Radiation & Radiative Transfer

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Motivation for «Radiation» lectures

- Understand the principles of Sun's and Earth's radiative emissions

- Understand how radiation is transmitted through the atmosphere
  - Complex because of the presence of gases, particles and clouds

- Understand the radiative balance of Earth

A couple of guidelines

- There is no stupid question
- Ask, also if you are unsure whether something has already been explained
- Say when the pace is too fast or too slow
- There will be polls (anonymous) and interactive sequences

Assignment
Launch 28.03.2025
Due on 14.05.2025 23.59

There is only one assignment. You won't be able to solve everything from the beginning. The idea is that you also learn to manage your time.

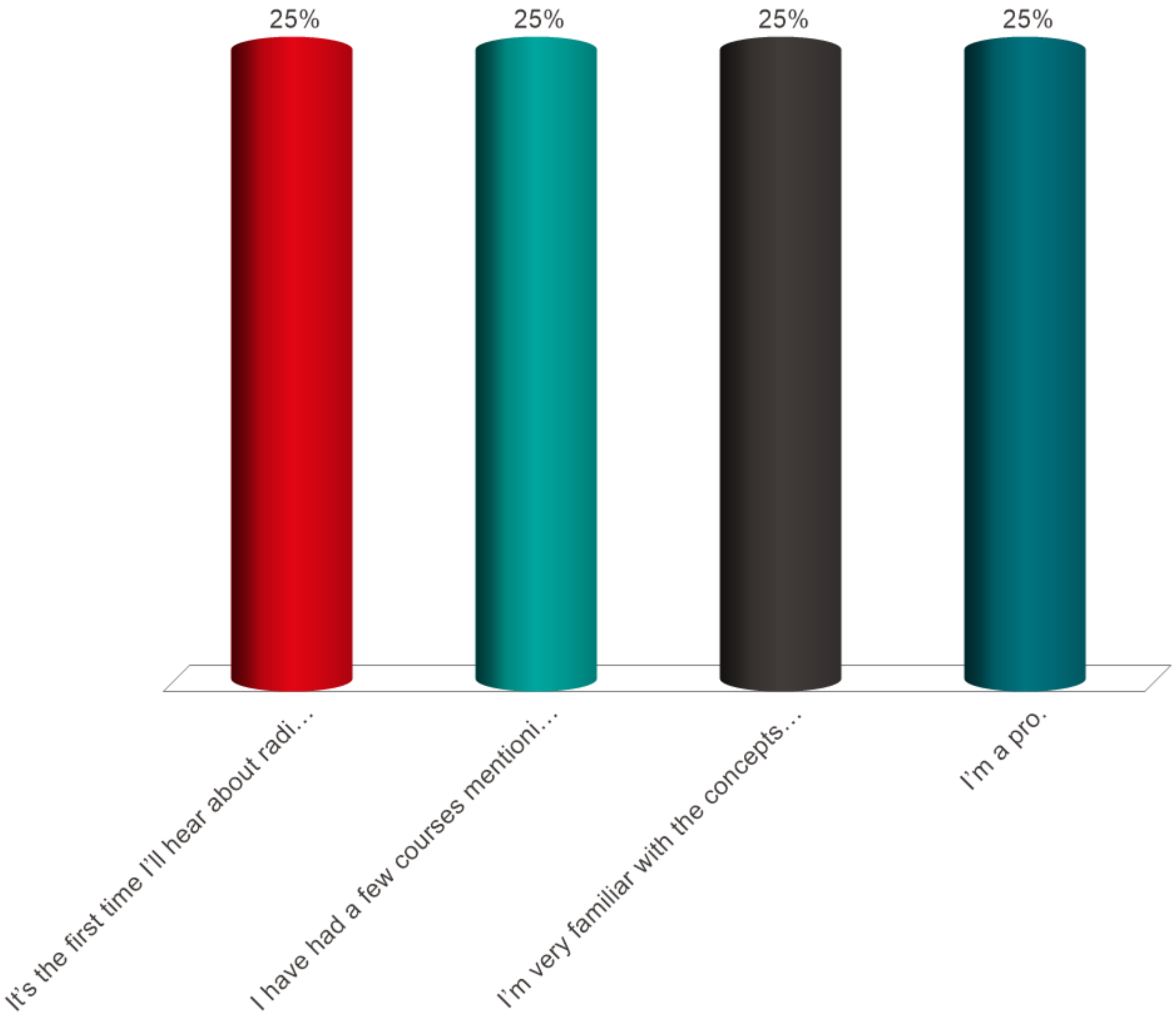
Interactive sequences

- We will use Turning Technologies in class for polls and short exercises.
- All answers are anonymous.
- Please go to: responseware.eu
- Enter as guest, do not provide any name or contact information.
- Be aware, the data will go outside of Switzerland, but will be erased when the session is closed.

- Let's try. Session ID is: **ENV320**

Have you heard about radiation?

A. It’s the first time I’ll hear about radiation.
B. I have had a few courses mentioning radiation.
C. I’m very familiar with the concepts of radiation.
D. I’m a pro.



Outline of radiation lectures

- Radiation principles and definition of radiant fluxes
- Basic radiation laws: Planck, Boltzmann, Wien and Kirchhoff
- Radiation emitted by Sun and Earth
- Extinction in the Atmosphere
- Radiative Transfer
- Radiation Balance of Earth → Climate Change

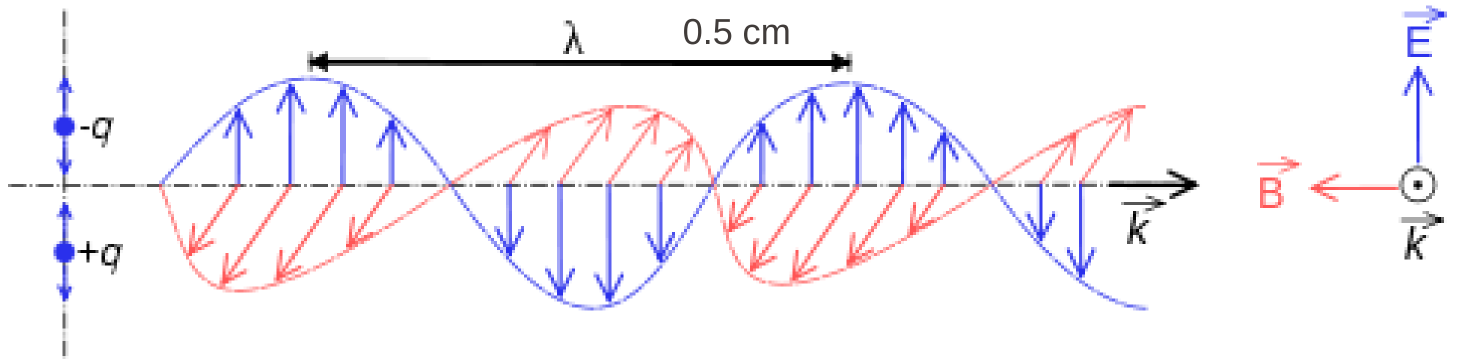
Basic description of electromagnetic radiation

Wave: An electromagnetic wave can be understood as an electrical charge oscillating in space and therefore generating both an electrical and magnetic field. The energy content is measured in **intensity or radiance (W m^{-2} sr^{-1}),** which is the integral over the wavelengths of the monochromatic intensities.

λ: wavelength, nm
n: wavenumber, cm^{-1}
ν: frequency, sec^{-1}, Hz
c* = 2.998x10^{8} ms^{-1}, velocity of light

$$n = \frac{1}{\lambda} = \frac{1}{0.5\ cm} = 2\ cm^{-1}$$

$$\nu = c^*\ n = \frac{c*}{\lambda} = \frac{3x108\ ms^{-1}}{0.005\ m} = 6x10^{10} Hz$$



E: electric field
B: Magnetic field
k: direction of propagation
q: charge

Some more basics

Energy: Joules (J)
Power: Watts (W = J s^{-1})
Power per unit area: W m^{-2}

Radiation can be:
Incident on, emitted from, reflected from, crossing

Basic description of electromagnetic (EM) radiation

Particles: When EM radiation interacts with matter, i.e. absorption, scattering, emission; it is always absorbed, scattered or emitted in discrete units (quanta) of energy, called photons.

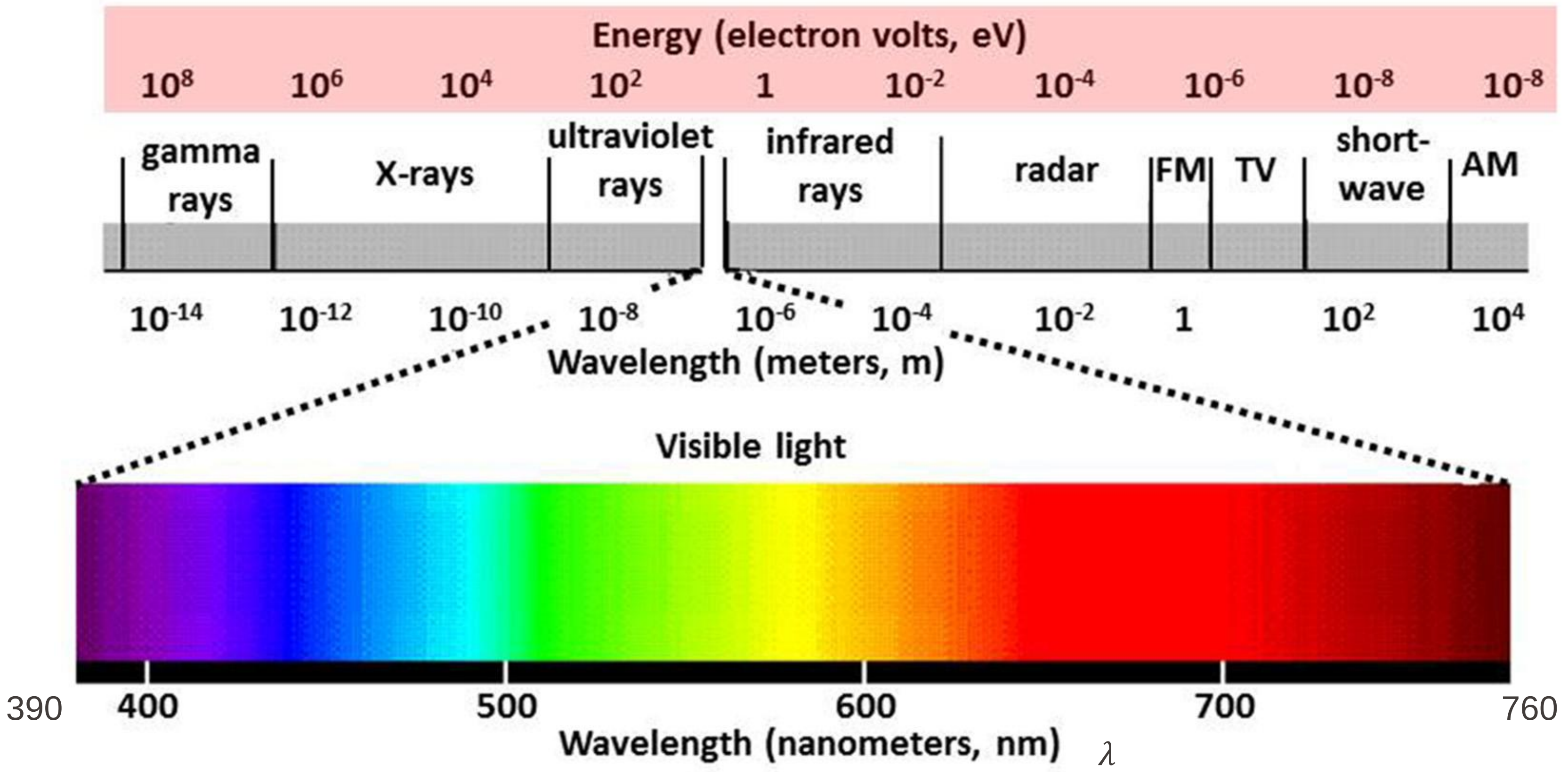
Energy of a photon:

$$E = h\nu$$

h is Planck's constant: 6.63×10^{-34} Js

Spectrum of electromagenetic radiation

1 eV = 1.60218*10^{-19} J

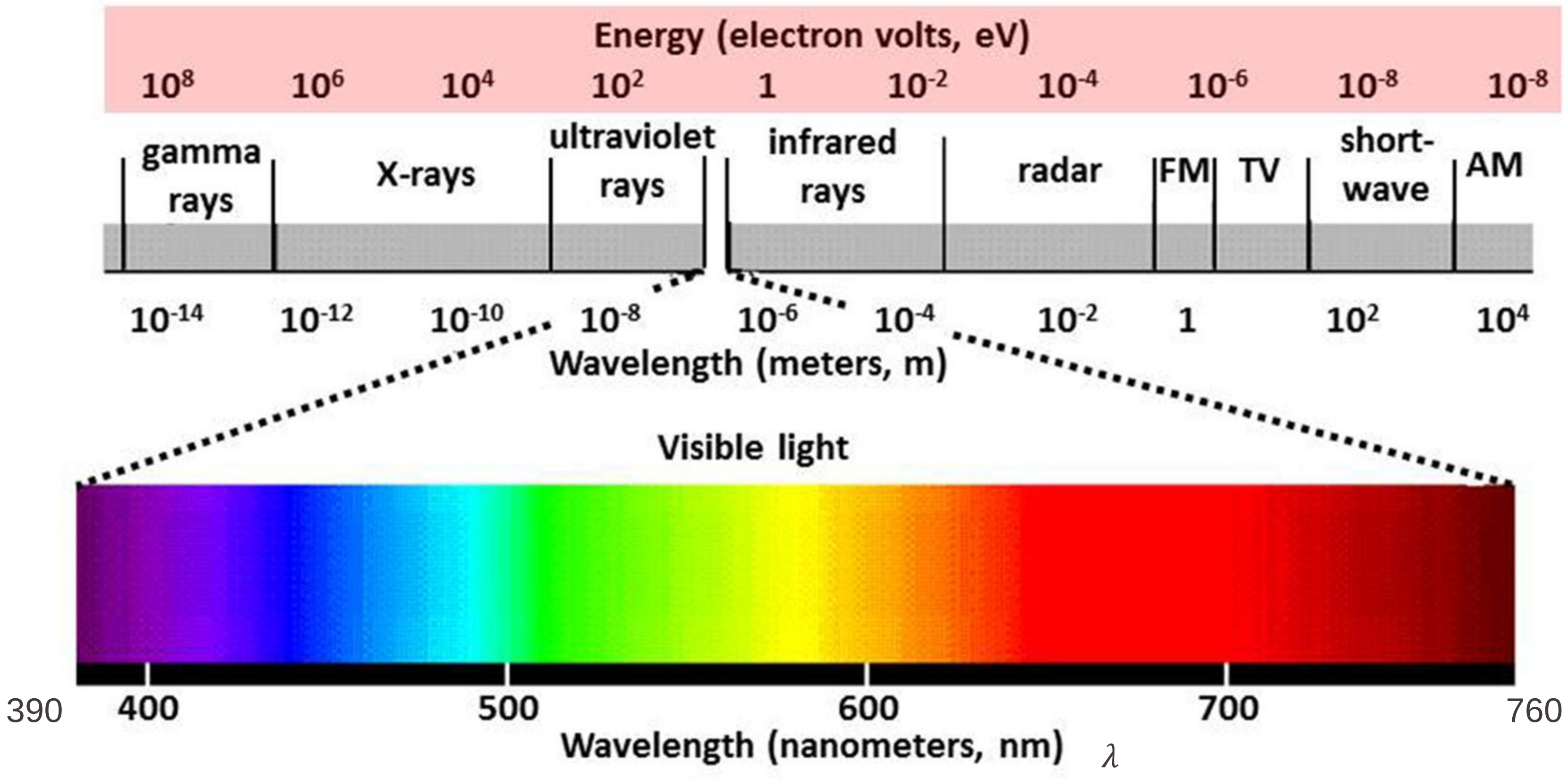


- Gamma rays, X-rays and the higher energy range of ultraviolet light constitute the ionizing part of the electromagnetic spectrum. "ionize" means breaking of one or more electrons away from an atom, an action that requires relatively high energies.
- Larger UV wavelengths can disrupt the inter-atomic bonds which form molecules, thereby breaking down molecules rather than atoms (example sunburn).
- Visible light, infrared and microwave frequencies cannot break bonds but can cause vibrations in the bonds which are sensed as heat.

