Climate theory – Nili Harnik
Class 2- Energy Balance

1st law of thermodynamics: $dQ=dU-dW$

dQ - amount of heat added
dU - change of internal energy
dW – work extracted from the system

Energy balance of the Earths system:

$dU=0$ for mean climate
(ignore the temporal climate variations we discussed last class)

$dW=0$ The work done by the Earth on its environments is small.

Energy balance : $dQ=0$

Heat gets transferred through **radiation, conduction or convection**

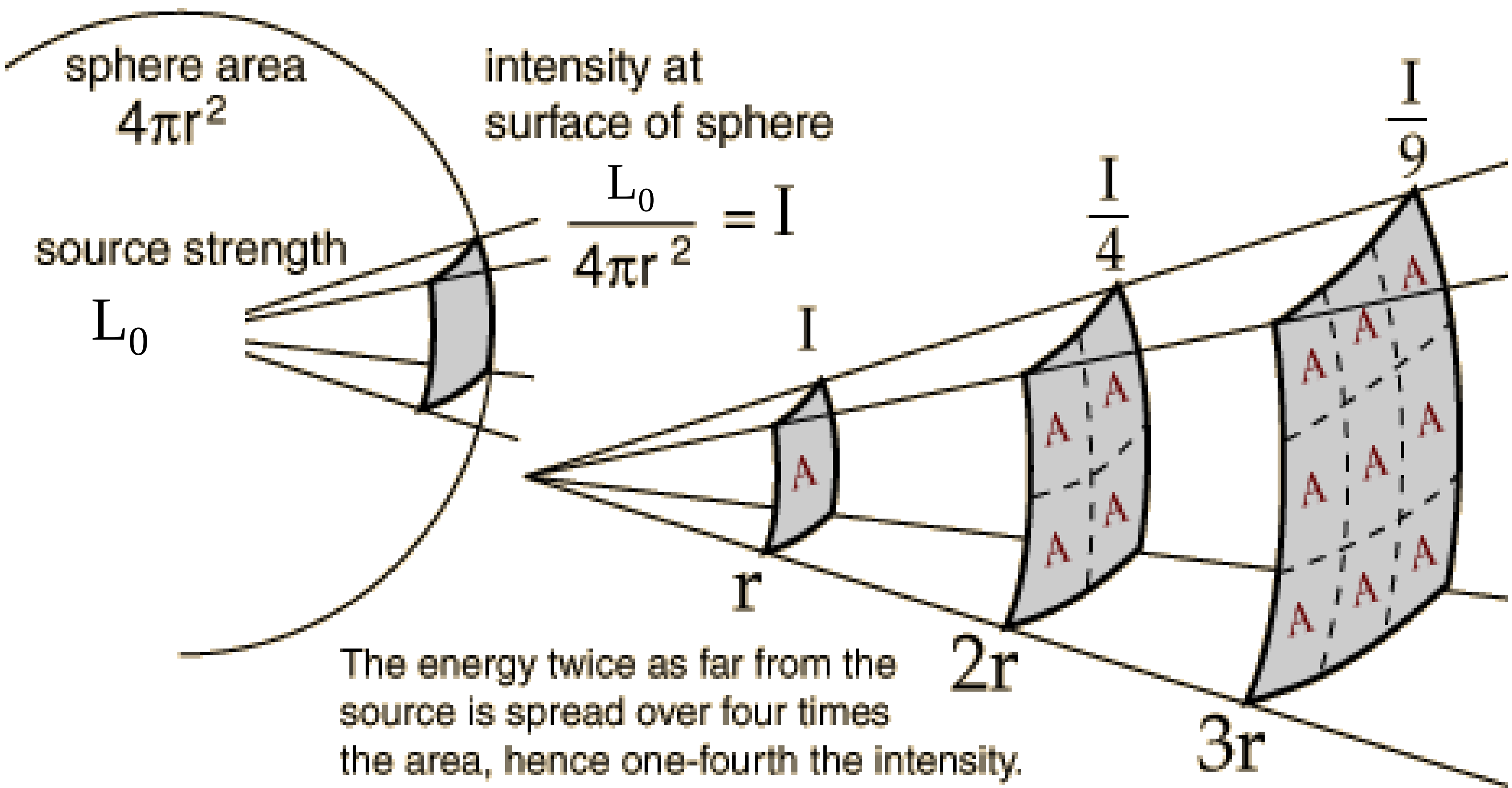
Sun: heated by its own internal energy source, cooled by radiating this energy away (sunlight, solar radiation)

Earth: heated by absorbing sunlight, cooled by radiating this energy away (terrestrial radiation)

Power - the rate at which energy is transferred, used, or transformed (SI units: Watts)

