74)	2000-2300
	3030 (3.3)	3000-3100
	visible	10600-22600
O_2	6329 (1.58)	6300-6350
	7874 (1.27)	7700-8050
	9433 (1.06)	9350-9400
	13158 (0.76)	12850-13200
	14493 (0.69)	14300-14600
	15873 (0.63)	14750-15900
N_2O	2222 (4.5)	2100-2300
	2463 (4.06)	2100-2800
	3484 (2.87)	3300-3500
CH_4	3030 (3.3)	2500-3200
	4420 (2.20)	4000-4600
	6005 (1.66)	5850-6100
CO	2141 (4.67)	2000-2300
	4273 (2.34)	4150-4350
NO_2	visible	14400-50000

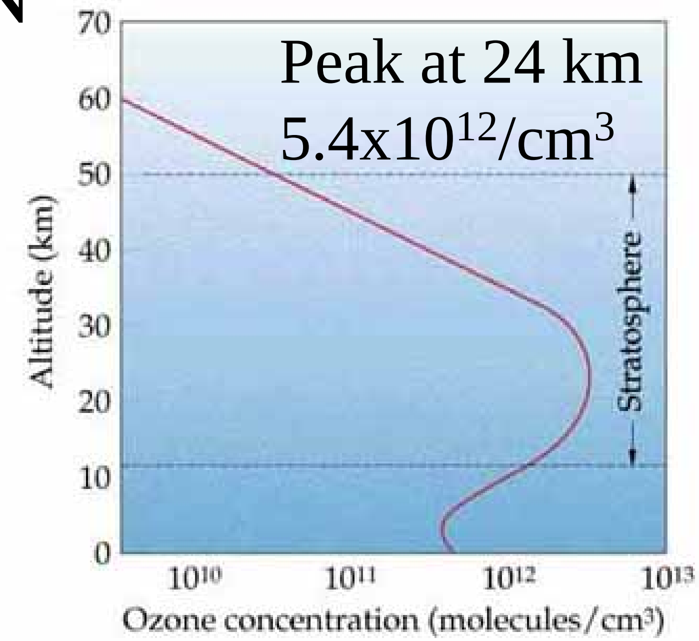


In the ultra-violet and visible, incident light from the Sun is absorbed and/or scattered. ***A principal absorber is ozone in the stratosphere*. UV-visible radiation ➔ heating wherever it is absorbed. As a result less solar radiation reaches the surface.**

Spectral absorption cross-sections of O_2 and O_3

$$k_a(\nu)=\sigma_a(\nu)N$$





- Bands of O_2 and O_3 at wavelengths < 1 μm are electronic transitions.
- These absorption bands cover a continuum because practically all absorption results in dissociation of the molecule (so the upper state is not quantized);
- Despite the small amount of O_3, no solar radiation penetrates to the lower atmosphere at wavelengths < 310 nm (because of large absorption cross-sections of O_3);

Transmissivity due to gases

Example

Calculate the transmission of O_3 lines over a range of 40 km for a line strengths of a) 10^{-17} cm^2/mol; b) 10^{-19} cm^2/mol; c) 10^{-21} cm^2/mol. Assume O_3 has a constant concentration given by 3 * 10^{12} molecules cm^{-3} .

$\mathcal{T}_g(\nu)$ = exp [– $\sigma_a(\nu)$N L]

a) = exp [– 10^{-17} cm^2/mol * 3 * 10^{12} mol cm^{-3}* 40 *10^5 cm]