- https://ozonedepletiontheory.info/what-is-radiation.html

Spectrum of electromagenetic radiation

1 eV = 1.60218*10^{-19} J



Some definitions

Visible: 0.39 – 0.76 µm, colors
Monochromatic: one single color, i.e. one single wavelength

Solar radiation: < 4 µm, shortwave
Terrestrial radiation: > 4 µm, longwave

Near infrared: 0.76 – 4.0 µm (solar radiation)
Infrared: terrestrial radiation

Microwave (10^{-3} – 10^{-1} m): not important for Earth's energy balance, but used in remote sensing (radar), can penetrate through clouds

In atmospheric science the following units are often used:

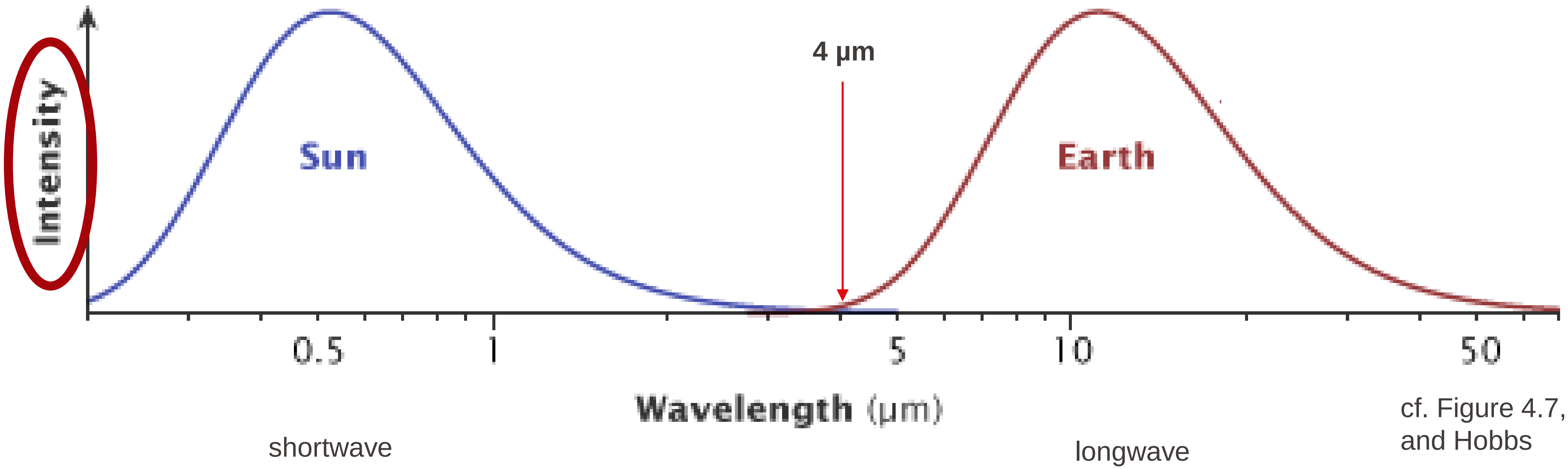
UV photon energy (eV)
VIS/IR wavelength in nm or µm
IR wavenumber (cm^{-1})
Microwave/radiowave frequency (Hz)

- https://ozonedepletiontheory.info/what-is-radiation.html

Solar and terrestrial emission spectra

Solar radiation: < 4 µm, shortwave
Terrestrial radiation: > 4 µm, longwave

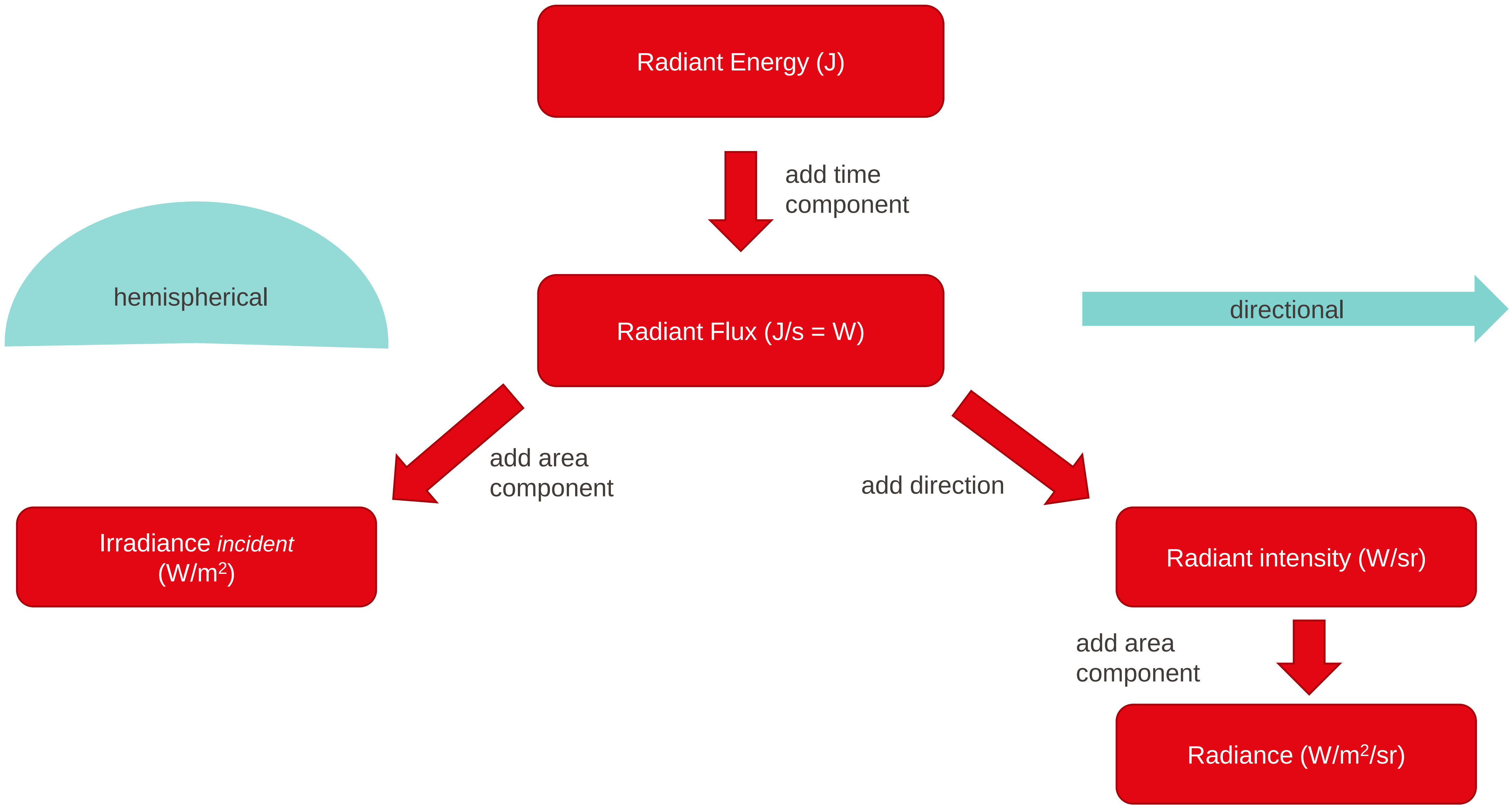
Near infrared: 0.76 – 4.0 µm (solar radiation)
Infrared: terrestrial radiation



cf. Figure 4.7, in Wallace and Hobbs

- https://earthobservatory.nasa.gov/features/EnergyBalance/page2.php

Quantifying radiation

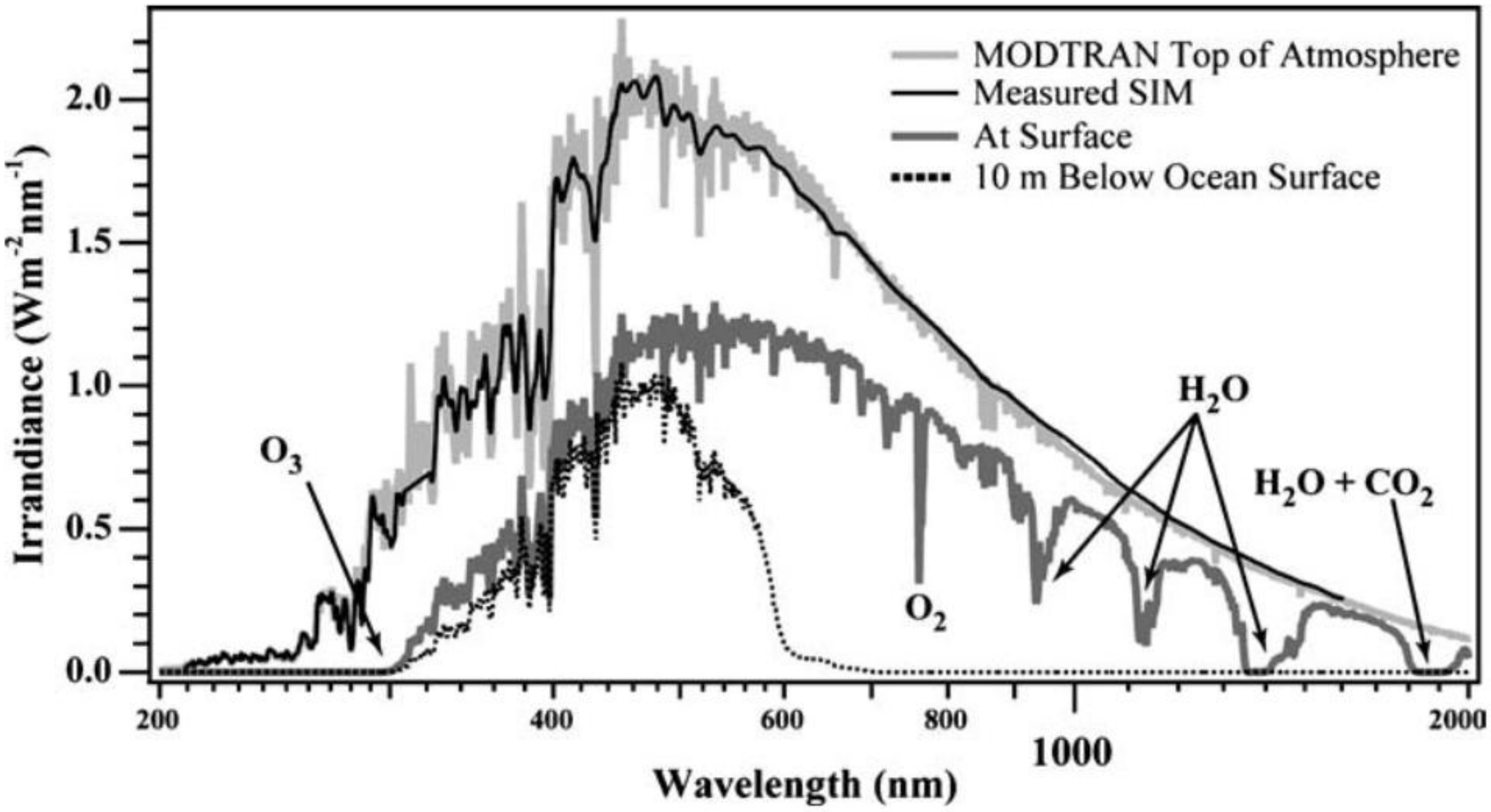


Some definitions

- **Radiation**: emission or transmission of energy in the form of waves or particles through space or through a material medium
- **Irradiance/Flux Density**: radiant flux (Watts) ***received*** by a ***surface*** per unit area, Symbol: *F*; Unit: W m^{-2}
  - **Spectral irradiance** is the irradiance of a surface per unit wavelength or frequency; Unit: W m^{-2} nm^{-1} or W m^{-2} Hz^{-1}
  - **Insolation/solar irradiance**: The incident radiant energy emitted by the sun which reaches a unit area over a period of time, typically measured over a horizontal area at the Earth's surface or at the top of Earth's atmosphere. Units: W m^{-2}

- **Radiance**: is the radiant flux emitted, reflected, transmitted or received by a given surface, per unit solid angle per unit projected area, Symbol: *I*; Units: W m^{-2} sr^{-1}
  - **Radiant intensity**: radiant flux emitted, reflected, transmitted or received, per unit solid angle, Units: W sr^{-1}
  - **Spectral intensity**: is the radiant intensity per unit frequency or wavelength, Units: W sr^{-1} Hz^{-1} or W sr^{-1} nm^{-1}

Solar radiation received on Earth – Irradiance/Flux Density



The intensity of electromagnetic radiation that reaches the surface of our planet is considerably less than that at the top of the atmosphere. “Something” in the atmosphere filters out energy.

The highest energy radiation is most effectively filtered out. This is very important because high energy radiation (gamma rays, x-rays, UV) penetrates the cells of living things and causes damage to them.

DOI: 10.1007/0-387-37625-9_9

SIM: Spectral Irradiance Monitor (SIM), MODTRAN is a model

Irradiance / Flux density (F)

Q: energy (J, kg·m^2·s^{-2})
A: area (m^2)
t: time (s)

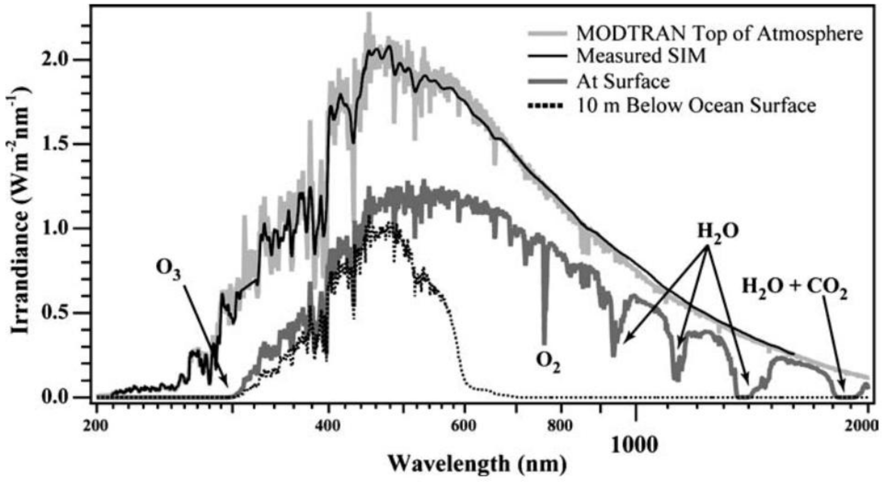
$$F = \frac{d^2\,Q}{dA * dt} \text{ (W m}^{-2}\text{)}$$

Radiation energy varies with
- Frequency (ν) or wavelength (λ)

F_λ Is the spectral flux at a specific wavelength
F_ν or at a specific frequency

$$F_\lambda = \frac{d^3\,Q}{dA * dt * d\lambda} \text{ (W m}^{-2}\text{ nm}^{-1}\text{)}$$

F_λ



Total Flux

$$F = \int_0^\infty F_\lambda \, d\lambda = \int_0^\infty F_\nu \, d\nu$$

$$\nu = \frac{c*}{\lambda} \Rightarrow d\nu = -c^* \lambda^{-2} d\lambda$$

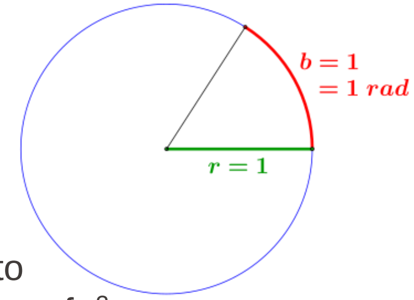
Different units!

Geometry of a sphere

Radiation energy varies with
- Angle ($\boldsymbol{\Phi}, \boldsymbol{\theta}$)

z: vertical direction (zenith)
$\boldsymbol{\theta}$: zenith angle (related to latitude, theta)
$\boldsymbol{\Phi}$: azimuth angle (related to longitude, phi)
d$\boldsymbol{\omega}$: area element on the surface of a sphere (element of a solid angle)

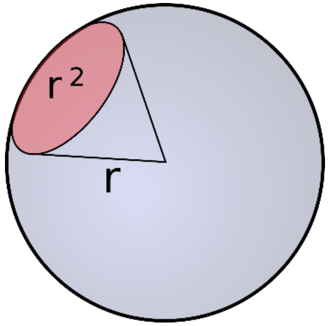
Area of a sphere:
Unit sphere: A=4π
Sphere with radius r: A=4πr^2



Solid angle:
Def. of steradian (sr): solid angle projected onto surface of a sphere with radius r, having an area of r^2
Solid angle of a sphere $\boldsymbol{\Omega}$ = 4 π sr

How «big» is a steradian?

1 Steradian = 1 radian x 1 radian (rad)
1 radian = 57 °
To cover a sphere: $4\pi sr = 12.6$ sr
To cover a hemisphere: $2\pi sr$

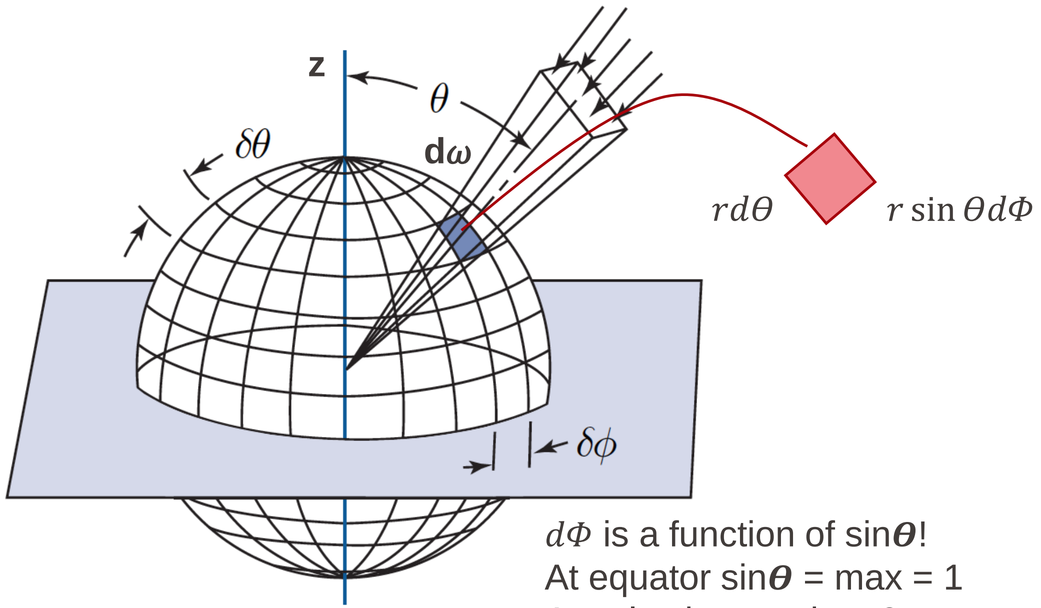


Images from Wikipedia

Solid angle of a unit sphere (sr)

$$\boldsymbol{\Omega} = \frac{A}{r^2}$$

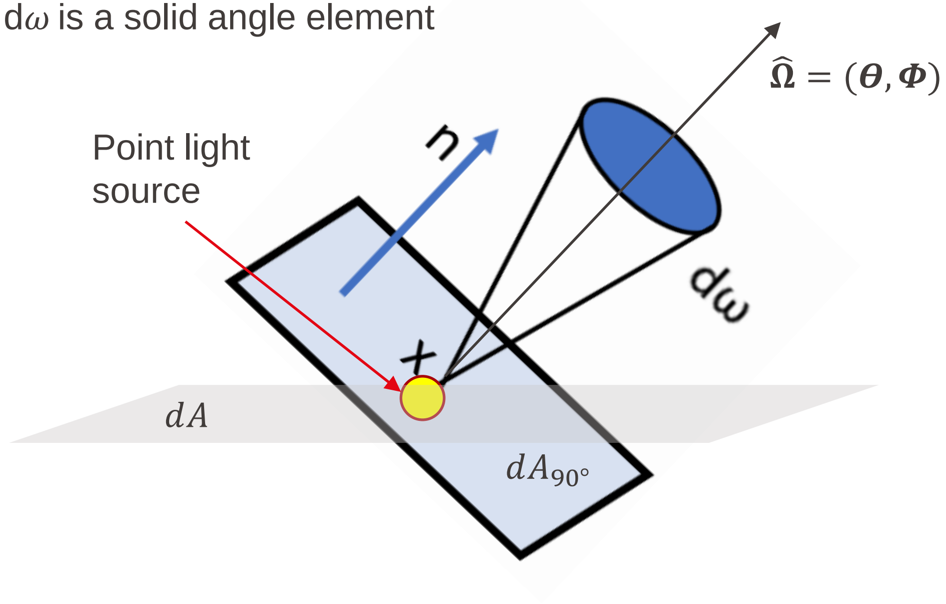
Differential solid angle for any diameter *r (cone)*: $\boldsymbol{A} = \boldsymbol{r^2}\mathbf{d}\boldsymbol{\omega} = r^2 \sin\Theta d\Phi d\Theta$