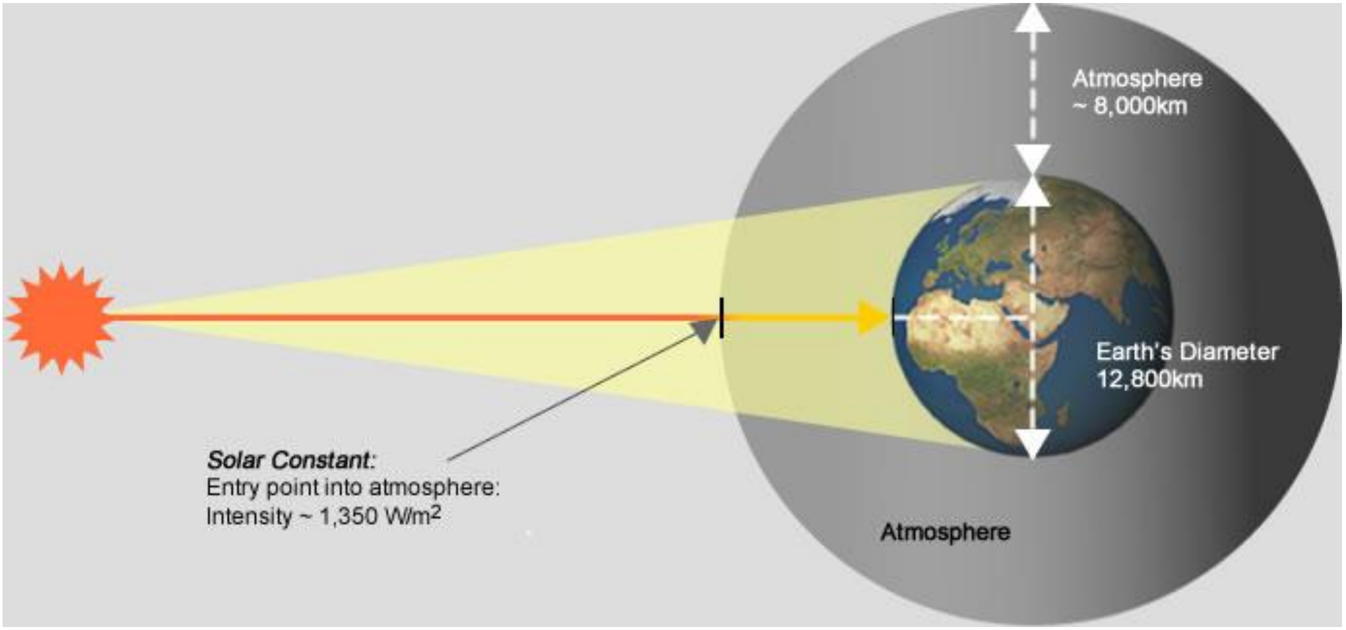
Irradiance - the power per unit area "hitting" a surface (Energy flux, Watt/m^2

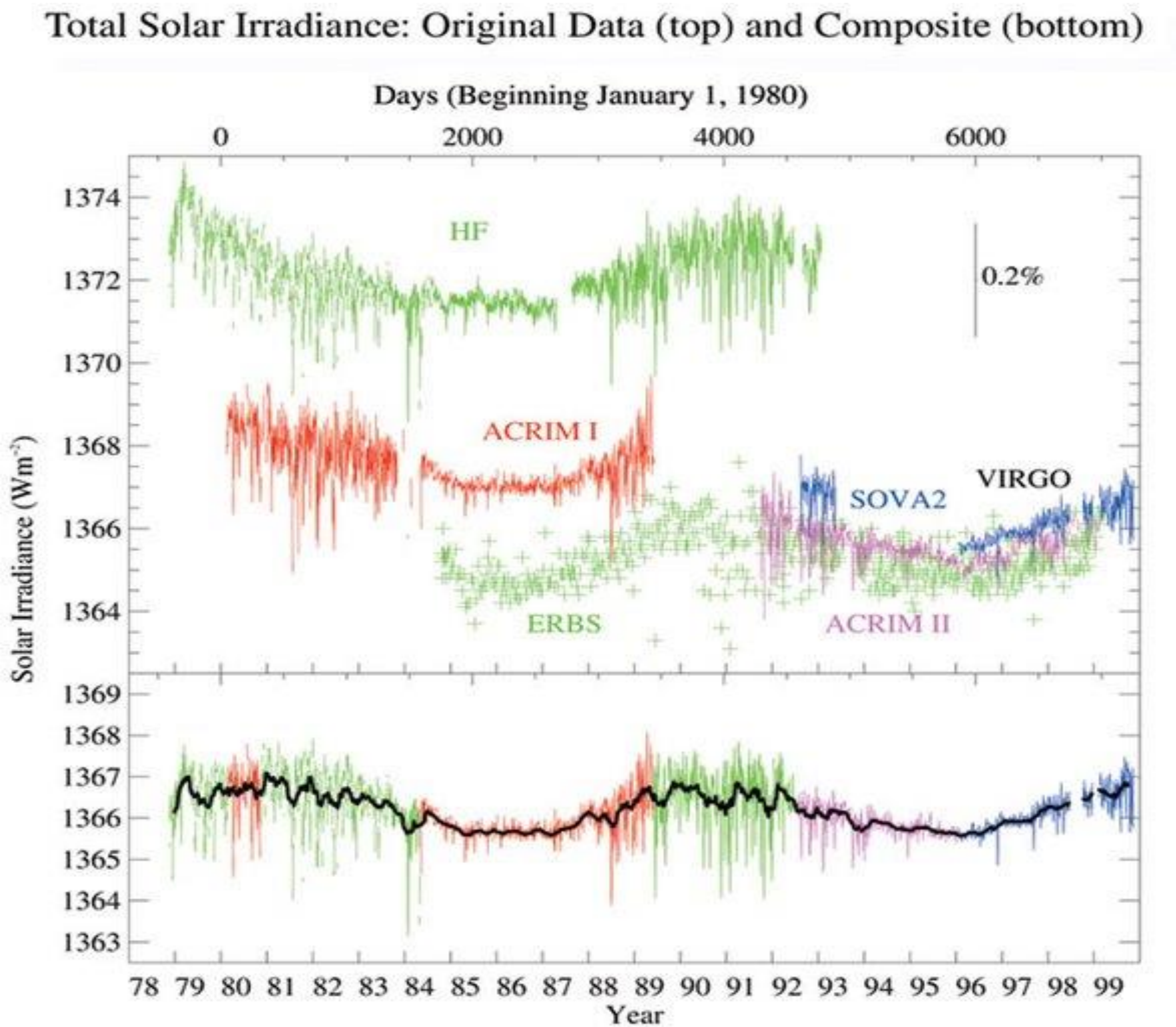
The solar flux decreases as inverse the distance from the sun.