= exp [– 120] ≈ 0.0 λ=0.25 μm

b) = exp [– 1.2] ≈ 0.3 λ=0.3 μm

c) = exp [– 0.012] ≈ 0.988 λ=0.35 μm

a) is opaque

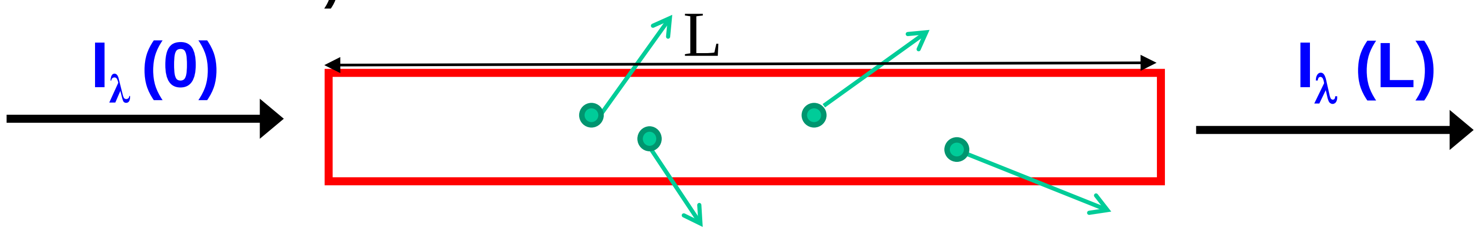
b) has mid-range transmission

c) Is nearly transparent.

Ozone is really screening out near UV radiation ➔ relevance of ozone hole for skin cancer

BEER-LAMBERT LAW: EXTINCTION LAW

Homogenous non-absorbing medium with scattering coefficient, k_s (per unit distance)



$$dI_\lambda = -\ k_s(\lambda)\ I_\lambda\ dL$$

and $I_\lambda(L) = I_\lambda(0)\ \exp\{-\ k_s(\lambda)\ L\}$ **(compare absorbing case)**

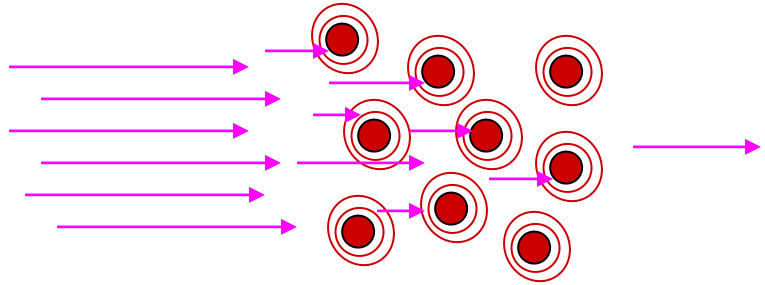
Scattering and absorbing media: $I_\lambda(L) = I_\lambda(0)\ \exp\{-\ k_e(\lambda)\ L\}$

with extinction coefficient: $k_e = k_s + k_a$

Extinction: total loss of light due to absorption and scattering of light out of path

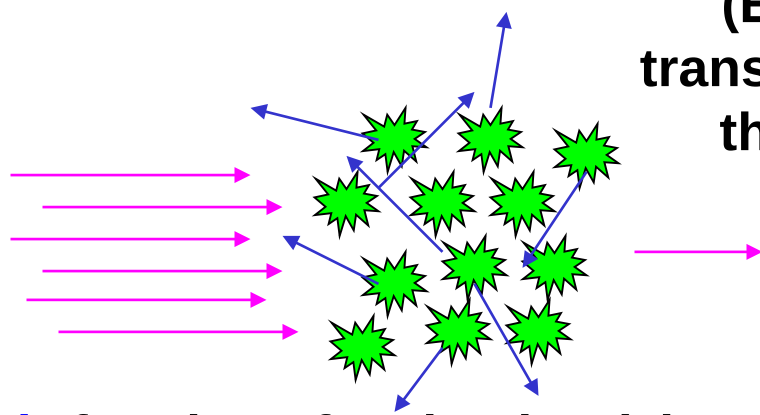
Extinction: Scattering plus Absorption

Absorption removes radiant energy from an E/M field, converting it to other forms of energy.



(Effect on transmittance is the same)

Scattering does not remove energy from an E/M field, but can redirect it, thereby making it a "source" of radiation for another direction.



Single scatter albedo (SSA): fraction of extinction (absorption + scattering) due to scattering processes:

$$\omega_o = \sigma_s / \sigma_e \qquad \sigma_e = \sigma_a + \sigma_s$$

$\omega_o = 1$ **all scattering (conservative)**

$\omega_o = 0$ **all absorption (non - conservative)**

How can we compute scattering and absorption cross sections of single particles?
How can we relate them to scattering and absorption coefficients?