$d\Phi$ is a function of sin$\boldsymbol{\theta}$!
At equator sin$\boldsymbol{\theta}$ = max = 1
At pole sin$\boldsymbol{\theta}$ = min = 0

Intensity / Radiance (I)

$\widehat{\Omega}$ is a **directional vector**
$dA_{90°}$ is an area element perpendicular to $\widehat{\Omega}$
dω is a solid angle element



Intensity I($\widehat{\Omega}$) is the radiation energy dQ traveling in a direction within the solid angle element dω centered on $\widehat{\Omega}$, crossing d$A_{90°}$.

$$I(\widehat{\Omega}) = \frac{d^3Q}{dA_{90°}d\omega\ dt} \quad (\mathrm{W\ m^{-2}\ sr^{-1}})$$

- **Radiance**: is the radiant flux emitted, reflected, transmitted or received by a given surface, per unit solid angle per unit projected area, Symbol: *I*; Units: W m^{-2} sr^{-1}
  - **Radiant intensity**: radiant flux emitted, reflected, transmitted or received, per unit solid angle, Symbol: *I*; Units: W sr^{-1}
  - **Spectral intensity**: is the radiant intensity per unit frequency or wavelength, Symbol: *I*; Units: W sr^{-1} Hz^{-1} or W sr^{-1} nm^{-1}

(note in Wallace and Hobbs Radiance = Intensity)

Spectral intensity

$$I = \int_{\lambda 1}^{\lambda 2} I_\lambda d\lambda = \int_{\nu 1}^{\nu 2} I_\nu d\nu \qquad (\mathrm{W\ m^{-2}\ sr^{-1}\ \mu m^{-1}})$$

Relation of Intensity and Flux

Intensity reaching a surface area dA: refers to a surface perpendicular to $\hat{\boldsymbol{\Omega}}$, i.e. $dA_{90°}$
To account for a horizontal surface, it needs to be projected onto the plane perpendicular to the zenith angle = 0.

$$I = \frac{d^3Q}{dA_{90°}d\omega\,dt} = \frac{d^3Q}{\cos\boldsymbol{\theta}\,dA\,d\omega\,dt} \qquad (\mathrm{W\,m^{-2}\,sr^{-1}})$$

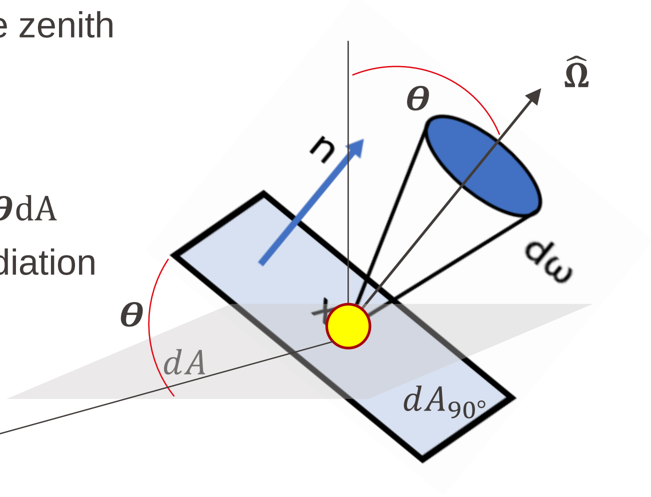
$$F = \frac{d^2Q}{dA*dt} \qquad (\mathrm{W\,m^{-2}})$$

$$\frac{dF}{d\omega} = \frac{d^3Q}{dA\,dt\,d\omega}$$

$$I = \frac{dF}{\cos\boldsymbol{\theta}\,d\omega}$$

$$dA_{90°} = cos\boldsymbol{\theta}\mathrm{dA}$$

«dilution» of radiation

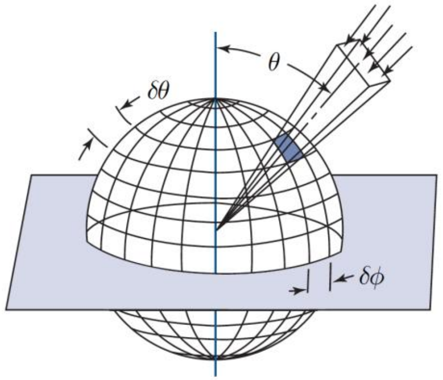


The radiant intensity in a given direction is equal to the irradiance at a point on the unit sphere centered at the source.

$$F = \int I(\boldsymbol{\Phi},\boldsymbol{\theta})\cos\boldsymbol{\theta}\,d\omega \qquad (\mathrm{W\,m^{-2}})$$

monochromatic
$$F_\lambda = \int I_\lambda(\boldsymbol{\Phi},\boldsymbol{\theta})\cos\boldsymbol{\theta}\,d\omega \qquad (\mathrm{W\,m^{-2}\,\mu m^{-1}})$$

Over total hemisphere
$$F_\lambda = \int_{2\pi} I_\lambda(\boldsymbol{\Phi},\boldsymbol{\theta})\cos\boldsymbol{\theta}\,d\omega$$



Relation of Intensity and Flux

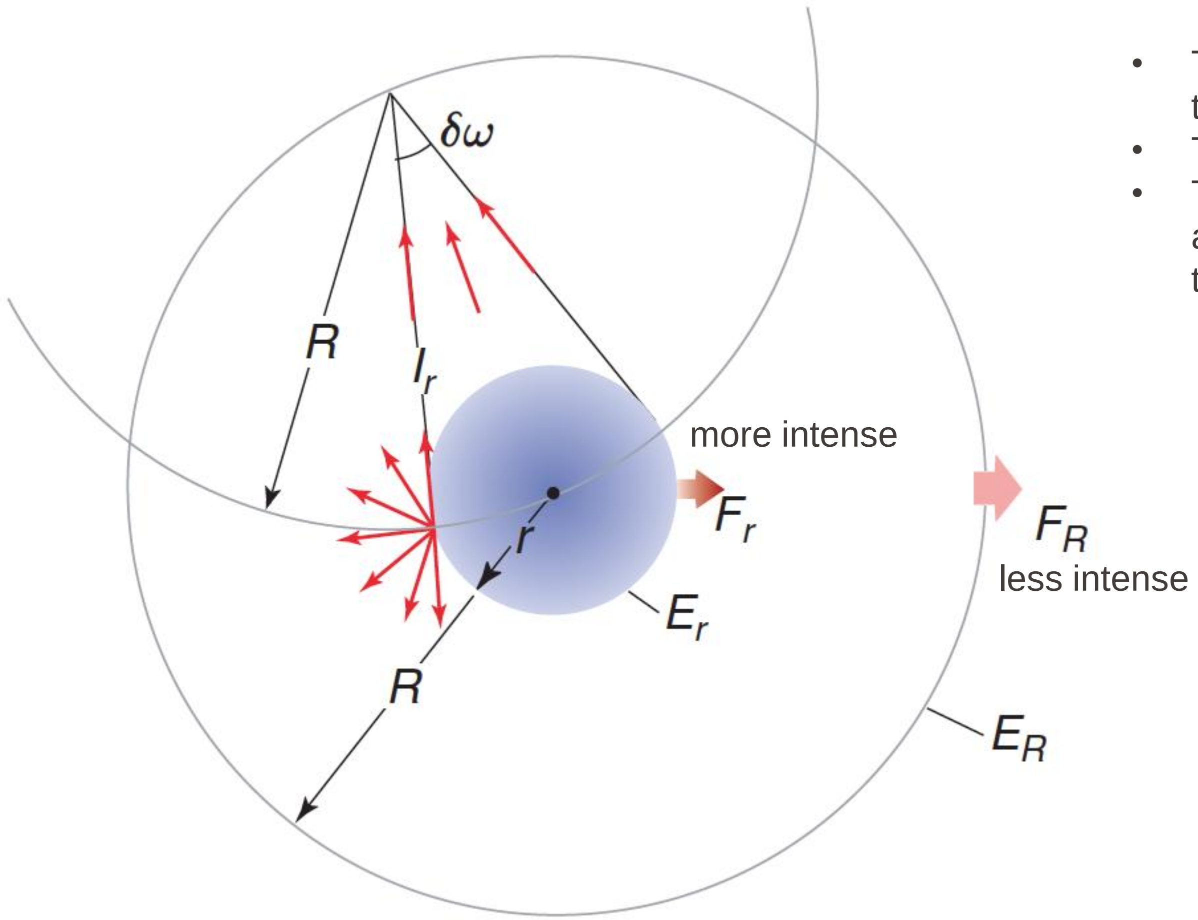


Fig. 4.4

Hypothetical situation for an emitting (smaller) sphere and how the radiation is distributed in space.

- The total emitted energy (*E_r*, *J*) is the same as the total energy going through a virtual sphere with a larger radius (*E_R*).
- The intensity (*I*, $W\ m^{-2}\ sr^{-1}$) is directional and independent of distance.
- The flux density (*F*, W/m^2) is directly proportional to the arc solid angle and inversely proportional to the square of the distance from the source.

$$E_r = E_R$$

$$I_r = I_R$$

$$F_r > F_R$$

$$F \propto \frac{1}{d^2}$$

Recap questions

- Which of the following statements are correct?
  - 1. Irradiance is flux density.
  - 2. Intensity depends on direction.
  - 3. Intensity depends on distance.
  - 4. Irradiance depends on distance.
  - 5. Only the flux density depends on the angle.

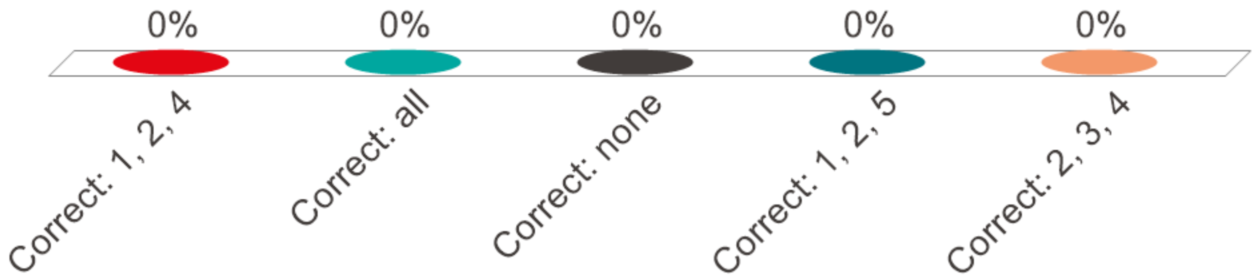
A. Correct: 1, 2, 4

B. Correct: all

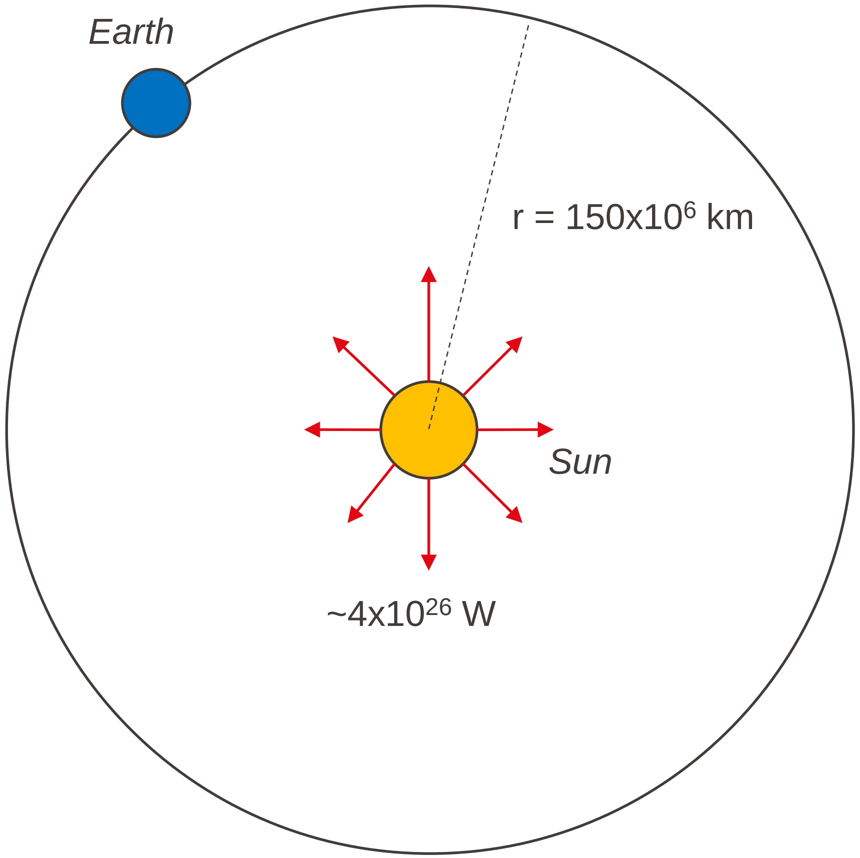
C. Correct: none

D. Correct: 1, 2, 5

E. Correct: 2, 3, 4



Solar radiation reaching Earth / solar constant



Sphere with radius r has a surface area $4\pi r^2$

So the radiation flux received by Earth is: $4x10^{26} / 4\pi r^2 \quad = 1370\ W\ m^{-2}$

Solar constant

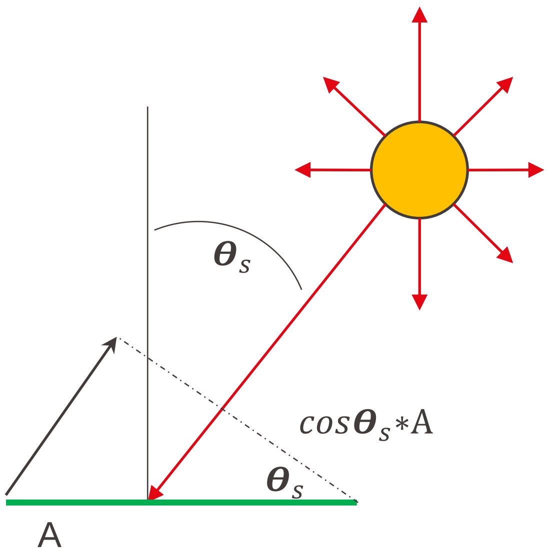
The solar constant is defined as the rate at which solar energy is received by a surface oriented perpendicular to the Sun's direction at the distance of the Earth's orbit. It is measured to be 1370 W m^{-2}.

$$\boldsymbol{S_0 = 1370\ W\ m^{-2}}$$

Is it constant?

- Different for each planet.
- Earth's orbit is eccentric (r varies by $\pm$1.75 %). Closer to the sun in January, farthest in July. The constant is defined for the average distance.
- It varies as the sun rotates (29-day cycle), bringing sunspots groups across the Earth-facing side of the Sun.
- It varies by 0.1 % over the 11-year solar cycle, with a maximum at sunspot maximum (next 2025).
- It increases as the Sun ages (1 % every 100 million years).

Radiation reaching Earth's top of atmosphere



$\boldsymbol{\theta}_s$ solar zenith angle

All light passing through the projected area is also incident on A.

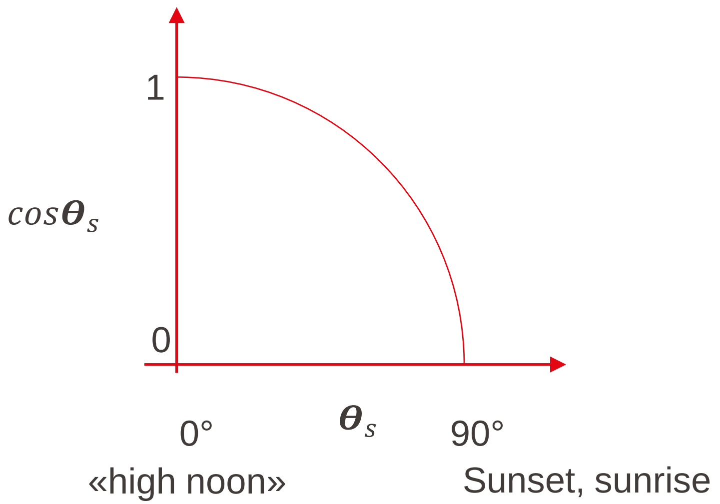
Power on projected area is:

$\boldsymbol{P} = \boldsymbol{S_0} * A * cos\boldsymbol{\theta}_s$ (W)

The power is distributed over area A. To calculate the flux we divide by A.