The suns's total energy output: $L_o = 3.9 \times 10^{26}$ W

At the top of the Earth's atmosphere, the flux is called **the solar constant**: S_{Ea} = 1367 W/m^2





Measurements of solar output at top of atmosphere, from 6 independent space-based radiometers since 1978 (top). This data has been re-calibrated and combined to produce the composite total solar irradiance graph (bottom). (Data Source: NASA - SOHO)

Solar flux reaching some of the other planets:

Distance from the sun (million km)

Mercury- 58

Venus- 108 — $S_{Ve} = S_E\ (150/108)^2 = 2637\ W/m^2$

Earth- 150 — $S_E = 1367\ W/m^2$

Mars- 227 — $S_{Ma} = S_E\ (150/227)^2 = 597\ W/m^2$

Jupiter- 773

Saturn- 1418

Uranus- 2853 — $S_{Ur} = S_E\ (150/2853)^2 = 4\ W/m^2$

Neptune- 4497

Blackbody Radiation

Planck's Law – relating the spectral irradiance E(λ,T) to temperature T and wavelength λ

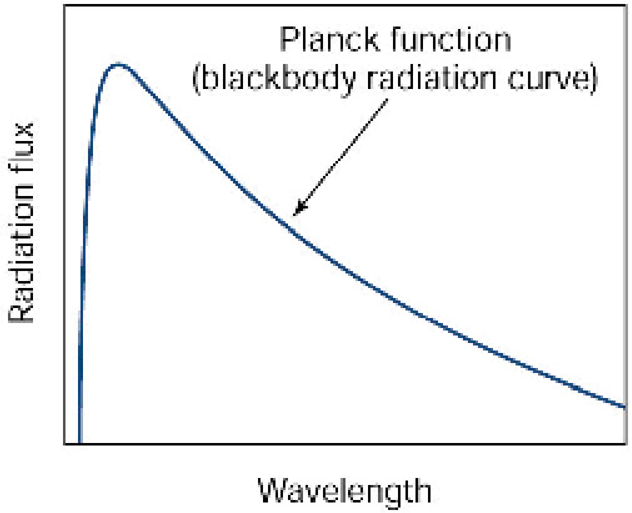
$$E(T,\lambda) = \frac{C_1}{\lambda^5\left[e^{C_2/\lambda T} - 1\right]}$$

E(λ,T) – spectral irradiance $W/m^2/m$

C_1, C_2 - constants

λ - the wavelength

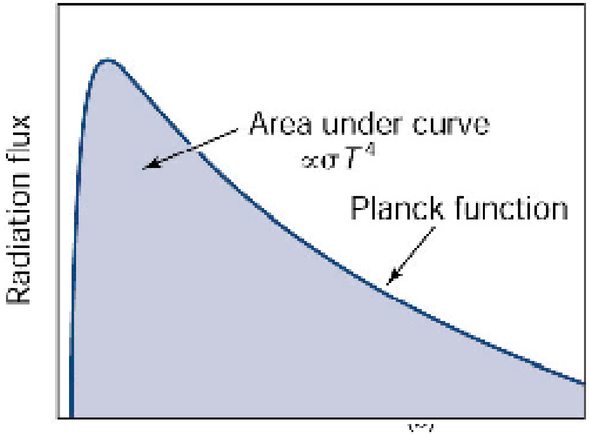
T - the absolute temperature in K.



Blackbody Radiation

Stefan-Boltzmann Law: relates the total energy flux F to absolute temperature T

$$F(T) = \sigma T^4$$



F

$\sigma = 5.67 \cdot 10^{-8}$ W/m²/K⁴ Stefan-Boltzmann constant

T - the absolute temperature in K

Irradiance at Sun's Photosphere

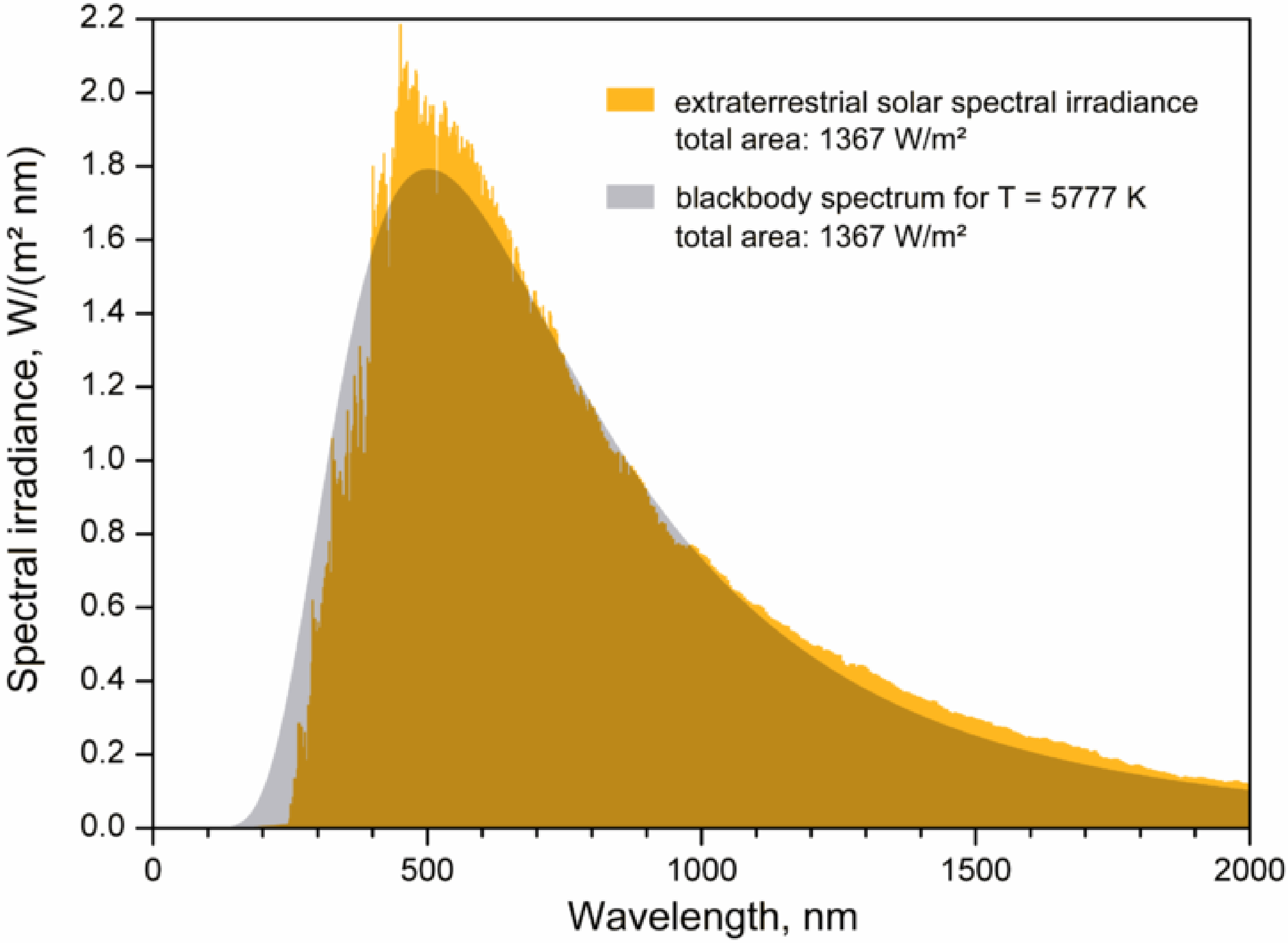
- The radius of the Sun's photosphere is about 6.96 x 10^8 m