The scattering optical thickness of our atmosphere

Compare the atmospheric transmissivity for Rayleigh scattering in UV with larger wavelength (600nm, 900 nm)

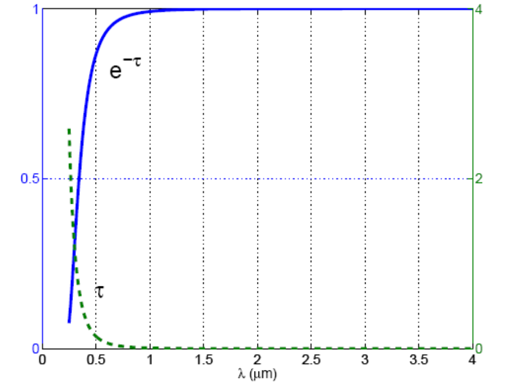
λ, nm	σ, cm^2
300	6.00×10^{-26}
400	1.90×10^{-26}
600	3.80×10^{-27}
1000	4.90×10^{-28}
10,000	4.85×10^{-32}

Transmission

$$\mathcal{T}(\lambda) = I_\lambda(L) / I_\lambda(0)$$
$$= \exp(-\tau) = \exp\{-k_s(\lambda)\, L\}$$
$$= \exp\{-\sigma\, c\, L\} = \exp\{-\sigma\, VCD\}$$

with Vertical Column Density of air (VCD) = 2.3×10^{25} molec/cm^2

Transmittance and τ for Rayleigh scattering



Transmissivity: $\mathcal{T}(\lambda = 300\text{nm}) = 0.25$ $\quad\tau = 1.4$

$\mathcal{T}(\lambda = 600\text{nm}) = 0.92$ $\quad\tau = 0.08$

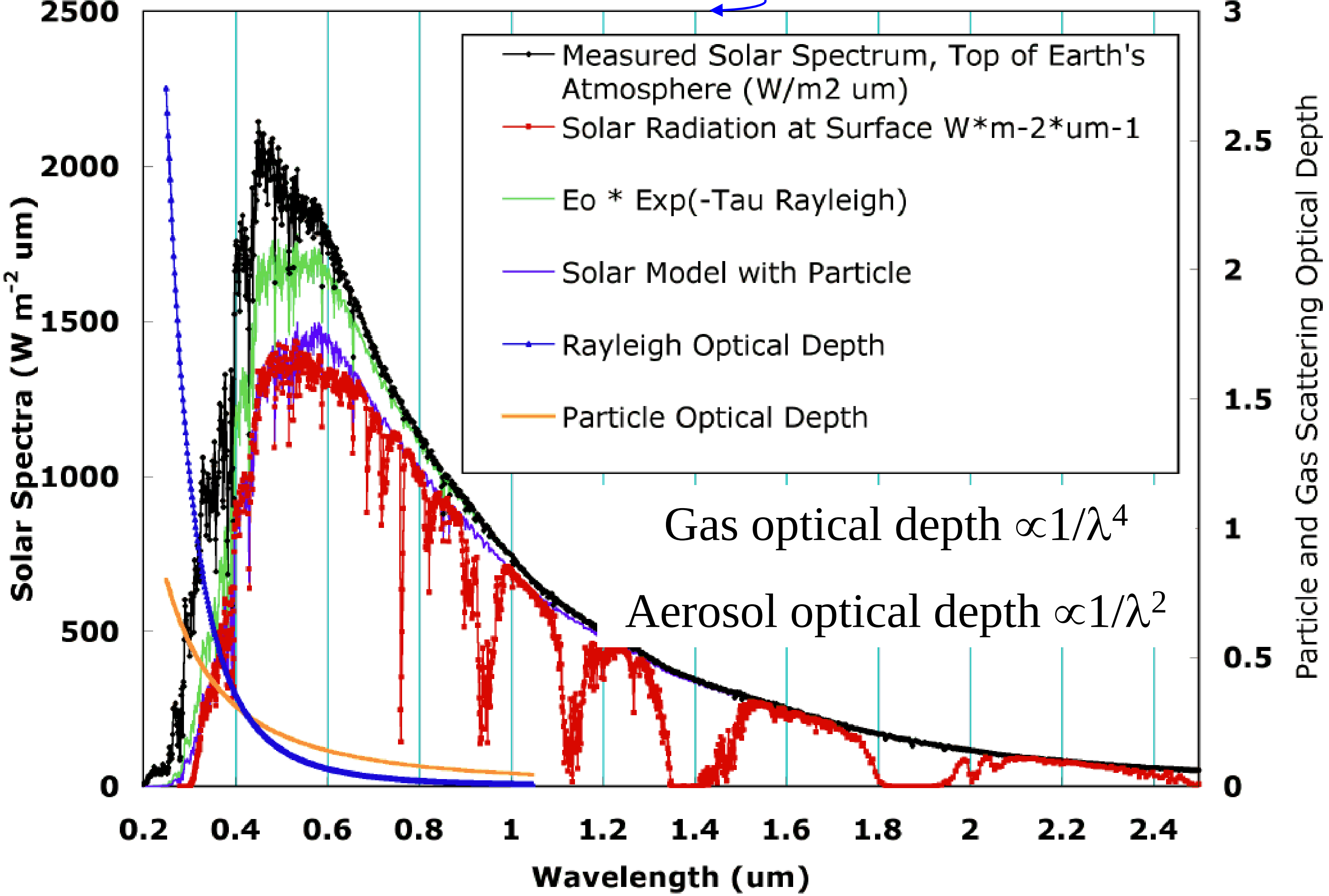
$\mathcal{T}(\lambda = 1000\text{nm}) = 0.99$ $\quad\tau = 0.01$