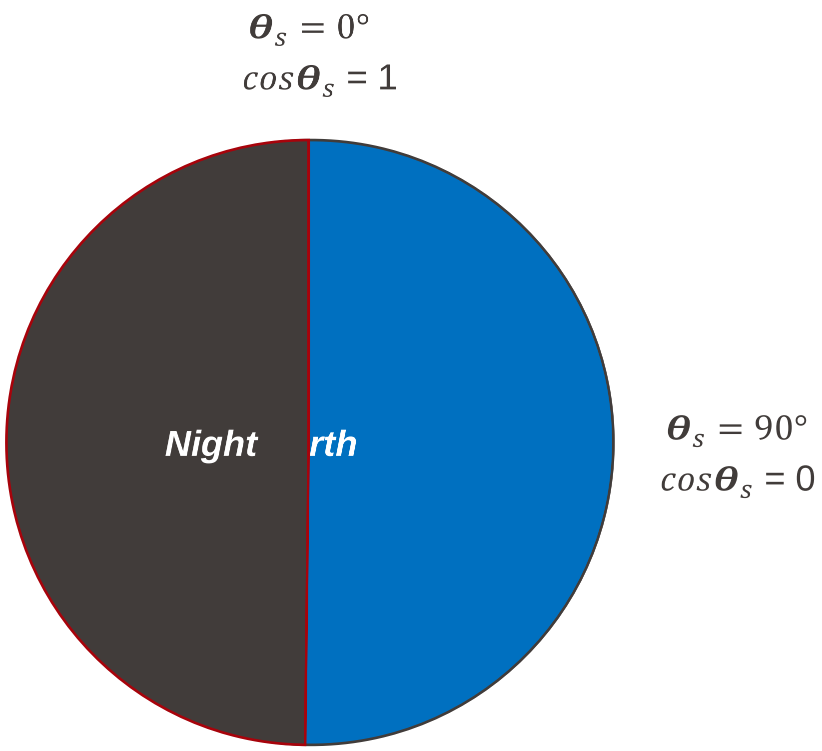
$$F = \frac{S_0 * A * cos\boldsymbol{\theta}_s}{A} = \boldsymbol{S_0} * cos\boldsymbol{\theta}_s \quad (W\ m^{-2})$$

This is the flux received at the top of the atmosphere.



Average flux received by Earth

Average over latitude, season, day and night



- 50 % night
- average zenith angle: 60 ° → cos60° = 0.5

1370 / 4 ~ 340 W m^{-2}

Average flux received by Earth

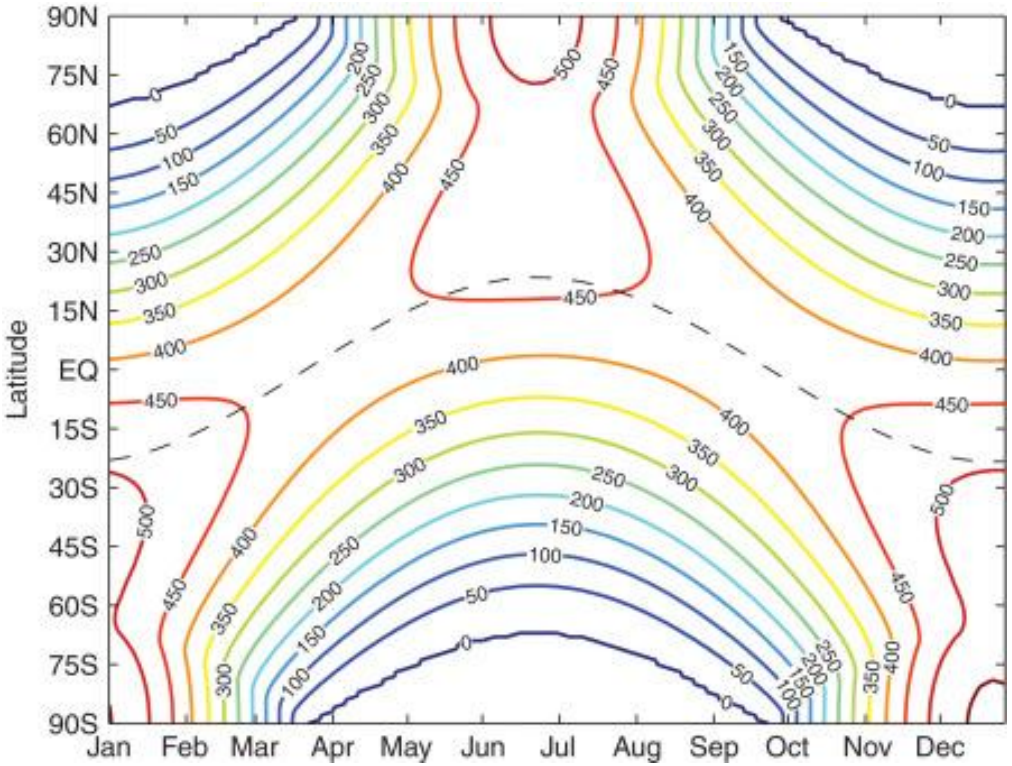


Figure 2.6. Contour graph of the daily average **insolation (flux density)** at the top of the atmosphere as a function of season and latitude. The contour interval is 50 Wm^{-2}. The heavy dashed line indicates the latitude of the subsolar point at noon.

Why more?

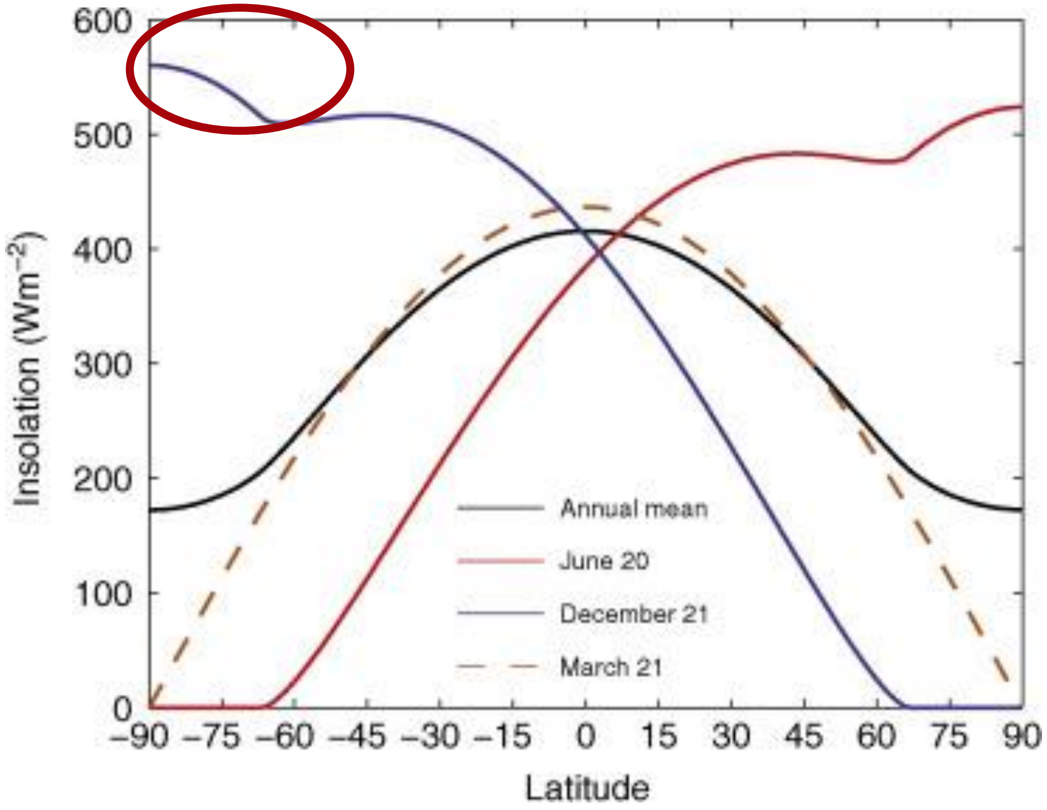
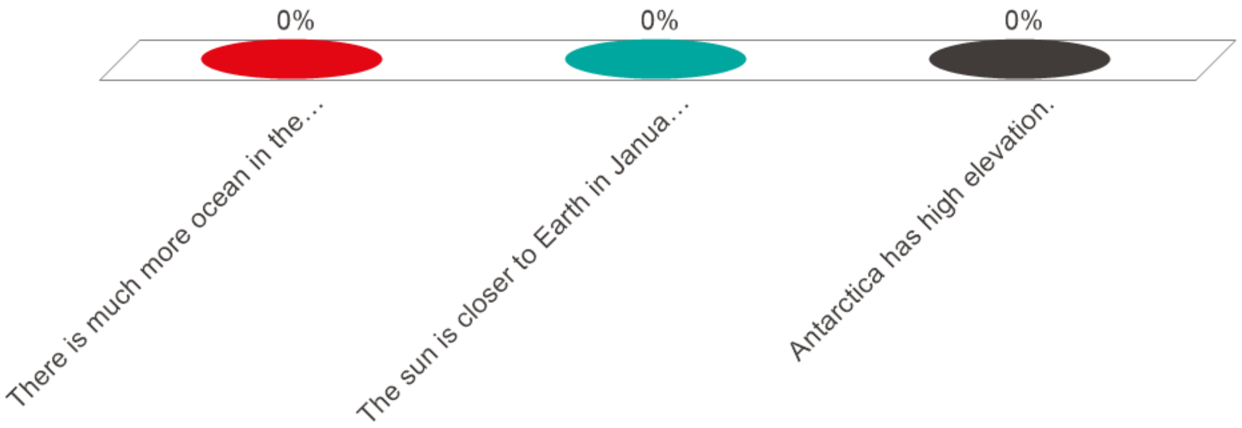


Figure 2.7. Annual-mean, solstice and equinox insolation as functions of latitude.

Dennis L. Hartmann, in Global Physical Climatology (Second Edition), 2016

Why do we see a different insolation between NH and SH summer?

A. There is much more ocean in the Southern Hemisphere.
B. The sun is closer to Earth in January than in July.
C. Antarctica has high elevation.



Blackbody radiation (*B*)

Definition: matter or object that absorbs all radation incident on it.
Example: coal, cavity (cave)

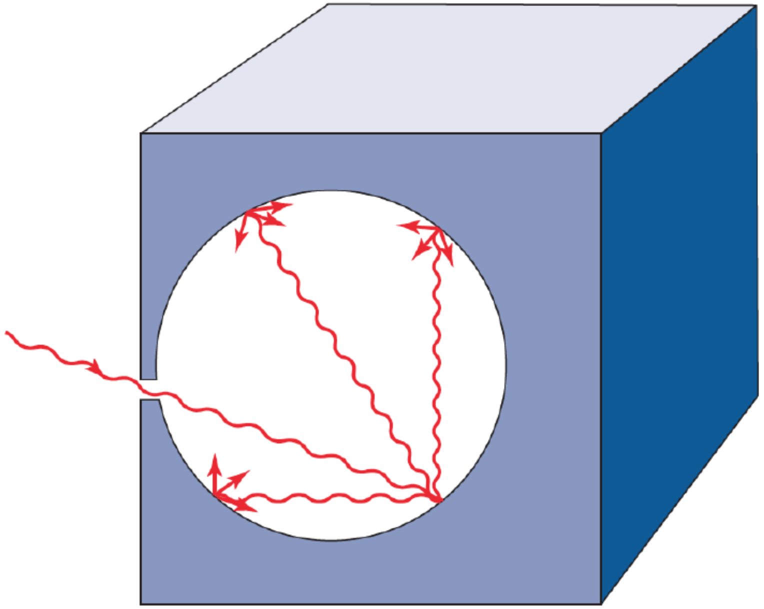


Fig. 4.5: Radiation entering a cavity

The radiation *emitted* by a blackbody (e.g. coming out the opening of a cavity) is *isotropic (same intensity independent of location)* and depends **only** on ***temperature***, not on the composition of the blackbody, nor on whether any radiation is incident on the blackbody.
The blackbody is losing energy by emission of radiation, so heat must be supplied to keep its temperature constant.

Blackbody radiation: Planck function

Monochromatic intensity of a blackbody (B_λ)

B_λ is a function of T and λ^5

$$\nu = \frac{c^*}{\lambda}$$

$$d\nu = -c^*\lambda^{-2}d\lambda$$

$$B_\lambda(\mathrm{T}) = \frac{2hc^{*2}/\lambda^5}{e^{hc^*/\lambda kT}-1} \qquad (\mathrm{W\ m^{-2}\ sr^{-1}\ \mu m^{-1}})$$

$$B_\nu(\mathrm{T}) = \frac{2h\nu^3/c^{*2}}{e^{h\nu/kT}-1} \qquad (\mathrm{W\ m^{-2}\ sr^{-1}\ Hz^{-1}})$$

k = Boltzmann's constant, 1.380649 x 10^{-23} J K^{-1}
h = Planck's constant, 6.63 x 10^{-34} J s
c* = speed of light, 299,792,458 m s^{-1}
T = Temperature (K)

Three key characteristics

1. Peak wavelength
2. Total intensity
3. Smooth slope for long wavelength (low frequency)

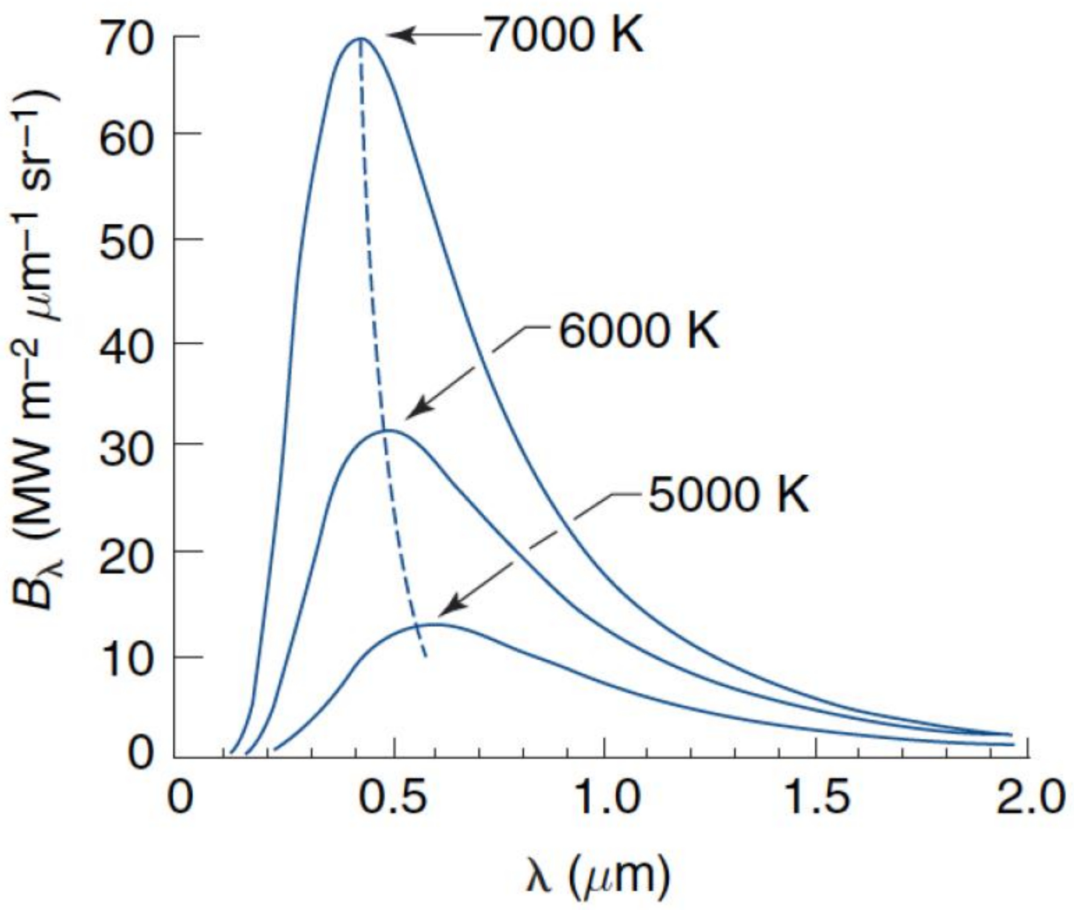


Fig. 4.6: Emission spectra of a blackbody at three different temperatures

Note the equations are from Physics of Climate, Peixoto and Oort, 1991 (p. 95)

Wien’s displacement law

Peak wavelength

Obtained by differentiating $B_\lambda(T)$ and setting equal to 0:

$\frac{dB_\lambda(T)}{d\lambda} = 0$ for $\lambda = \lambda_{max} \rightarrow$

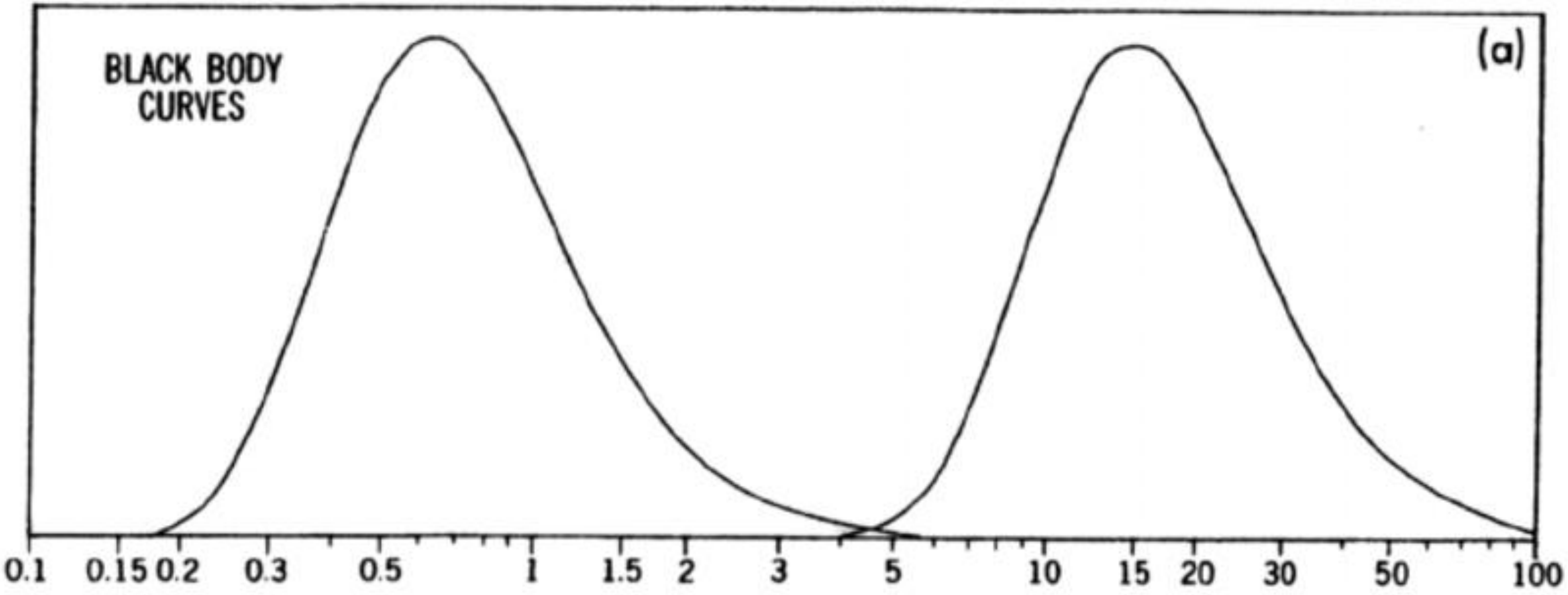
λ_{max} *T = const. = 2.897x10^{-3} (m K)

Wien’s displacement law

$$\lambda_{max}\,(\mu m) = \frac{2897\,(\mu m K)}{T\,(K)}$$

With Wien’s displacement law, we can calculate the temperature of a body, if we know its emission spectrum.