$$Irradiance_{Photosphere} = \frac{L_0}{4\pi r_{photosphere}^2} = \frac{3.9\times10^{26}\,W}{4\pi\left(6.96\times10^{8}\,m\right)^2} = 6.4\times10^{7}\,Wm^{-2}$$

- The emission temperature, if the sun was a black body would be,

$$Irradiance = \sigma T_e^4$$

$$T_e = \sqrt[4]{\frac{Irradiance}{\sigma}} = \sqrt[4]{\frac{6.4\times10^{7}\,Wm^{-2}}{5.67\times10^{-8}\,Wm^{-2}K^{-4}}} = 5796K$$

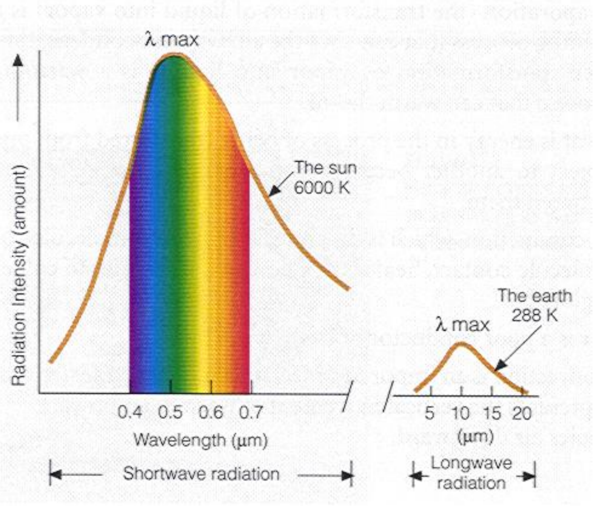


extraterrestrial solar spectral irradiance
total area: 1367 W/m²
blackbody spectrum for T = 5777 K
total area: 1367 W/m²
Spectral irradiance, W/(m² nm)
Wavelength, nm
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
0
500
1000
1500
2000

Blackbody Radiation

Wein's law: relates the wavelength of maximum emission λ_{max} to the absolute temperature T:

$$\lambda_{max} = \frac{2898}{T}$$



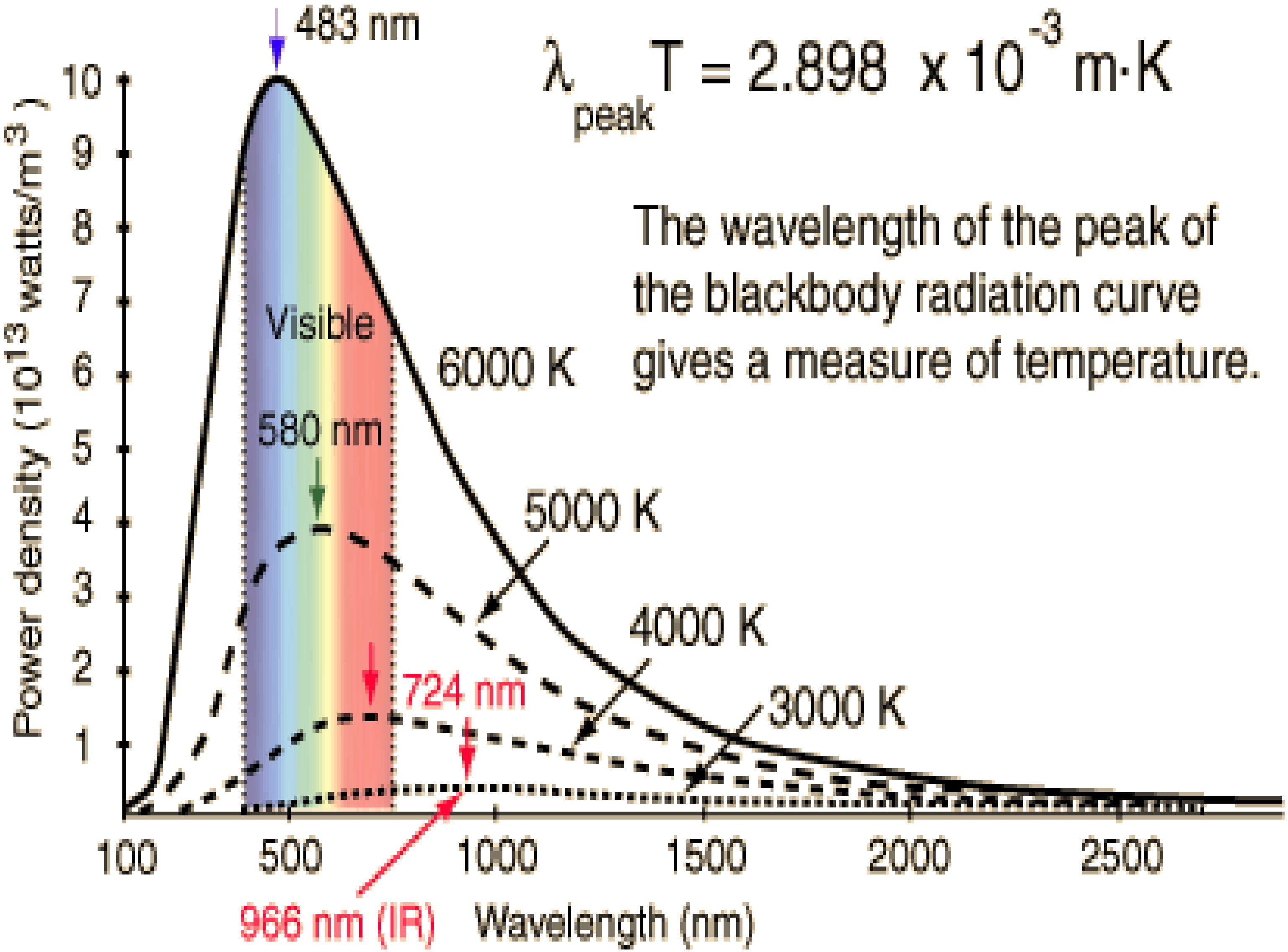
λ_{max} - wavelength in microns

T - the absolute temperature in K.

Sun: T=5796K → λ_{max} = 0.5 microns (Green light)

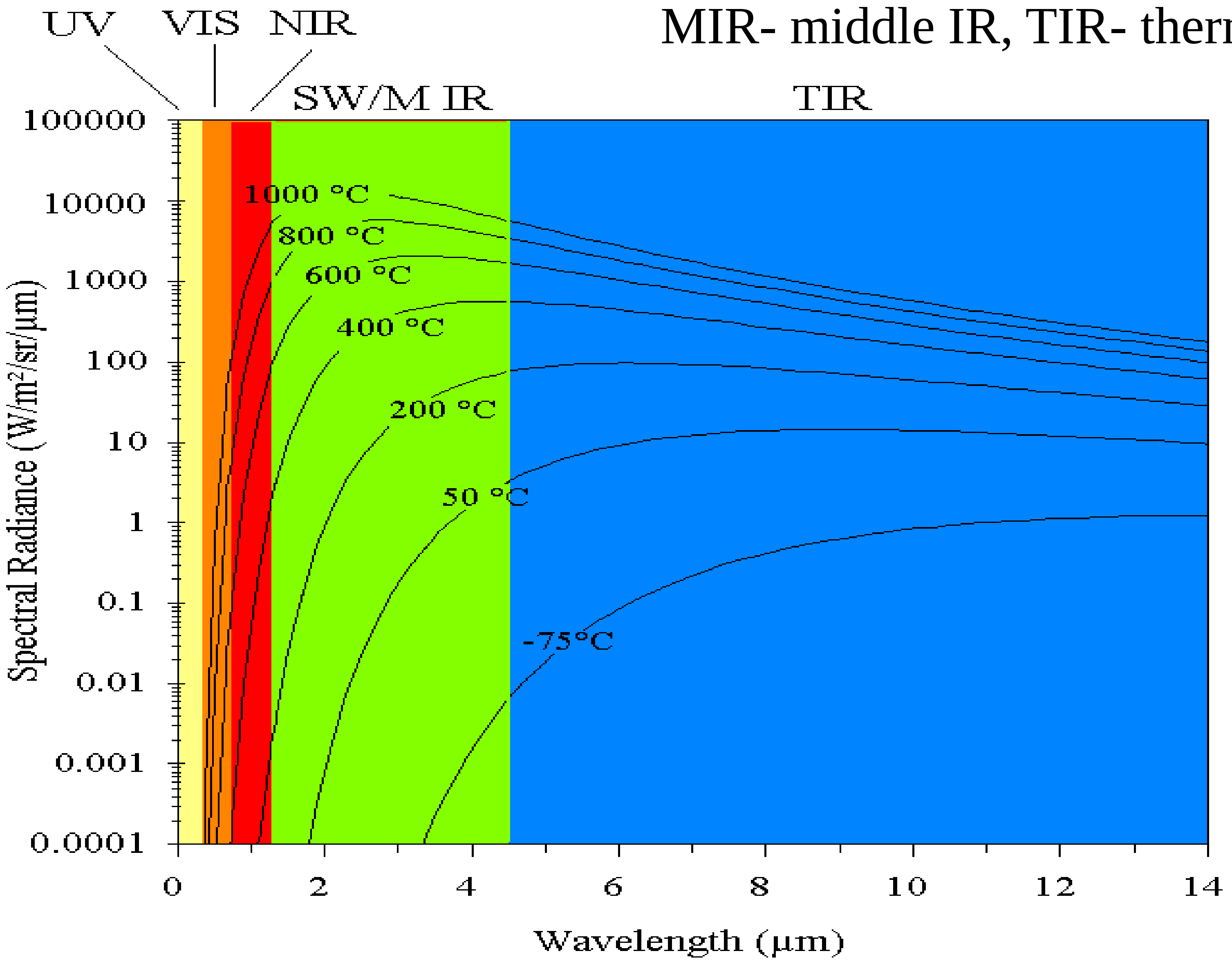
Note- atmosphere scatters blue light so sun appears yellow

Earth: T=288 K → λ_{max} = 10 microns (Infra Red)