Only 25% of direct light reaches surfaces in UV at 300 nm but 99% at 1000nm.

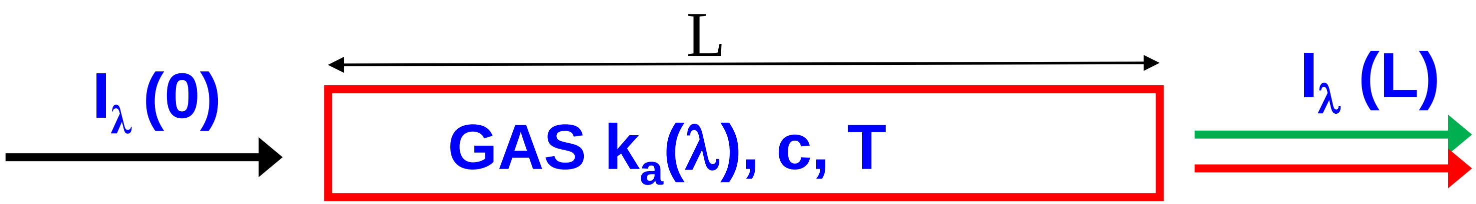
SOLAR SPECTRUM

1. Rayleigh (gas) scattering,
2. O_2, N_2, water vapour absorption
3. Aerosol particles extinction

Contributions to extinction of solar radiation from TOA to surface



Accounting for emission



There are 2 signals emerging:

1. **Radiance transmitted by the gas in the cell:** $\mathcal{T}(\lambda)\, I_o(\lambda)$
2. **Radiance emitted by the gas in the cell:** $\varepsilon(\lambda) \times B(\lambda,T)$

Emissivity is related to absorptance a(λ) of the layer (fraction of radiance being absorbed)

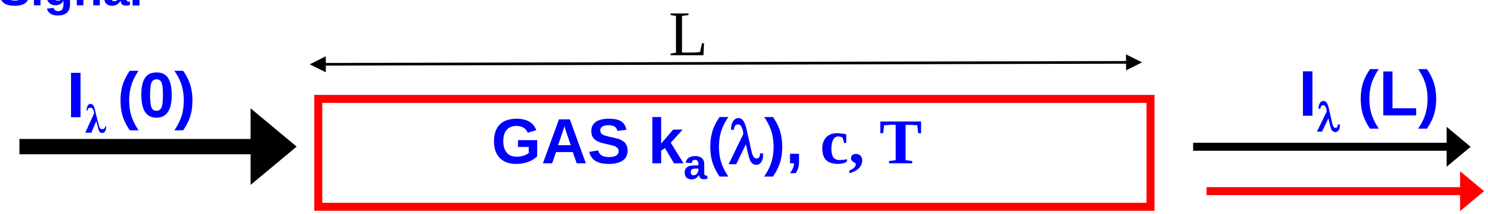
We neglect scattering (valid for gases in the IR)