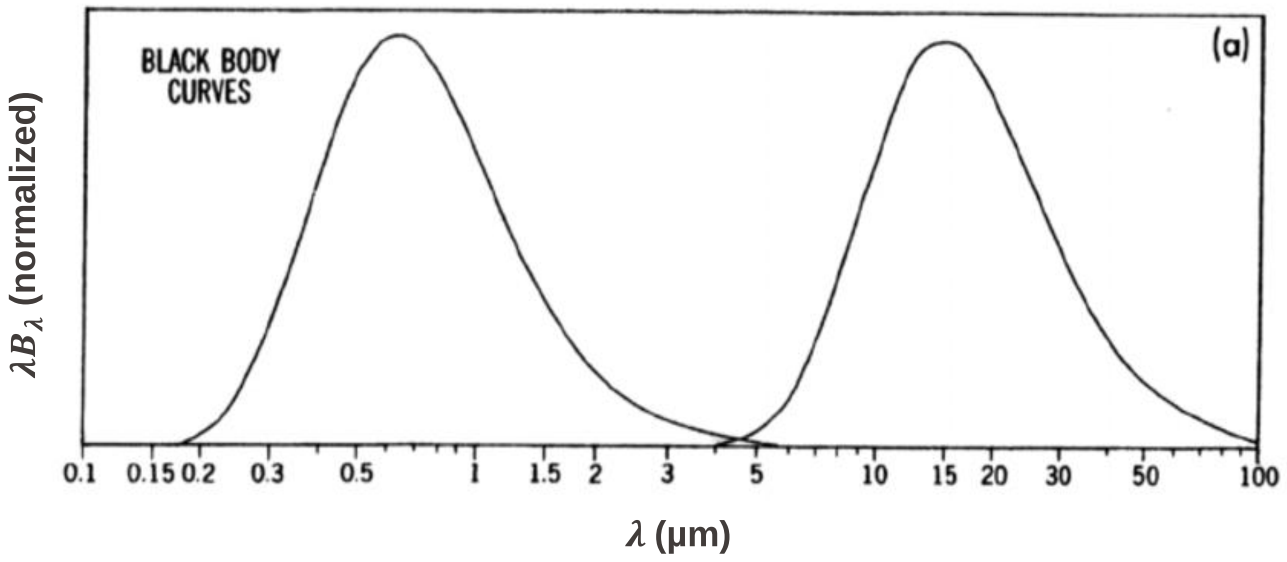
λB_λ (normalized)



λ (μm)

What are the temperatures of the two bodies?

Get together in groups of 3 people.
You have ~5 minutes time.



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Stefan-Boltzmann law

Total intensity

Integration of the Planck function over all wavelengths

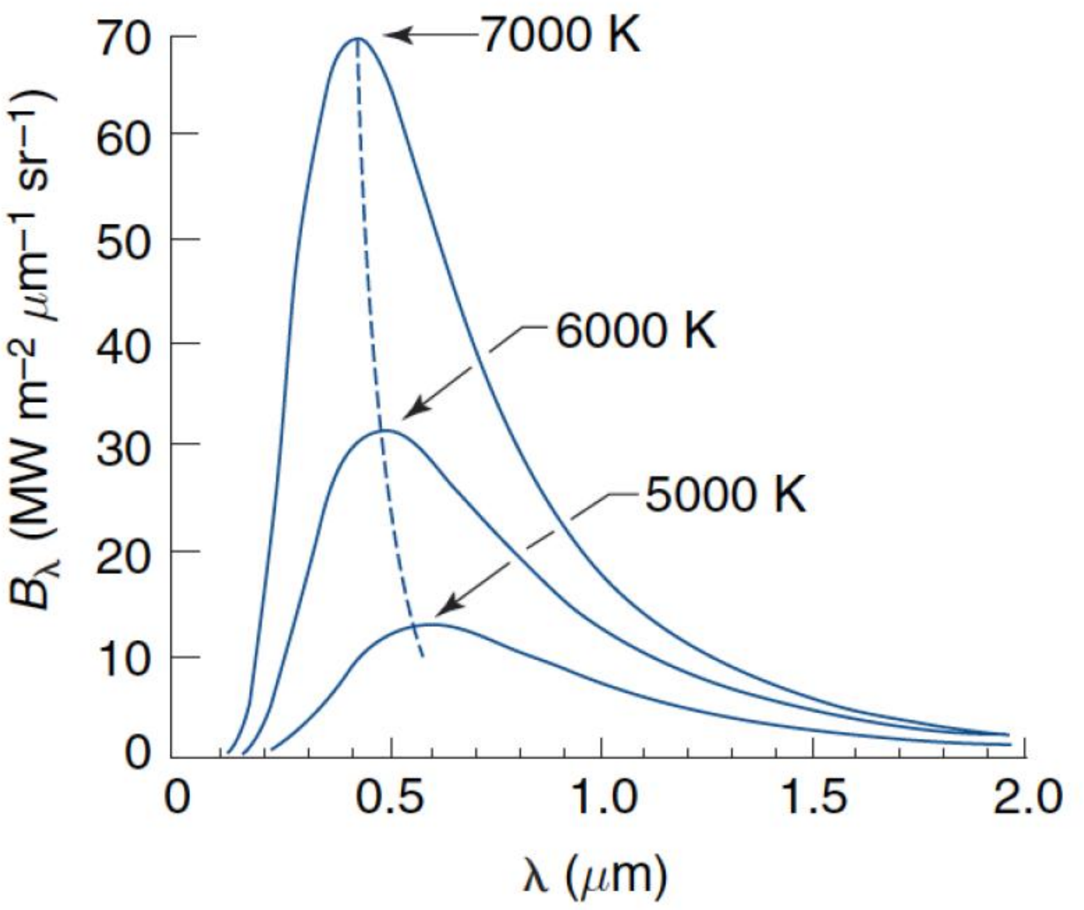
$B(T) = \int_0^\infty B_\lambda(T)d\lambda \sim T^4$ T in K, B(T) in W m^{-2} µm^{-1} sr^{-1}

Integration over all angles of a hemisphere covering a horizontal surface (*B(T)* is independent of direction): total flux F_B

* F_B (T) = πB(T) =$\pi\int B_\lambda(T)d\lambda = \sigma T^4$

σ = 5.67 × 10^{-8} W m^{-2} K^{-4} Stefan-Boltzmann constant
Note, the Boltzmann constant is something different
F_B (T) has the unit W m^{-2}

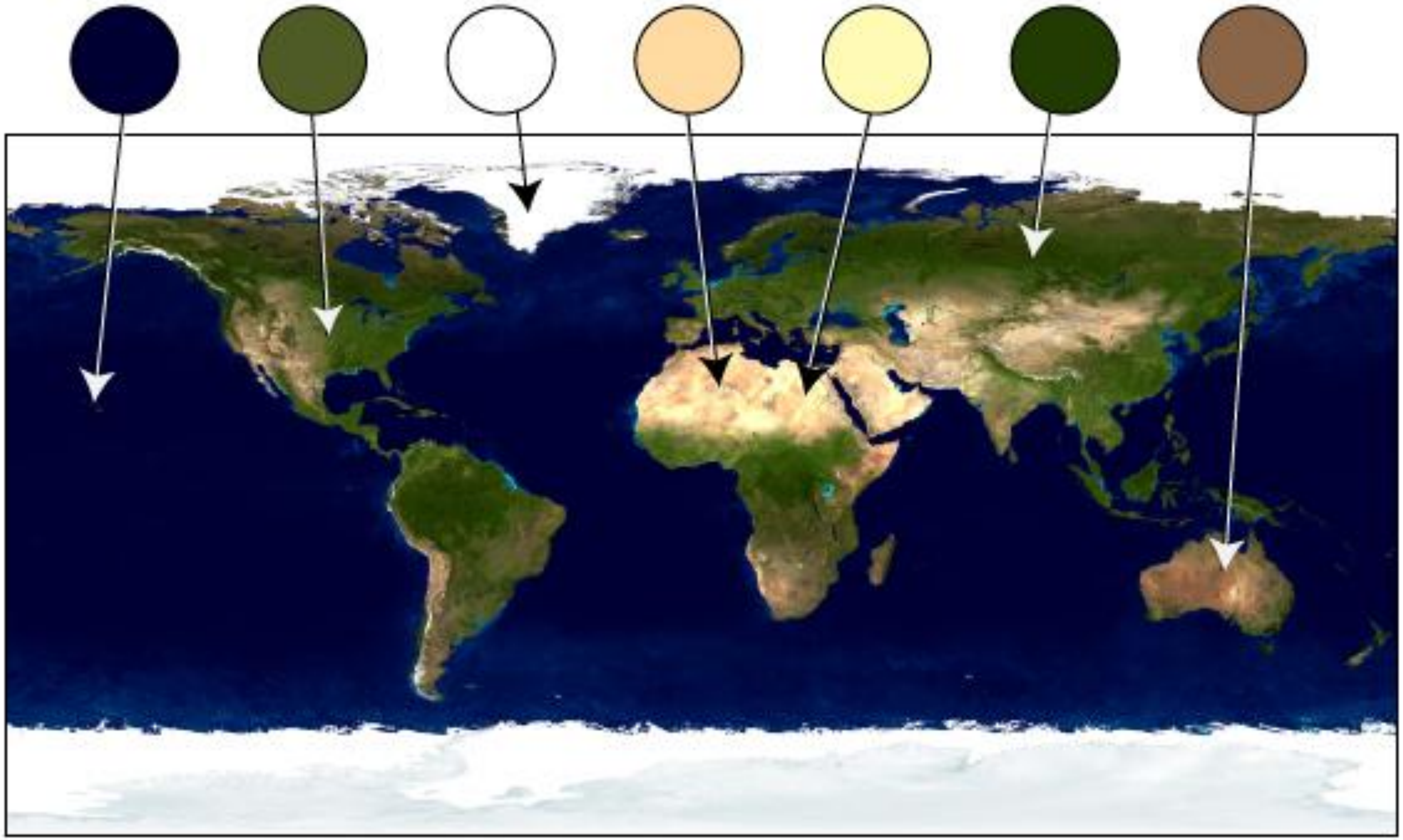
If you know the flux density F_B of a blackbody you can calculate the equivalent **blackbody temperature** or **effective emission temperature (**$\boldsymbol{T_E}$**).** T_E is the temperature a blackbody would need to emit radiation at the measured rate *F*. If the body is a blackbody then T_E and *T* of the body are equal.



* For details see *Physics of Climate, Peixoto and Oort, 1991 (p. 95f)*

Albedo

Reflectivity of a surface
1: fully reflective
0: complete absorption



https://scied.ucar.edu/learning-zone/how-climate-works/albedo-and-climate

Earth's albedo

Water (ocean), zenith angle: 45, 60, 70, 80°	0.05, 0.08, 0.12, 0.22
Fresh/worn asphalt	0.04/0.12
Conifer forest (summer)	0.08–0.15
Deciduous trees	0.15–0.20
Savanna	0.20–0.25
Green grass	0.25
Desert sand	0.30–0.40
New concrete	0.55
Ocean Ice	0.50–0.70
Old snow	0.45–0.80
Clouds	0.60–0.90
Fresh snow	0.80–0.90

Planetary albedo, incl. atmosphere and clouds: ~ 0.3

Stefan-Boltzmann law

Total intensity

Integration of the Planck function over all wavelengths

$B(T) = \int_0^\infty B_\lambda(T)d\lambda \sim T^4$ T in K, B(T) in W m^{-2} μm^{-1} sr^{-1}

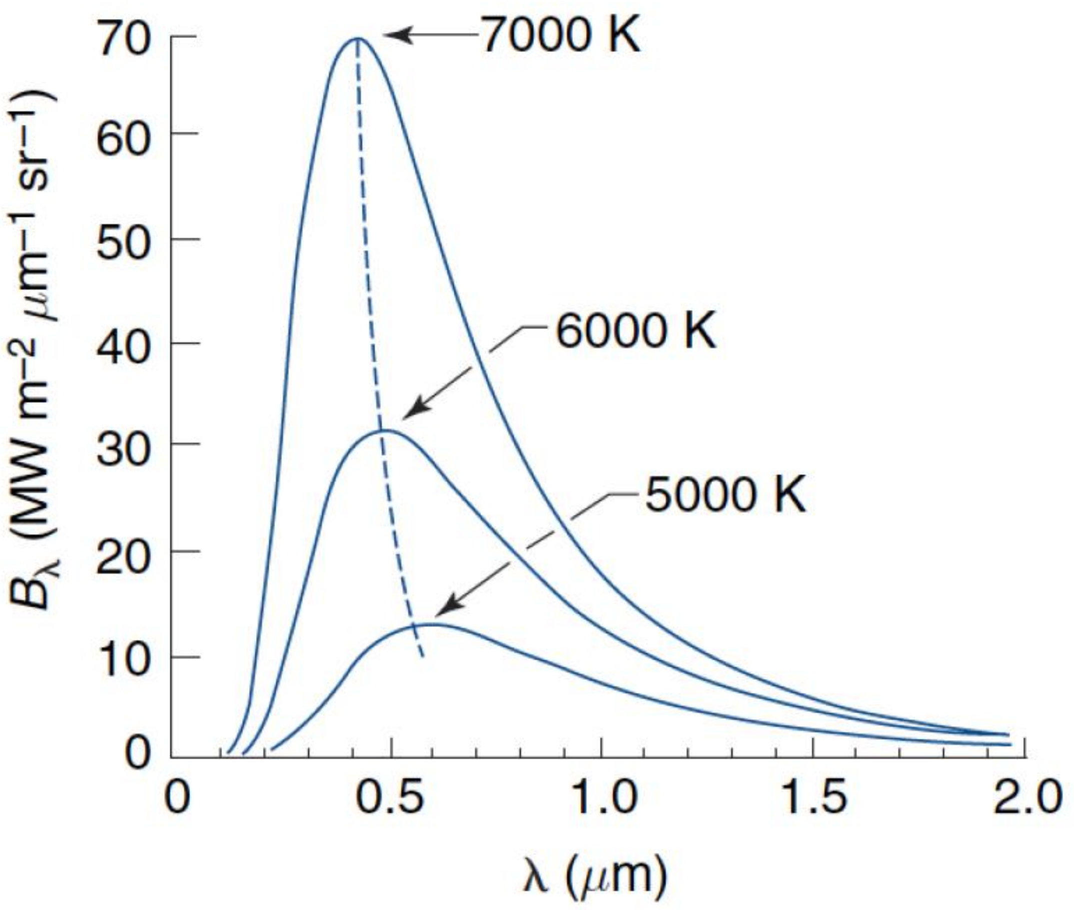
Integration over all angles of a hemisphere covering a horizontal surface (B(T) is independent of direction): total flux F_B

F_B (T) = πB(T) $=\pi\int B_\lambda(T)d\lambda = \sigma T^4$

σ = 5.67 × 10^{-8} W m^{-2} K^{-4} Stefan Boltzmann constant

If you know the flux density F_B of a blackbody you can calculate the equivalent blackbody temperature or effective emission temperature (T_E). T_E is the temperature a blackbody would need to emit radiation at the measured rate F. If the body is a blackbody then T_E and T of the body are equal.

But, not all bodies are perfect blackbodies.

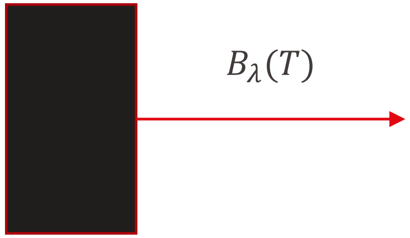


Radiative properties of non-black materials (grey bodies, e.g. gases)

Some definitions:

ε_λ = emissivitiy at wavelength λ
α_λ = absorptivity at wavelength λ
r_λ = reflectivity at wavelength λ
T_λ = Transmissivity at wavelength λ

Blackbody: ε = 1, α = 1 for all λ
Intensity of emission $B_\lambda(T) = I_\lambda / \alpha_\lambda$



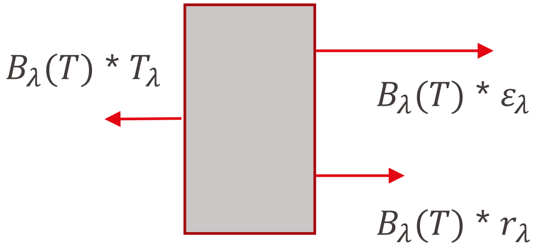
Grey body: defined as α_λ is the same over all λ and < 1
$\alpha_\lambda + r_\lambda + T_\lambda = 1$; $I_\lambda < B_\lambda(T)$

$$\alpha_\lambda = \frac{I_\lambda\,(absorbed)}{I_\lambda\,(incident)}$$

$$r_\lambda = \frac{I_\lambda\,(reflected)}{I_\lambda\,(incident)}$$

$$T_\lambda = \frac{I_\lambda\,(transmitted)}{I_\lambda\,(incident)}$$

$\varepsilon_\lambda = (1 - r_\lambda) = \frac{I_\lambda\,(emitted)}{B_\lambda(T)}$ (if T_λ is negligible)



Kirchhoff's law

$I_\lambda = B_\lambda(T)^* \alpha_\lambda$

For I_λ to be different from zero, both $B_\lambda(T)$ and α_λ need to be different from zero. Hence, for a body to be able to emit energy at a given wavelength and a given temperature it is necessary that a black body also emit energy at that temperature AND that the body be able to absorb it. Since the emissivity is defined as the ratio of the emitted intensity to the Planck function, Kirchhoff's law is:

$$\varepsilon_\lambda = \frac{I_\lambda\,(emitted)}{B_\lambda(T)}$$

$$\varepsilon_\lambda = \alpha_\lambda = 1$$

«A body that absorbs well, radiates well.»