483 nm
$\lambda_{peak} T = 2.898 \times 10^{-3}$ m·K
The wavelength of the peak of the blackbody radiation curve gives a measure of temperature.
Power density (10^{13} watts/m^3)
10
9
8
7
6
5
4
3
2
1
Visible
580 nm
6000 K
5000 K
4000 K
3000 K
724 nm
966 nm (IR)
100
500
1000
1500
2000
2500
Wavelength (nm)

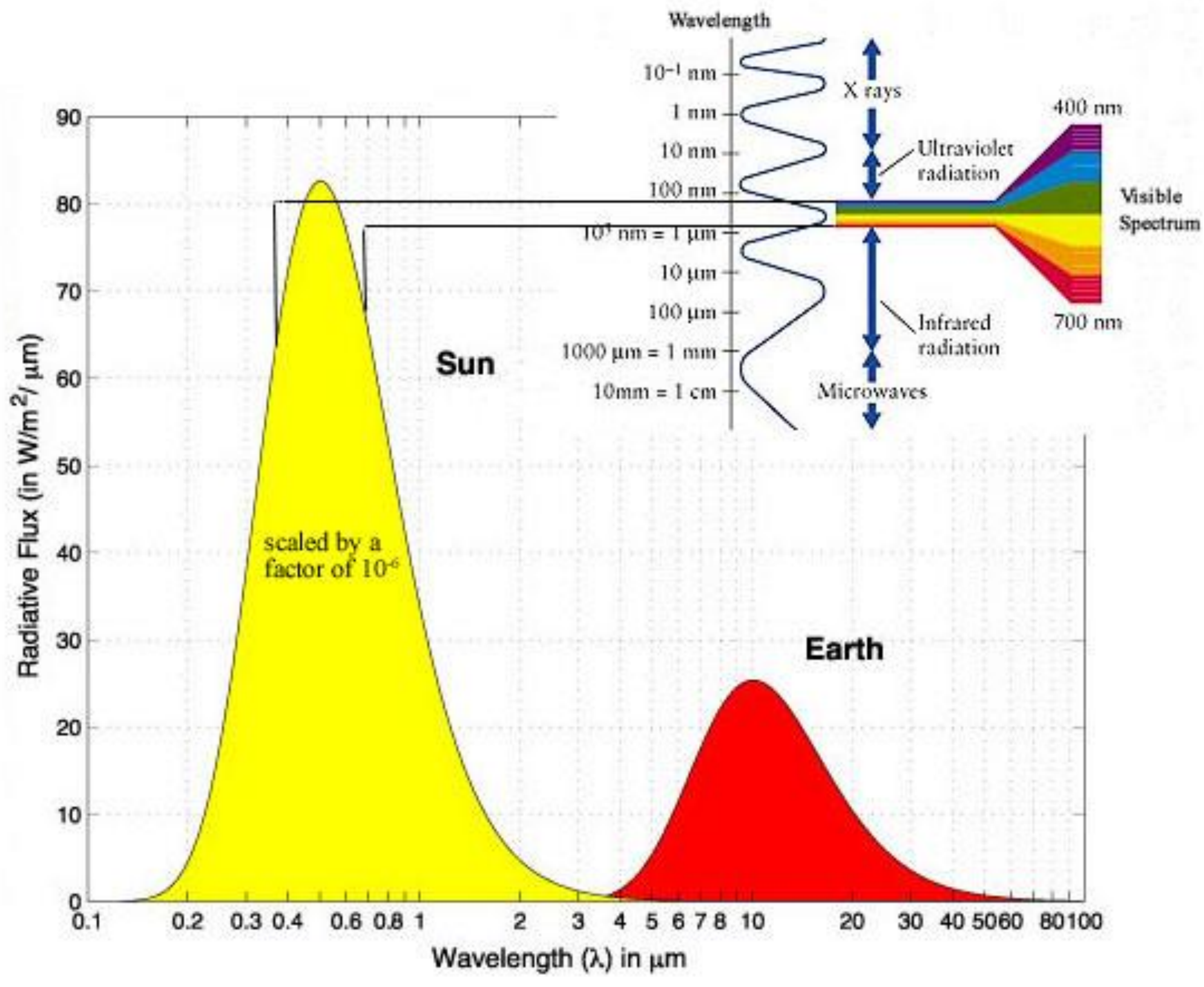
MIR- middle IR, TIR- thermal IR



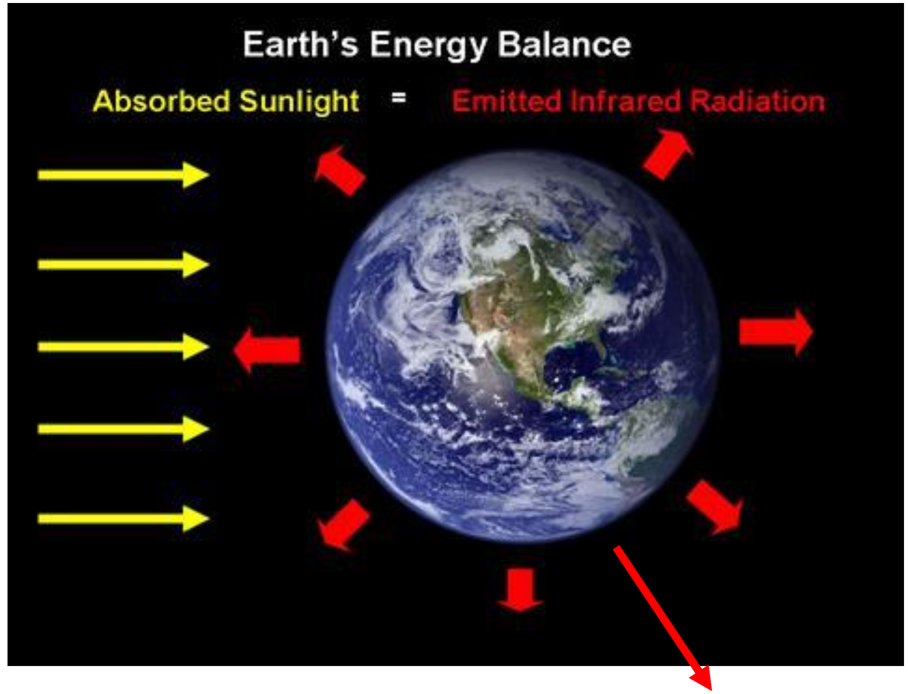
In “climate language” :