$\mathcal{T}(\lambda) + a(\lambda) = 1 \Rightarrow a(\lambda) = 1 - \mathcal{T}(\lambda)$ Radiation is either transmitted or absorbed

In thermal equilibrium (Kirchhoff's law) $\varepsilon(\lambda) = a(\lambda) = 1 - \mathcal{T}(\lambda)$

IR TRANSMISSION FOR ISOTHERMAL LAYER

Total Signal



Hence, Total Signal, I(λ) is given by

==> $I_\lambda(L) = \mathcal{T}(\lambda)\, I_\lambda(0) + (1 - \mathcal{T}(\lambda)) \times B(\lambda, T)$

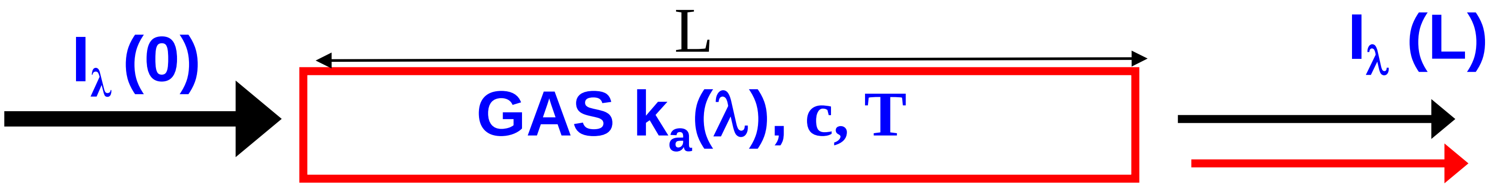
Limiting cases:

1) $\mathcal{T}(\lambda) \approx 1 \rightarrow I_\lambda(L) \approx \mathcal{T}(\lambda)\, I_\lambda(0)$ **[Known as a WINDOW]**

2) $\mathcal{T}(\lambda) = 0 \rightarrow I_\lambda(L) = B(\lambda, T)$ **[Known as 100% absorption or saturation]**

N.B. : If: a) term 1 >> term 2 or b) if T_{gas} = 0 K (!)
then Eqn. 1) would be true and conventional use of $\mathcal{T}(\lambda)$ alone is fine, e.g. uv-visible on Earth or hot source relative to cold gas.

Hot nebula



$$I_\lambda(L) = \mathcal{T}(\lambda)\, I_\lambda(0) + (1 - \mathcal{T}(\lambda)) \times B(\lambda, T)$$

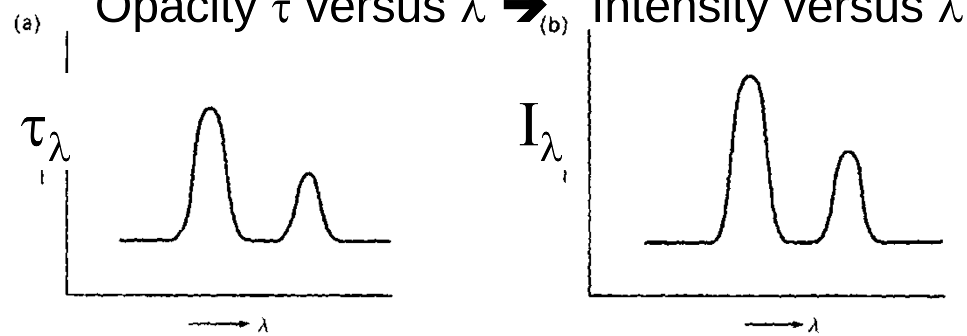
Imagine first the case in which $I_\lambda(0)=0$, i.e. solely emission from the volume of gas (with constant source function). $I_\lambda = B_\lambda (1 - e^{-\tau_\lambda})$