Assumption: Local thermodynamic equilibrium :
temperature of environment and body are equal.

Works for molecules in the atmosphere < 60 km as long as their absorption and emission behavior does not change (i.e. their collision frequency must be faster than the frequency of the incident radiation). In that condition, the gas is in *local thermal equilibrium* (LTE).
(→ see also aerosol lecture later for details)

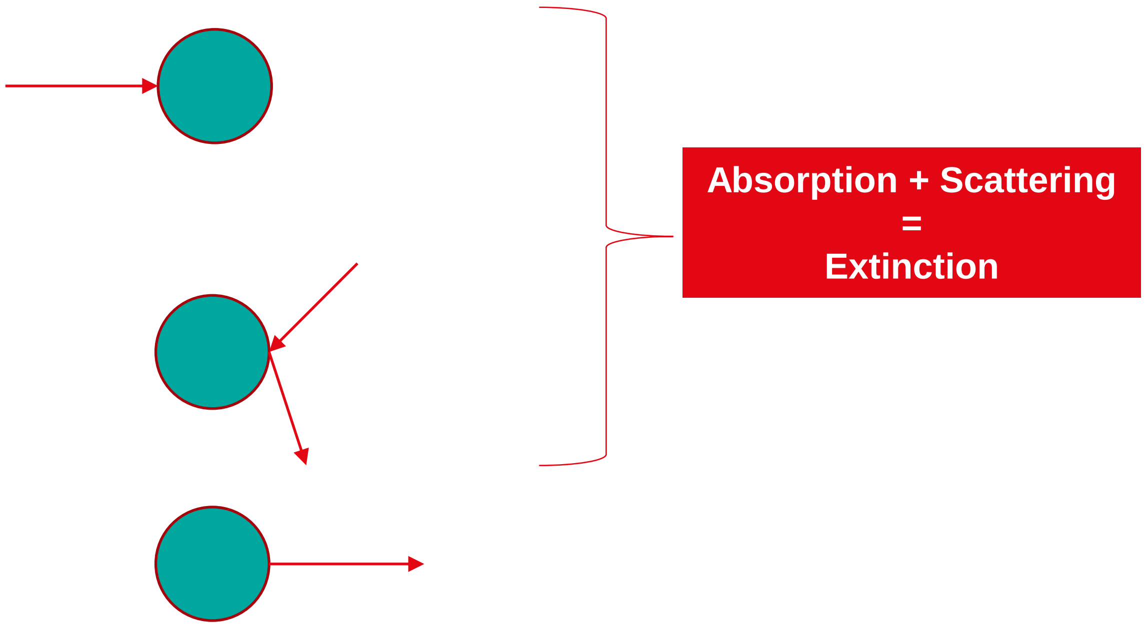
Interaction of radiation with matter

Definitions

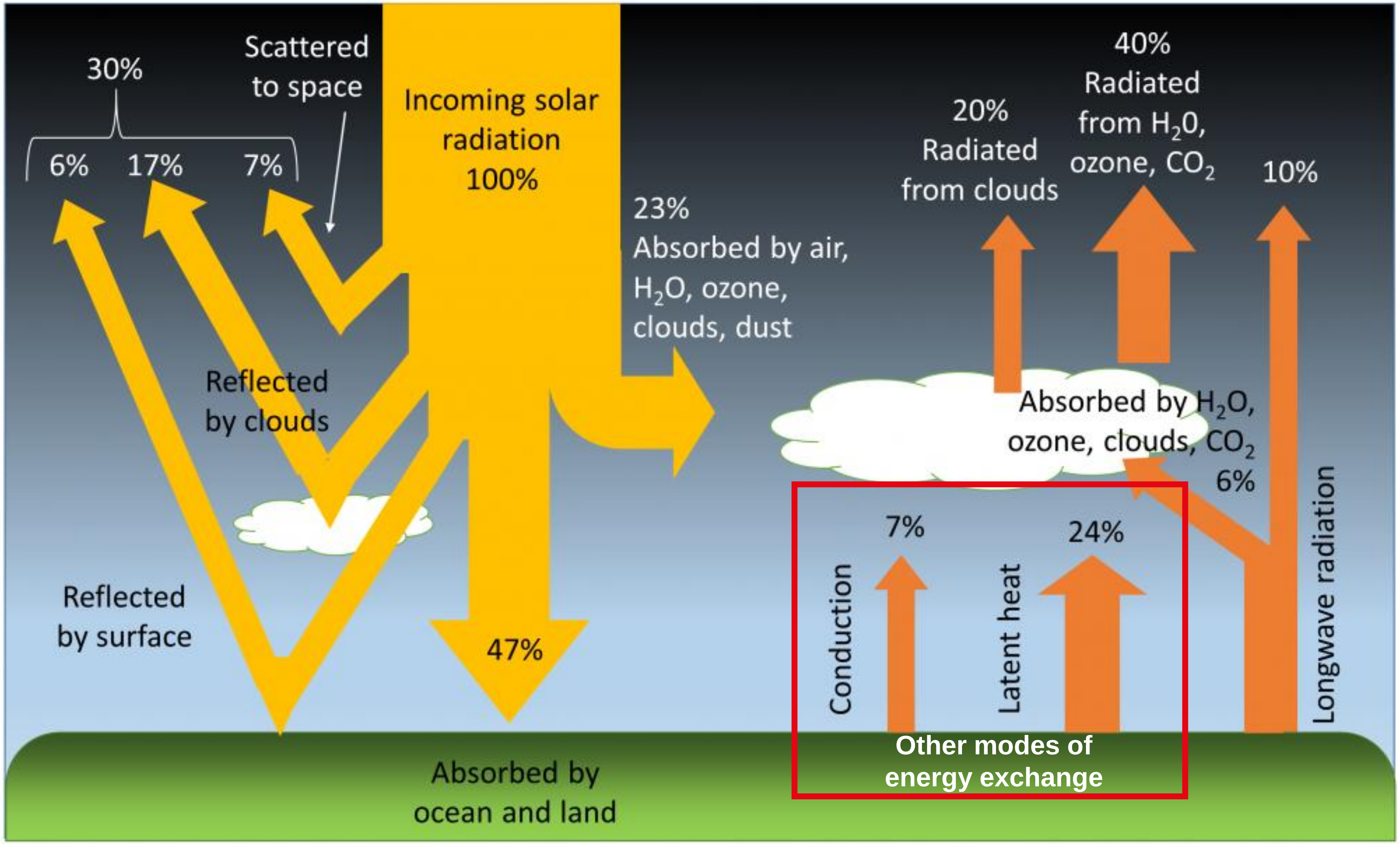
1. **Absorption**: A photon is destroyed. Its energy is distributed by collision into other forms of energy (vibration, rotation…). The frequency of subsequently emitted raditation is independent of the frequency of the absorbed photon.

2. **Scattering/Reflection**: The photon changes direction but not frequency.

3. **Emission**: A photon is created. The molecule emitting the photon loses internal energy (vibrational, rotational…) equivalent to the energy of the photon.



Interaction of radiation with Earth's atmosphere and surface



https://rwu.pressbooks.pub/webboceanography/chapter/8-1-earths-heat-budget/

Motivation for radiative transfer considerations

- Earth's atmosphere is composed of a variety of molecules, aerosols, and clouds, which all absorb and scatter solar as well as terrestrial radiation.
  - absorption + scattering = extinction

- To understand the energy balance of Earth, we need to understand the radiative transfer through the atmosphere.

Extinction

Beer-Lambert-Bouguer Law for **extinction**

$$dI_\lambda = -I_\lambda \rho r k_\lambda ds$$

ρ = density of air (measure for the number of molecules)
r = mass of gas per unit mass of air
k_λ = mass extinction coefficient ($m^2\ kg^{-1}$) (measure of effectiveness of scattering and absorption)

Note contributions of different gases are additive.

Extinction is proportional to:

- to the radiation intensity
- path length *ds* (mass and gas properties)

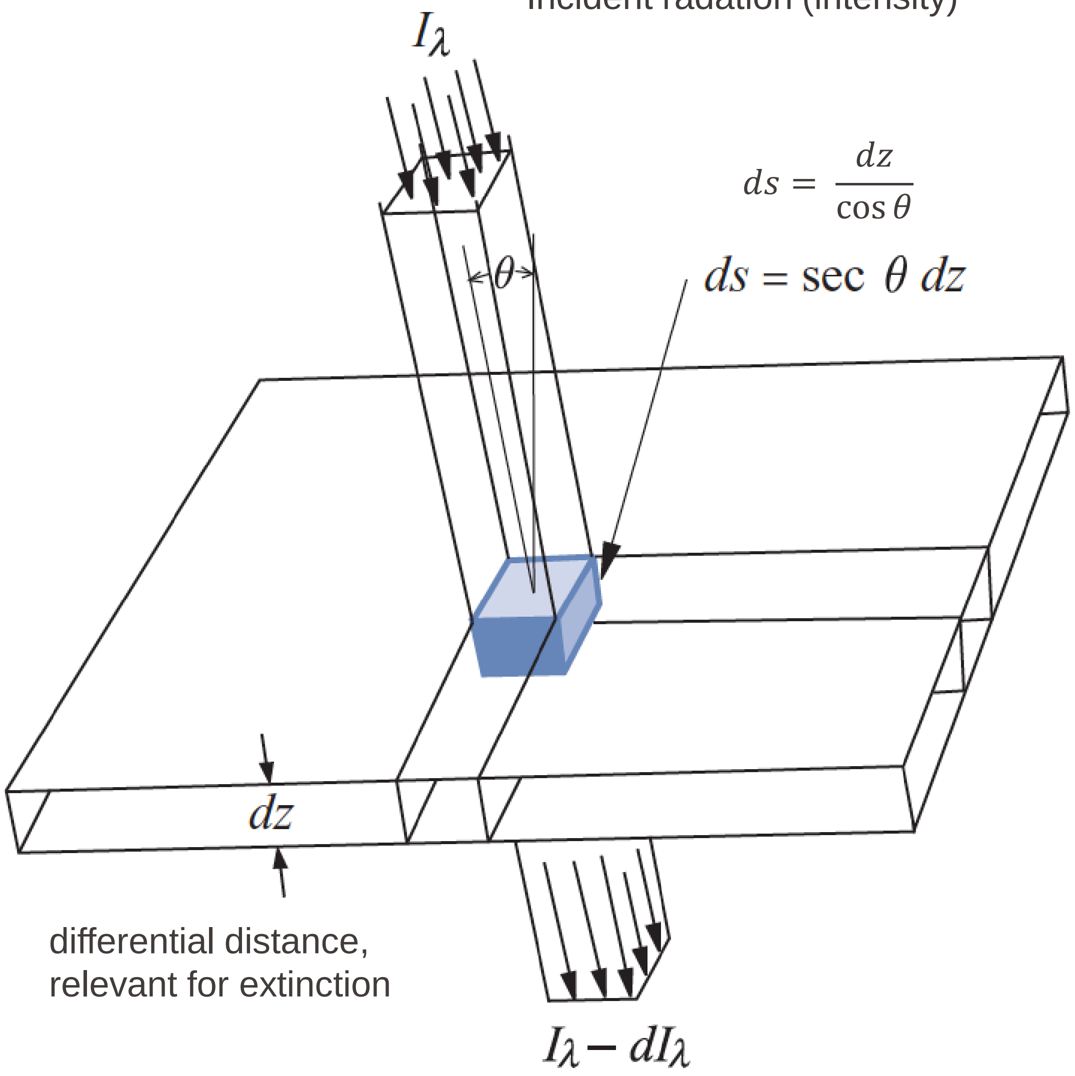


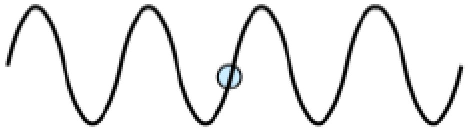
Figure 4.10

Scattering regimes and phase function

Dimensionless size parameter for particles (chi): $\chi = \frac{2\pi r}{\lambda}$

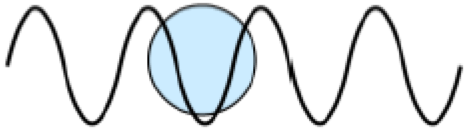
$\chi \ll 1$, $\boldsymbol{Rayleigh\ regime}$ $\quad k_\lambda \propto \lambda^{-4}$

Electro-magnetic field constant over particle



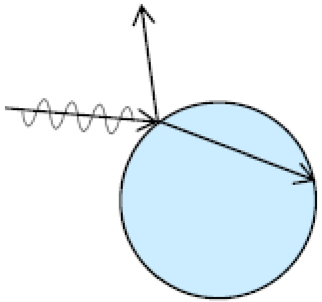
$0.1 < \chi < 50$, $\boldsymbol{Mie}$ $scattering$

Electro-magnetic field varies over particle



χ > 50, **geometric** optics

Electro-magnetic field decays over particle



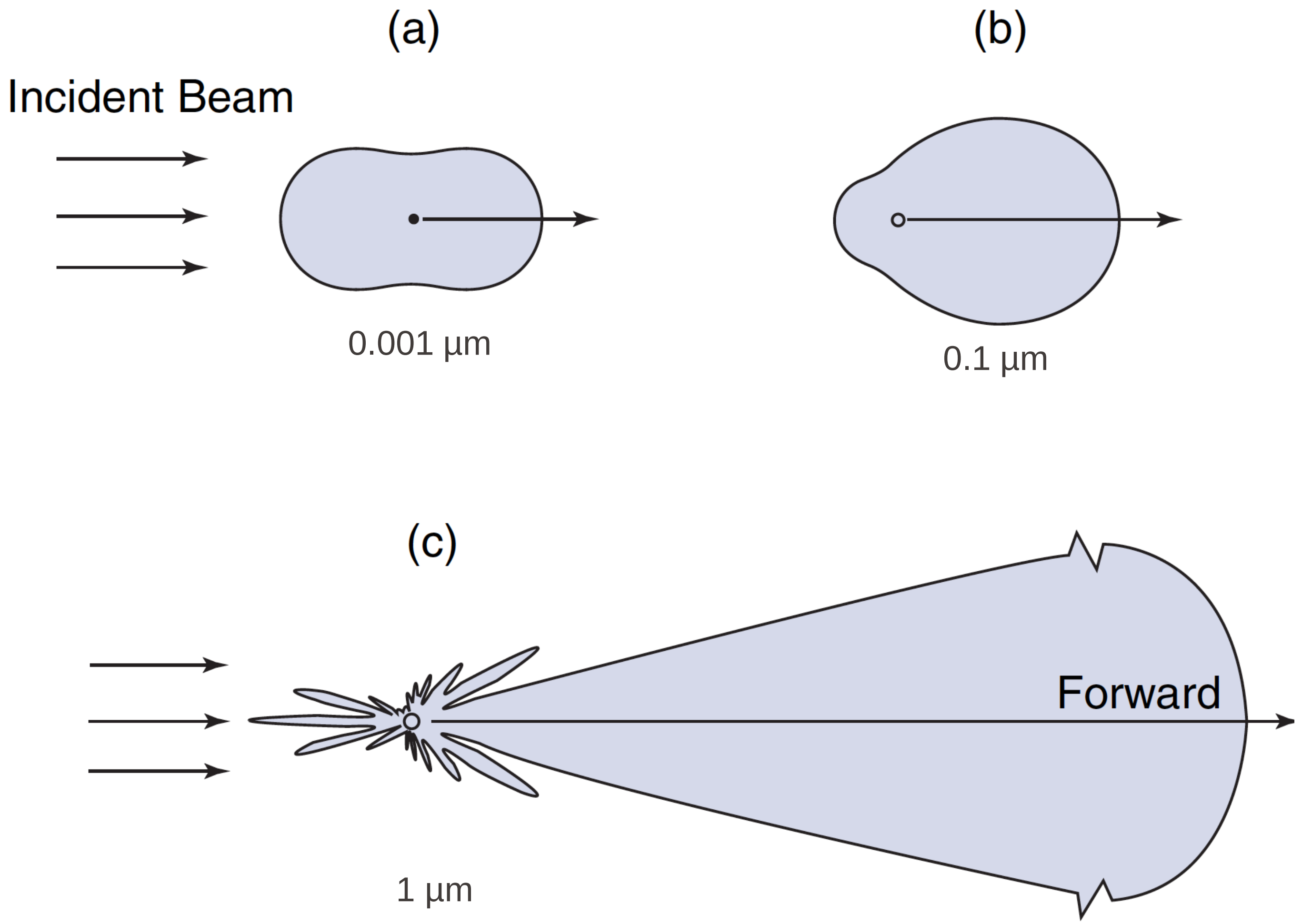
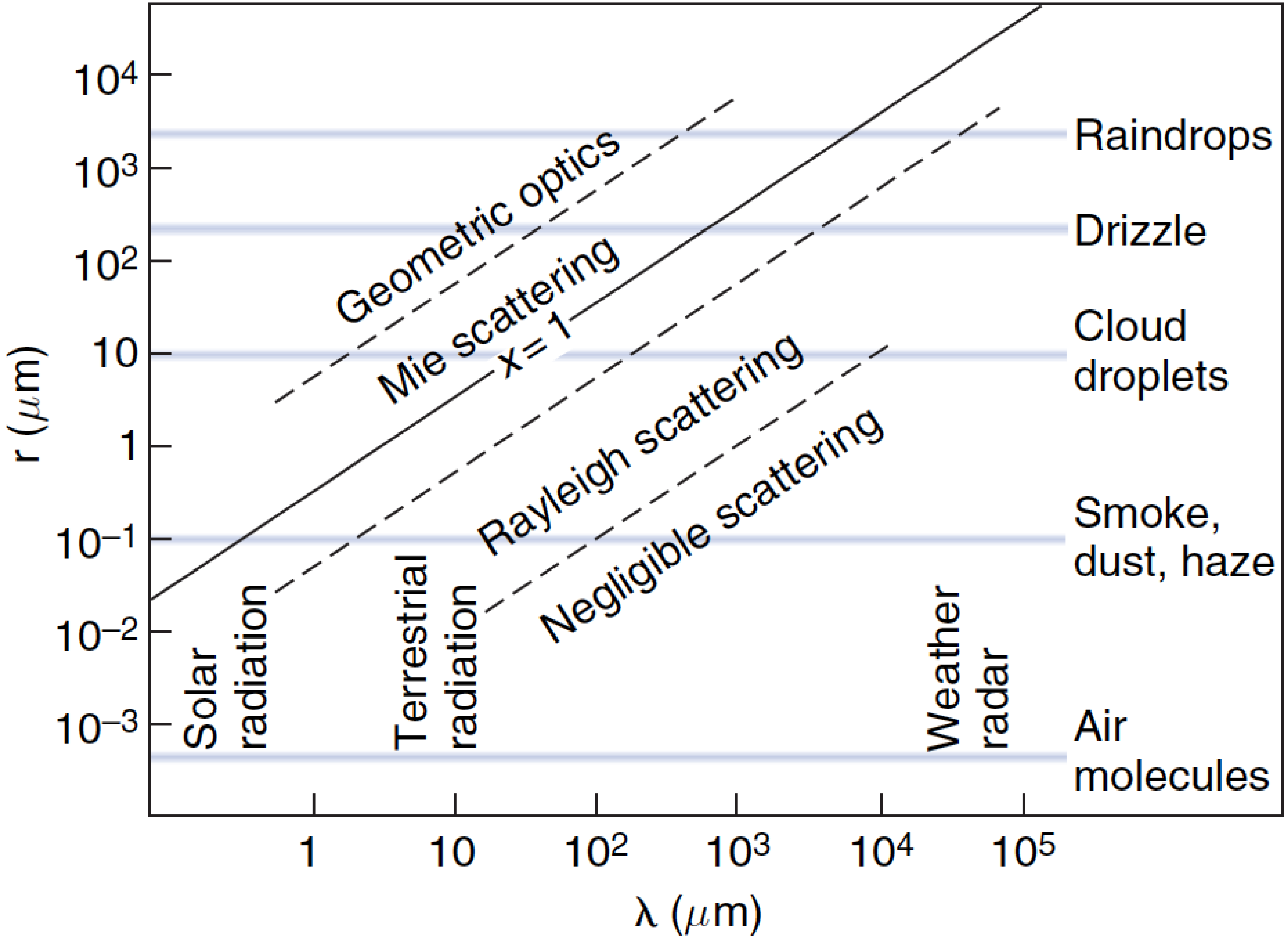


Fig. 4.12: Direction probability of scattering. The phase function describes how much light is scattered in each direction.