Solar radiation – short wave UV 9%, VIS 45%, IR 46%(mostly NIR, some MIR)

Earth radiation – long wave. (mostly TIR, some MIR)



$S_{Ea} = 1367\ W/m^2$



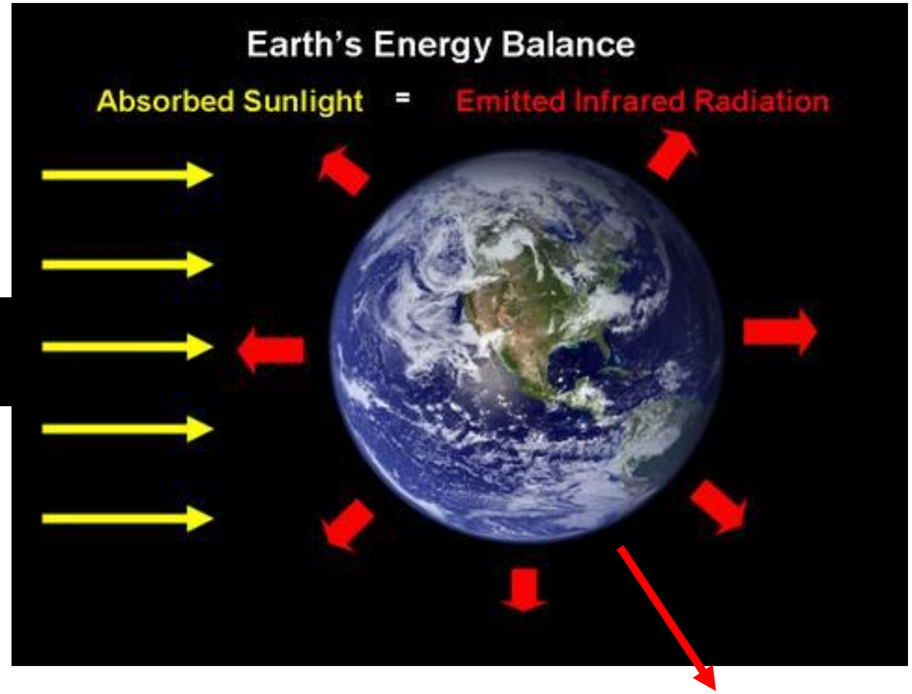
$F_{Ea} = \sigma T^4 \sim 240\ W/m^2$

Energy balance: incoming flux = outgoing flux

How does this work out? Geometric factor

Earth intercepts solar radiation at a disk of area πr_e^2 but the radiation falls on the surface of the entire (rotating) sphere, of area $4\pi r_e^2$. So the daily globally averaged incoming solar flux per unit area of the earth is actually $I = S_{Ea}/4 = 342\ W/m^2$

$S_{Ea} = 1370\ W/m^2$



$F_{Ea} = \sigma T^4 \sim 240\ W/m^2$

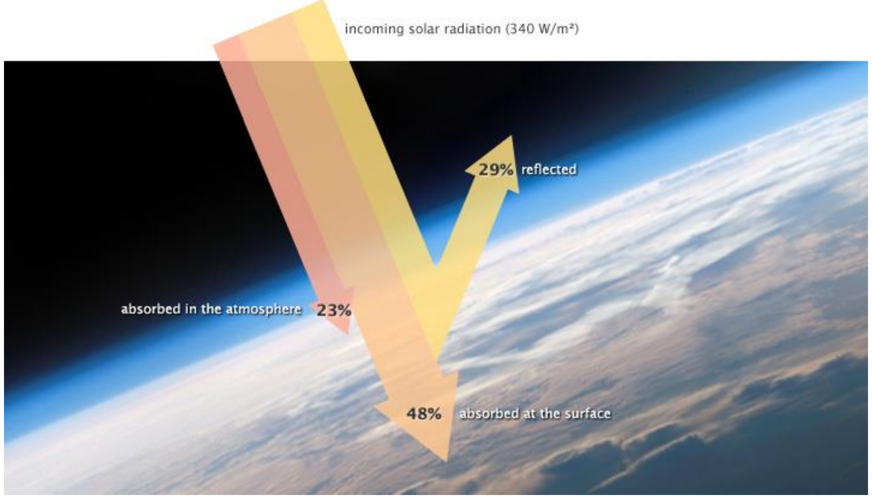
Alternative view:

Total solar energy intercepted by earth: $S_{Ea}\pi r_e^2$

Total terrestrial radiation emitted to space: $F_{Ea}4\pi r_e^2$

→ $I = S_{Ea}/4$

To heat the earth, solar radiation has to be absorbed, but about 30% of the radiation gets reflected back to space, by clouds or the earth's surface.