We have two limiting cases:

Opacity τ versus λ ➔ Intensity versus λ

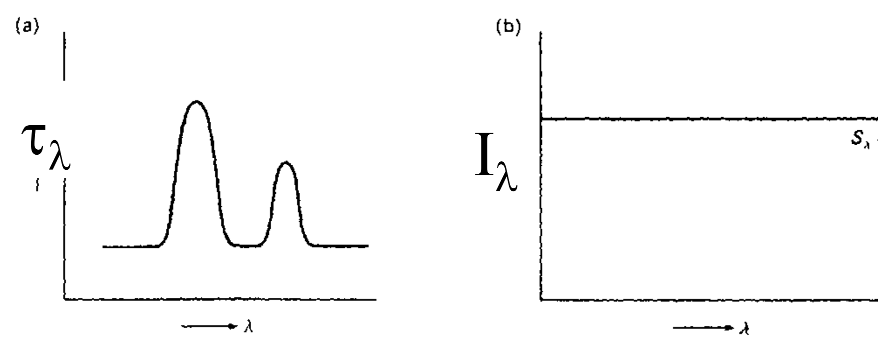
- Optically thin case (τ_λ<<1)

$$e^{-\tau_\lambda} \approx 1 - \tau_\lambda \Rightarrow I_\lambda = \tau_\lambda B_\lambda$$



- Optically thick case (τ_λ>>1)

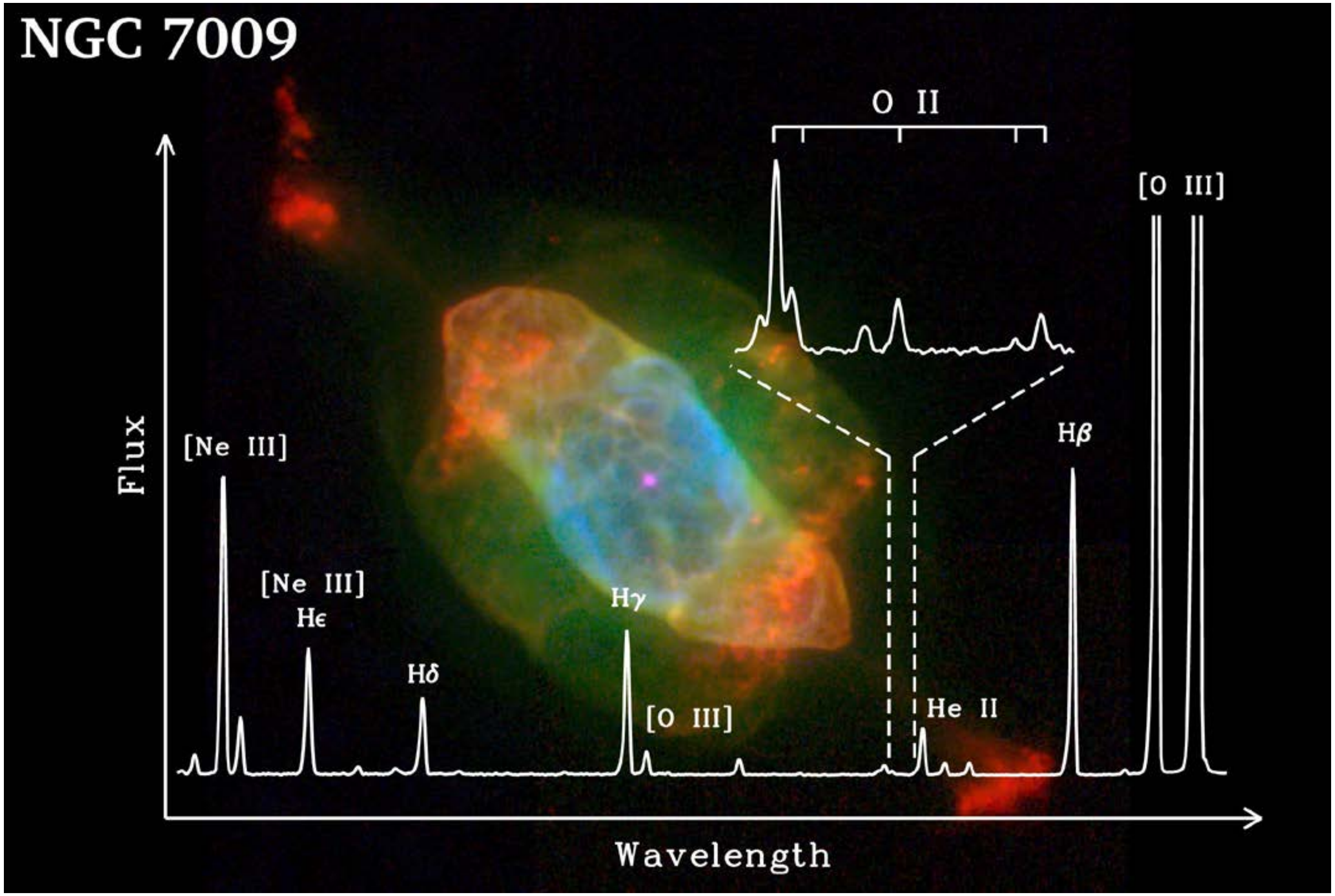
$$e^{-\tau_\lambda} \approx 0 \Rightarrow I_\lambda = B_\lambda$$