Scattering regimes and atmospheric constituents



several mm, heavy precipitation

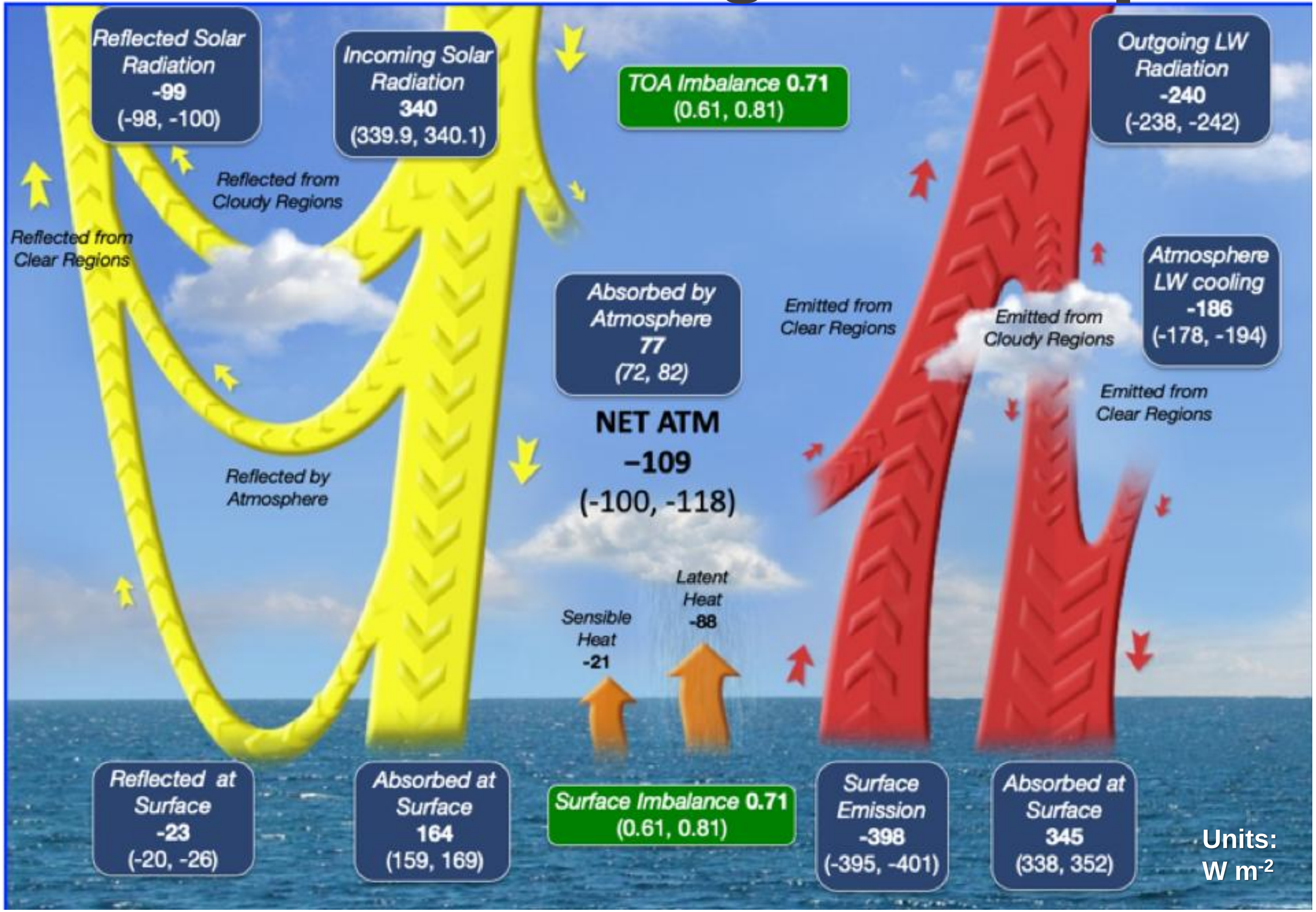
mm

10 – 1000 μm

~100 nm

< 1 nm

Radiative transfer through the atmosphere



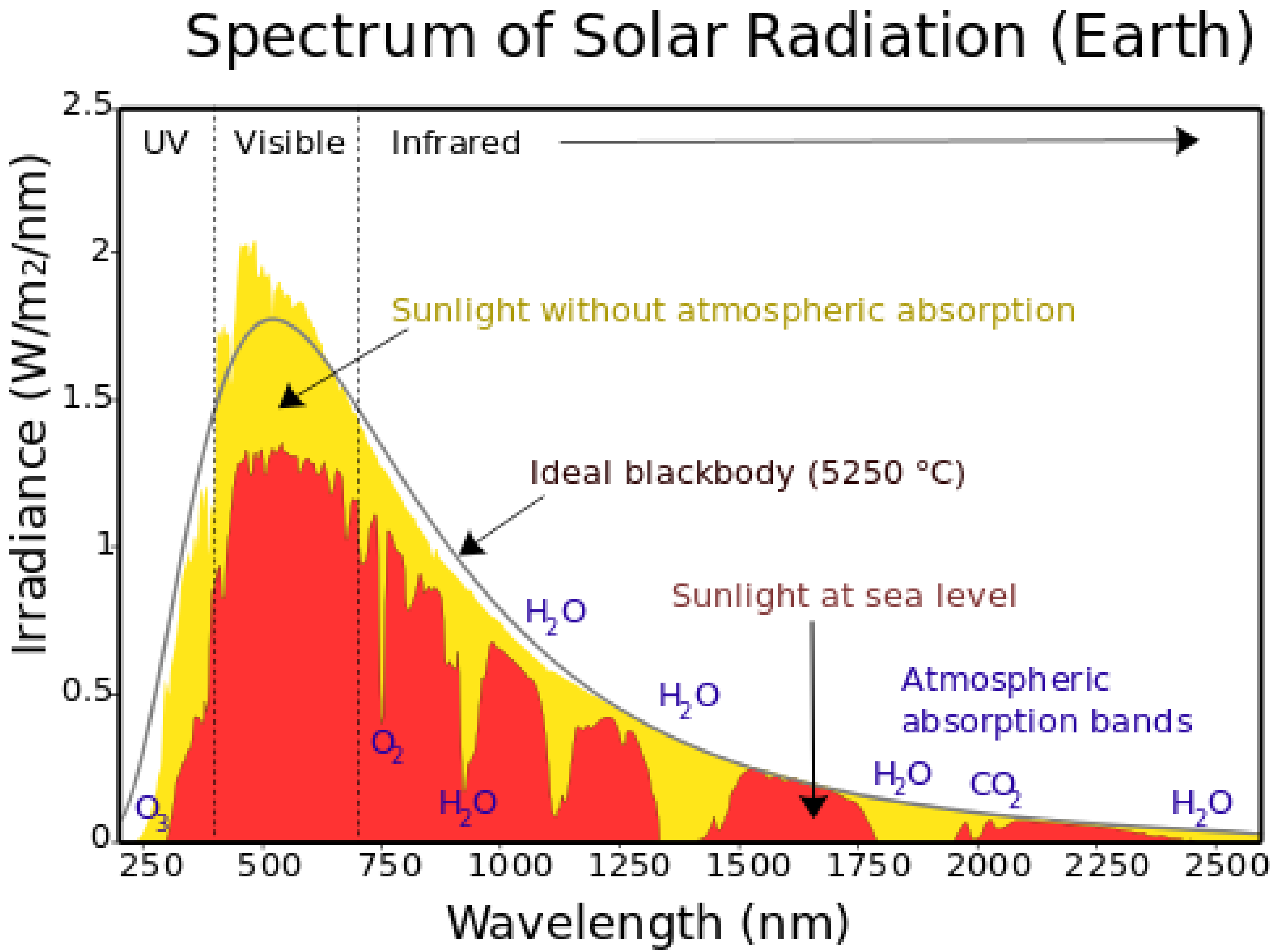
Absorption and scattering (reflection)

Absorption and re-emission

Surface has a net positive imbalance, atmosphere a net negative, that is globally averaged.
Need sensible and latent heat process to equilibrate.

https://ceres.larc.nasa.gov/science/

Absorption by atmospheric gases



Absorption continua

Lyman-α: Hydrogen electron falls from energy level n=2 (orbital) to n=1 and emits radiation in space (deeper radiation penetration into atmosphere)

Radiation interaction: absorption (scattering, emission) in quantities of photons. Photons contain energy:

$$E = h\tilde{\nu}$$

h Planck constant (6.626*10^{-34} Js)

Absorption continua in x-ray and UV range caused by:

- Photoionization (remove electrons from atoms, extreme ultraviolet $\lambda \leq 0.1\ \mu m$, happens in ionosphere)
- Photodissociation (break molecules, ultraviolet $\lambda \leq 0.31\ \mu m$, happens down to stratosphere, O_2 breakup important of O_3 production)

→ energy is converted into kinetic energy (temperature increase of gas).

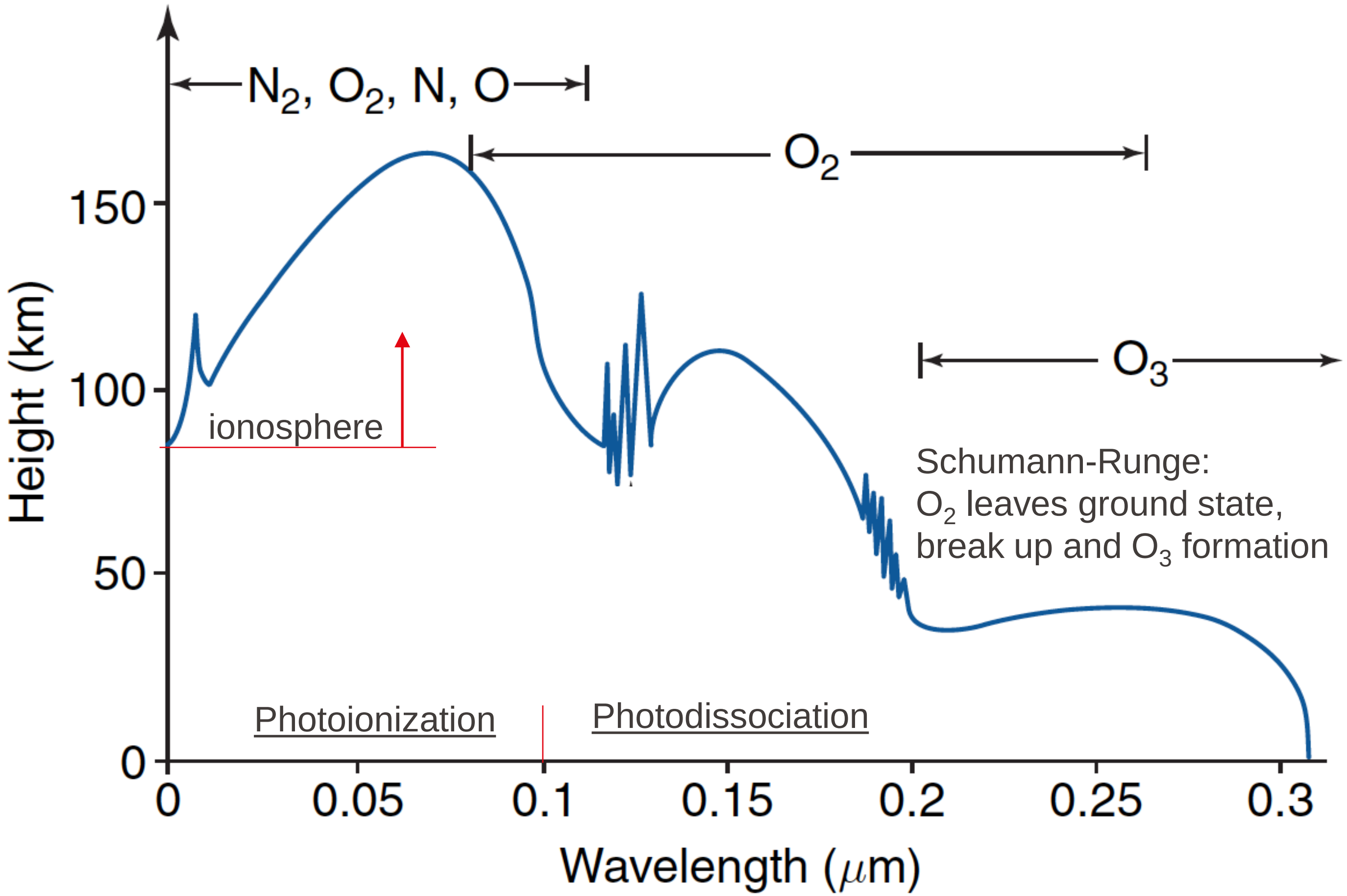
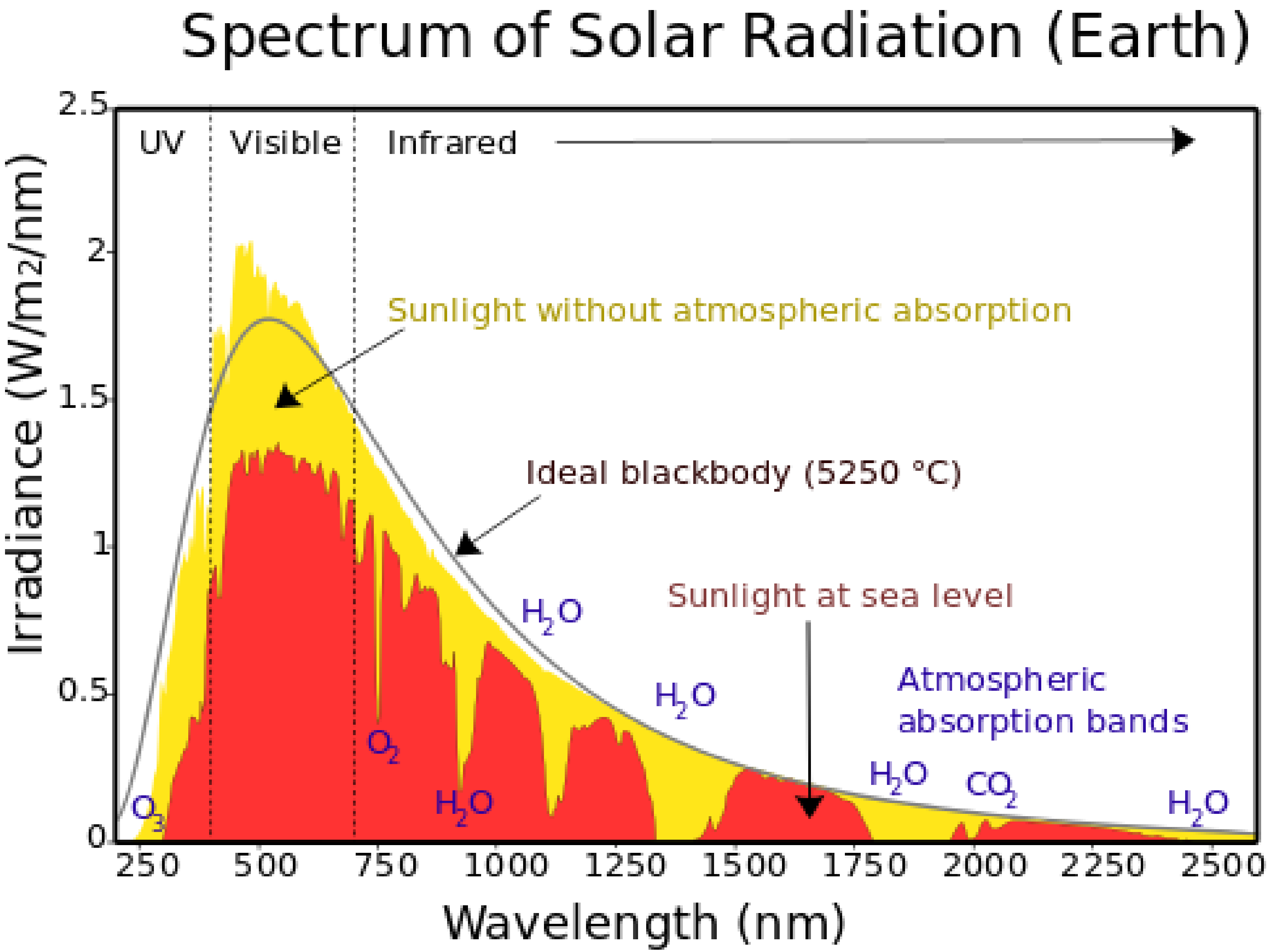


Figure 4.20: depth of penetration of solar UV radiation

Depletion of UV radiation in atmosphere!