It behaves like a black body

Hot low density nebular gas

Example of emission lines for optically thin nebulae



The optical thickness is strongly dependent on wavelength ➔ peaks corresponding to absorption bands of different elements in the nebula

Absorption versus emission

$$I_\lambda(L)=I_\lambda(0)e^{-\tau_\lambda} + B_\lambda(T)(1-e^{-\tau_\lambda})$$

Imagine now $I_\lambda(0)\neq 0$, again with two extreme cases:

- Optically thin case (τ_λ<<1) $\quad I_\lambda(L)=I_\lambda(0)\,(1-\tau_\lambda)+\tau_\lambda B_\lambda(T)=I_\lambda(0)+\tau_\lambda[B_\lambda(T)-I_\lambda(0)]$

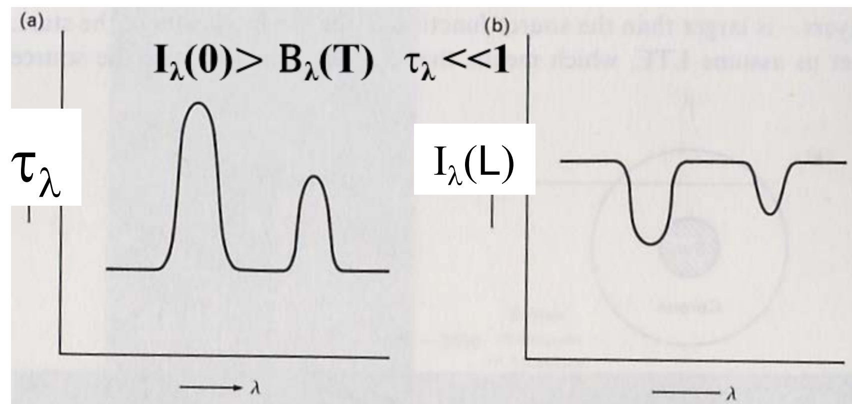
(a) If $I_{\lambda 0}>B_\lambda$, so there is something subtracted from the original intensity which is proportional to the optical depth – we see absorption lines on the continuum intensity I_λ.
EXAMPLE: stellar photospheres

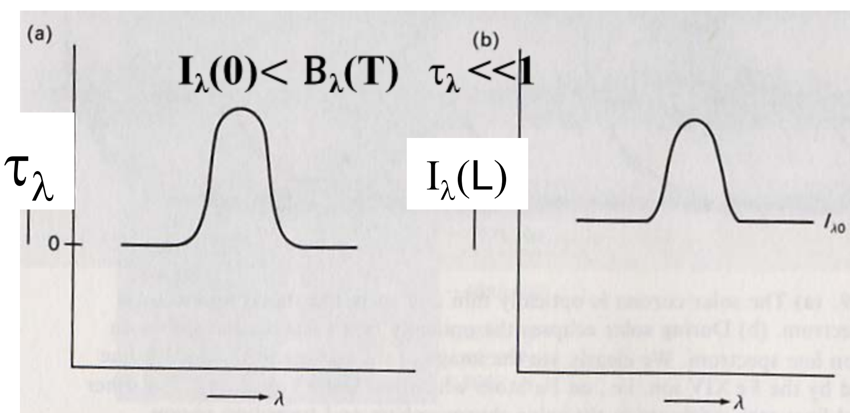
(b) If $I_{\lambda 0}<B_\lambda$, we will see emission lines on top of the background intensity.

Example: Solar UV spectrum

- Optically thick case (τ_λ>>1):

Planck function as before. $\quad I_\lambda(L)=B_\lambda(T)$





Opacity τ versus λ ➔ Intensity versus λ

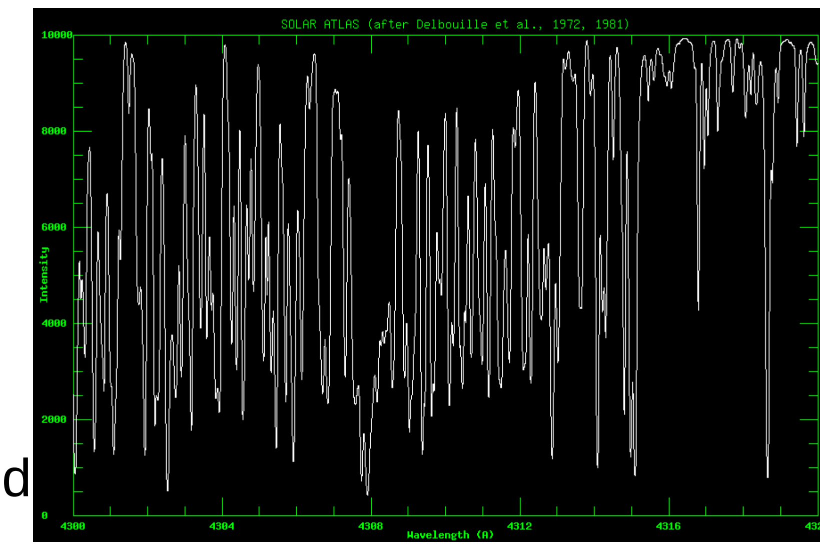
Absorption lines? Outward decreasing temperature

In a star absorption lines are produced if

$I_{\lambda 0} > B_{\lambda}$ i.e. the intensity from deep layers is larger than the source function from top layers.

In LTE, the source function is $B_{\lambda}(T)$, so the Planck function for the deeper layers is larger than the shallower layers. Consequently the deeper layers have a higher temperature than the top layers (since the Planck function increases at all wavelengths with T).

(Instances occur where LTE is not valid, and the source function declines outward in parallel with an increasing temperature).



Solar Spectrum (4300-4320 *angstrom=0.43-0.432 micron*) ➔ absorption lines

Absorption versus emission spectra

Emission line spectra

- Optically thin volume of gas with no background illumination (emission nebula)
- Optically thick gas in which the source function increases outwards (UV solar spectrum)

Absorption line spectra

- Optically thick gas in which source function declines outward, generally T decreases outwards (Stellar photospheres)
- Optically thin cold gas penetrated by background radiation (Interstellar matter between us and the star)

What do you need to know?

- ❑ **Emission and Absorption**
- ❑ **Isothermal layer model**

I_λ (0)

GAS $k_e(\lambda) = k_a(\lambda) + k_s(\lambda)$, T

I_λ (L)

$$\boxed{I_\lambda (L) = \mathcal{T}(\lambda)\, I_\lambda(0) + (1 - \mathcal{T}(\lambda))\, B_\lambda (T)}$$

transmissivity: $\mathcal{T}(\lambda) = \exp\{-k_e(\lambda)\, L\} = \exp\{-\tau\}$

- ❑ **Lambert Beer Law (optical depth, transmissivity)**