Absorption by atmospheric gases

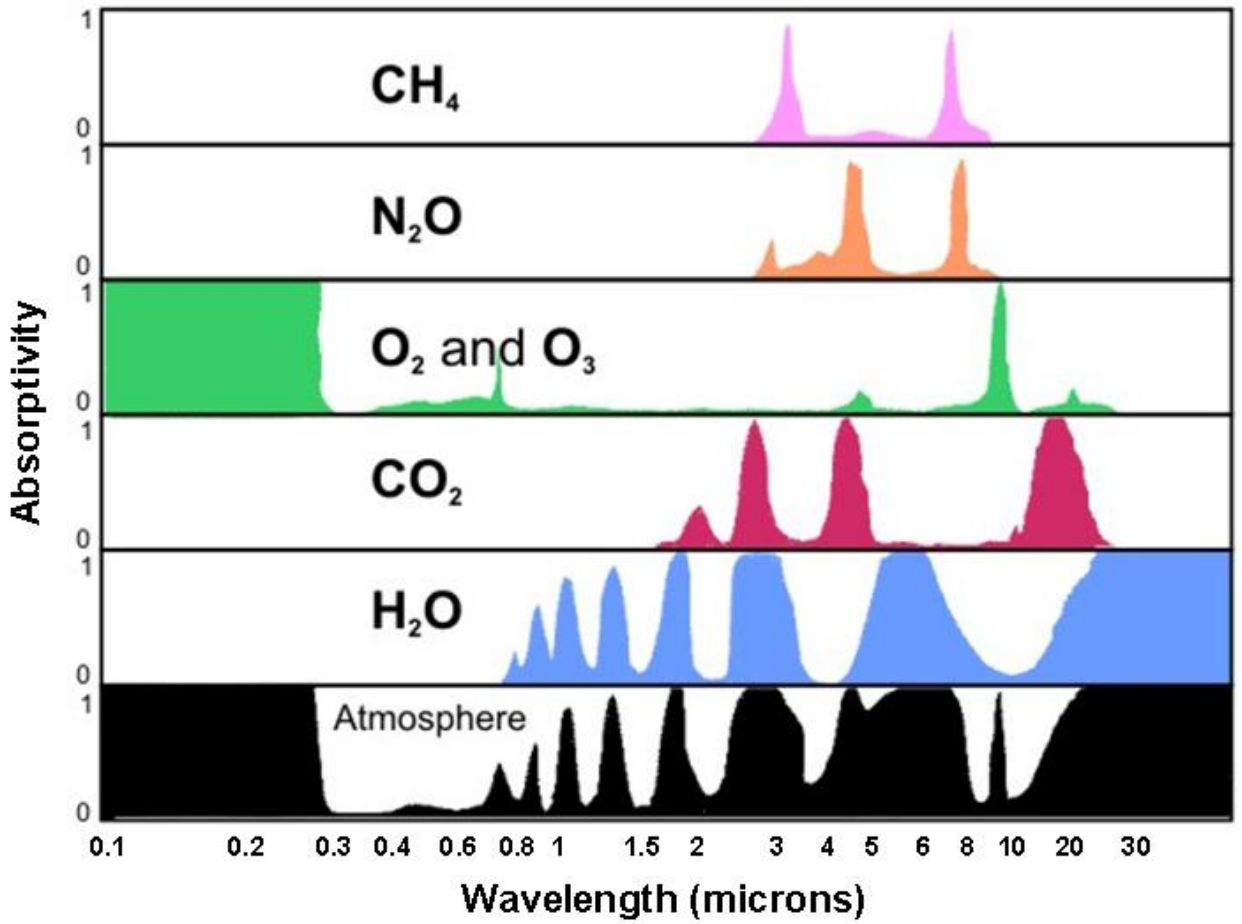


Absorption by gases

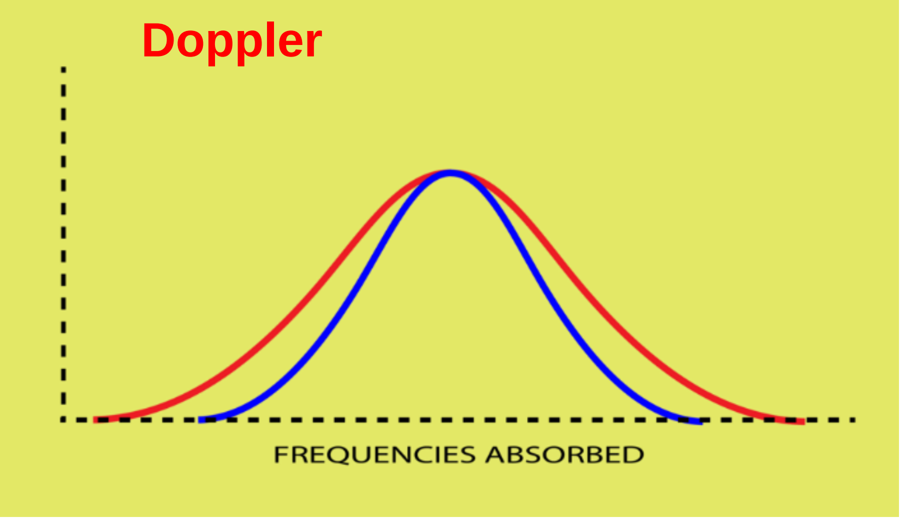
Absorption lines, mostly in visible and infrared spectrum, caused by internal energy state of gas molecule, only discrete energy transitions are possible.

$$E = E_0 + E_v + E_r + E_t$$

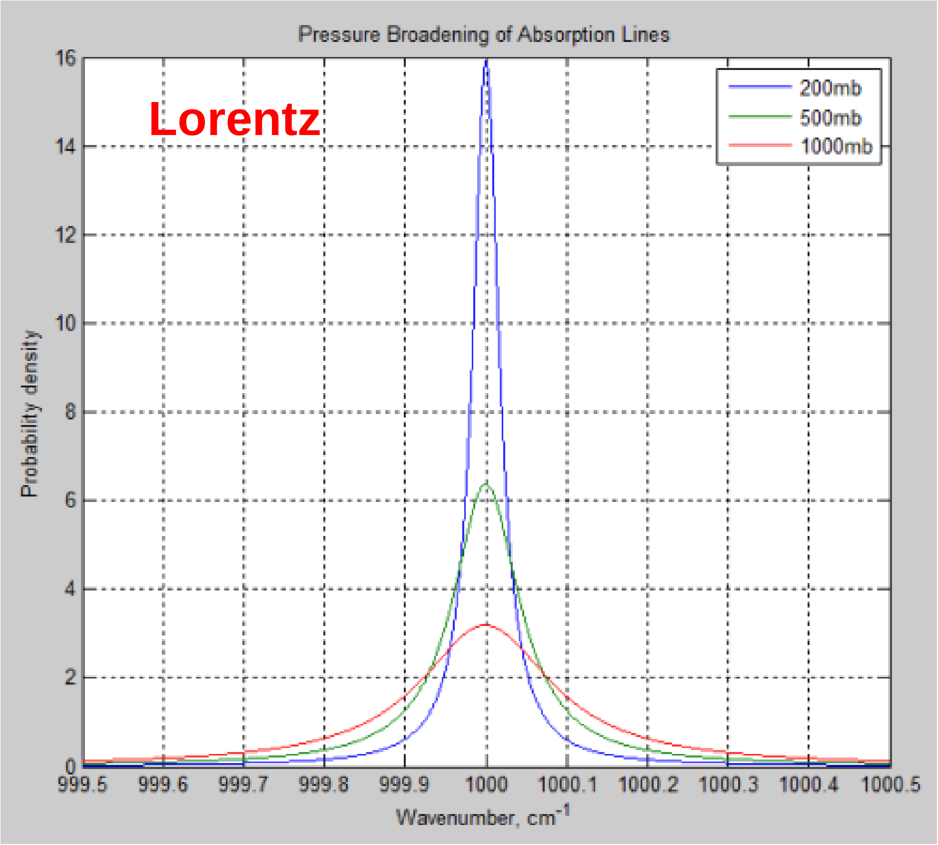
E_0 Energy level of orbits
E_v vibrational energy level
E_r rotational energy level
E_t translational energy (random motion)
.



Line Broadening



As a beam of light passes through an atomic vapor, the atoms will absorb a certain range of the beam's frequencies. The range depends on the velocity distribution – that is, on the temperature. **Atoms at lower temperatures (blue curve)** absorb fewer frequencies than at **higher temperatures (red curve).** This phenomenon, called **Doppler broadening (temperature effect)**, can be measured spectroscopically and thus can serve as a thermometer.

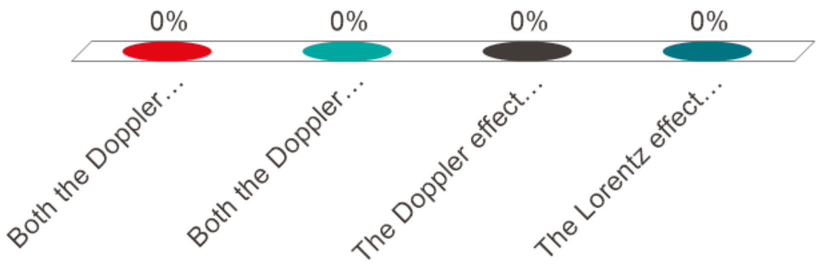


In addition there is the Lorentz effect (pressure effect): molecules collide with each other and change energy levels. Depends on density and temperature.

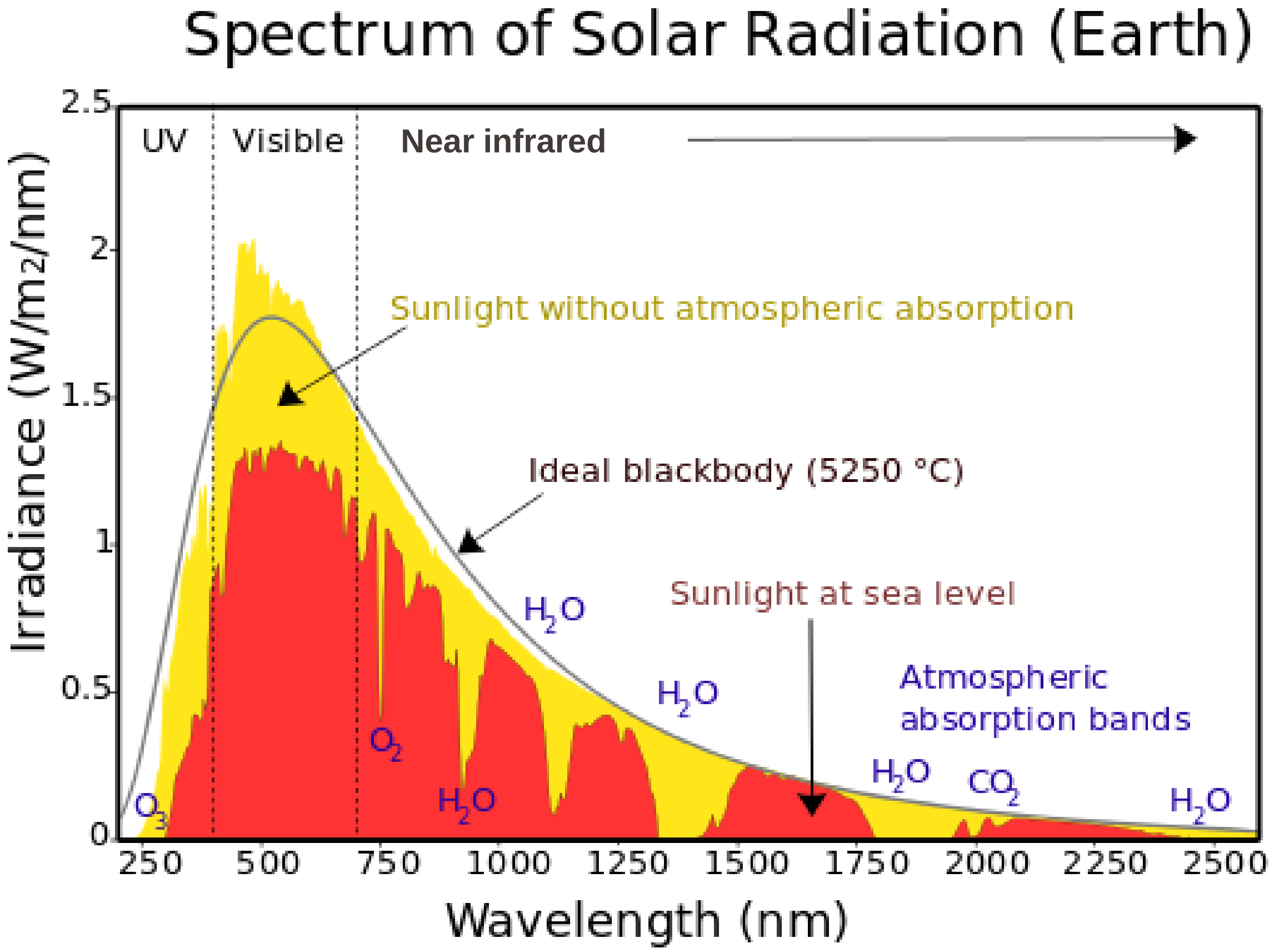
https://www.nist.gov/image/dopplerbroadeningpng

Relevance of Doppler and Lorentz effects

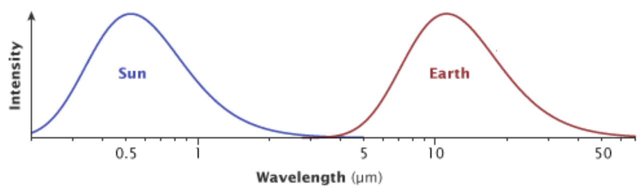
A. Both the Doppler and Lorentz effects are larger in the lower atmosphere.
B. Both the Doppler and Lorentz effects are larger in the higher atmosphere.
C. The Doppler effect is more important in the upper atmosphere.
D. The Lorentz effect is more important in the upper atmosphere.



Absorption by gases



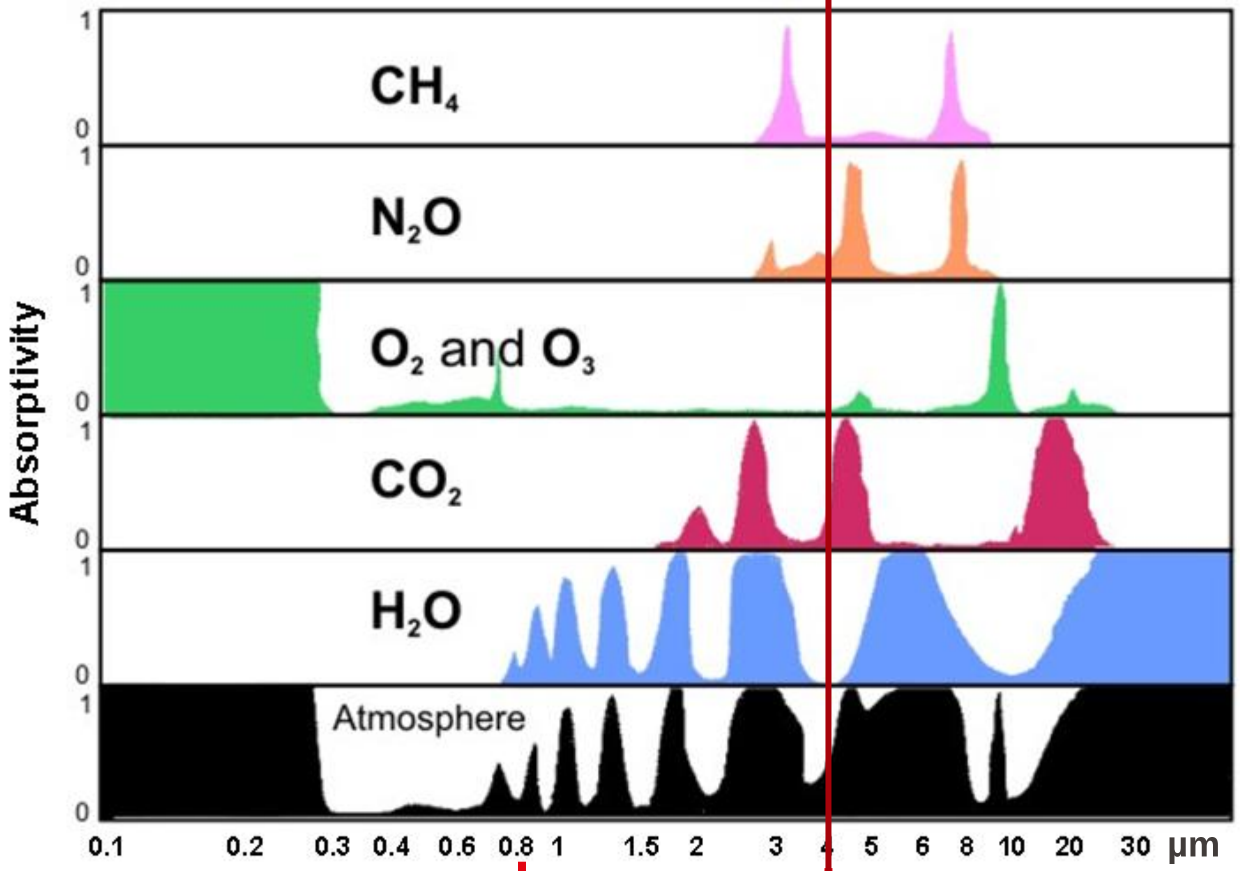
And here?



- https://www.e-education.psu.edu/meteo300/node/686

Absorption by gases

Strong absorption by greenhouse gases!



UV-visible | near infrared | thermal infrared

terrestrial radiation