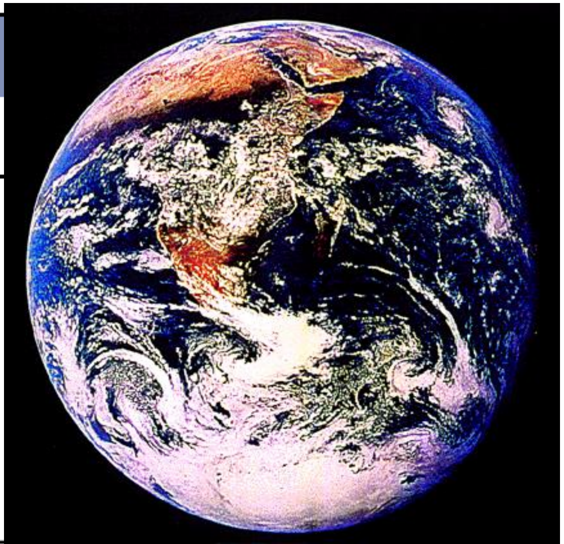


Albedo (α)- the ratio of reflected to incident radiation

TABLE 2-1

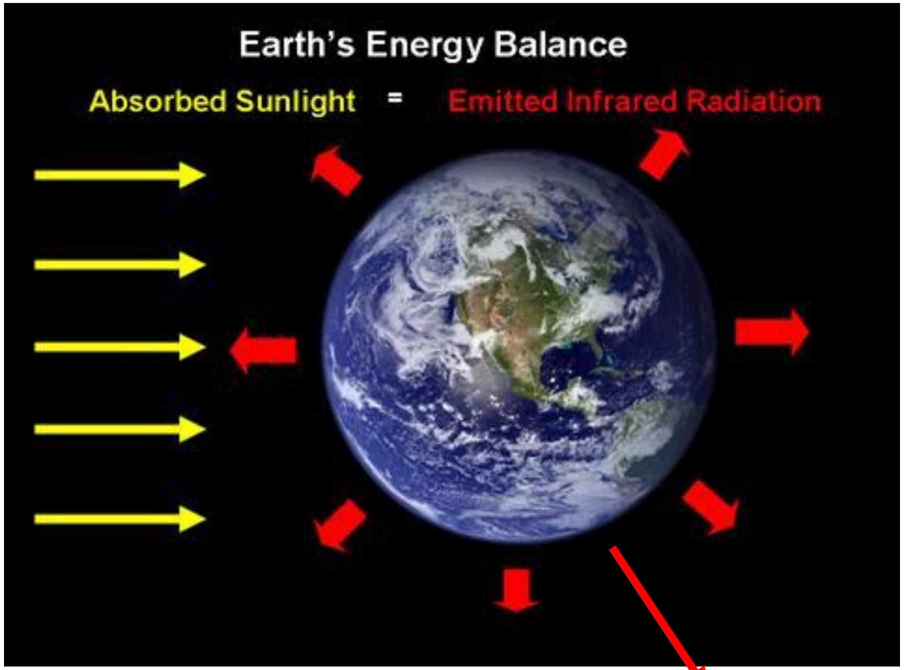
Albedos of Some Common Surfaces

Type of Surface	*Albedo*
Sand	0.20–0.30
Grass	0.20–0.25
Forest	0.05–0.10
Water (overhead Sun)	0.03–0.05
Water (Sun near horizon)	0.50–0.80
Fresh snow	0.80–0.85
Thick cloud	0.70–0.80



Global mean $\alpha \sim 0.3$

S_{Ea} = 1367 W/m^2



$F_{Ea} = \sigma T^4 \sim 240$ W/m^2

Taking this reflection into account:

$I = S_{ea}(1-\alpha)/4 = 240 W/m^2$

The implied effective temperature of the earth:

$$T = \sqrt[4]{\frac{S_{Ea}(1-\alpha)}{4\sigma}} = 255^o K = -18^o C$$

too cold…

Measured surface temperate (T_s) is actually 288 K.
The difference is due to the *natural greenhouse effect*.

This corresponds to a radiative flux of $F_s = \sigma T_s^4$

The *transmissivity* τ of the atmosphere is the ratio between the flux transmitted out to space and that emitted by the surface:

$$\tau = T_e^4 / T_s^4 = 0.61$$

Absorptivity = 1- τ = 39% - the amount of emitted surface radiation absorbed by the atmosphere.

This is done mainly by water vapor, but this picture is too simplistic- lets get a glimpse of the more complex picture

Lets do it for other planets – rough estimates because numbers vary a lot depending on source…
Venus: (470C) a very thick atmosphere of CO_2

$$T = \sqrt[4]{\frac{S_{Ve}(1-\alpha)}{4\sigma}} = \sqrt[4]{\frac{2637(1-0.67)}{4\sigma}} = 249^o K = -24^o C$$

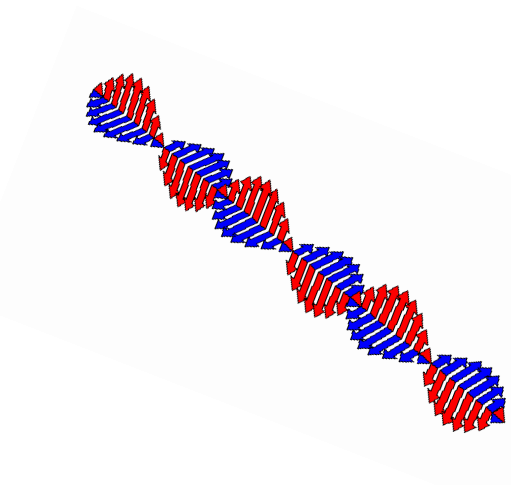
Mars: (Ts=-58C), a very thin atmosphere (0.5% of atmosphere)

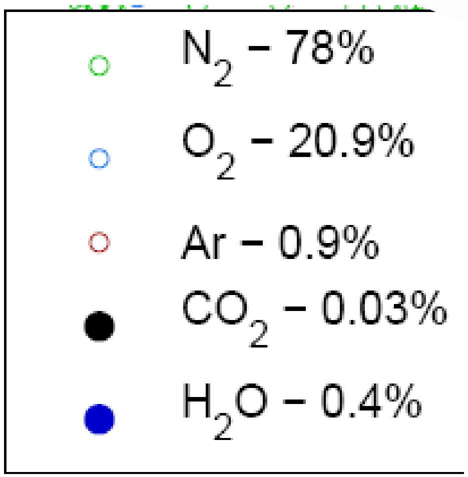
$$T = \sqrt[4]{\frac{S_{Ma}(1-\alpha)}{4\sigma}} = \sqrt[4]{\frac{597(1-0.29)}{4\sigma}} = 207^o K = -65^o C$$

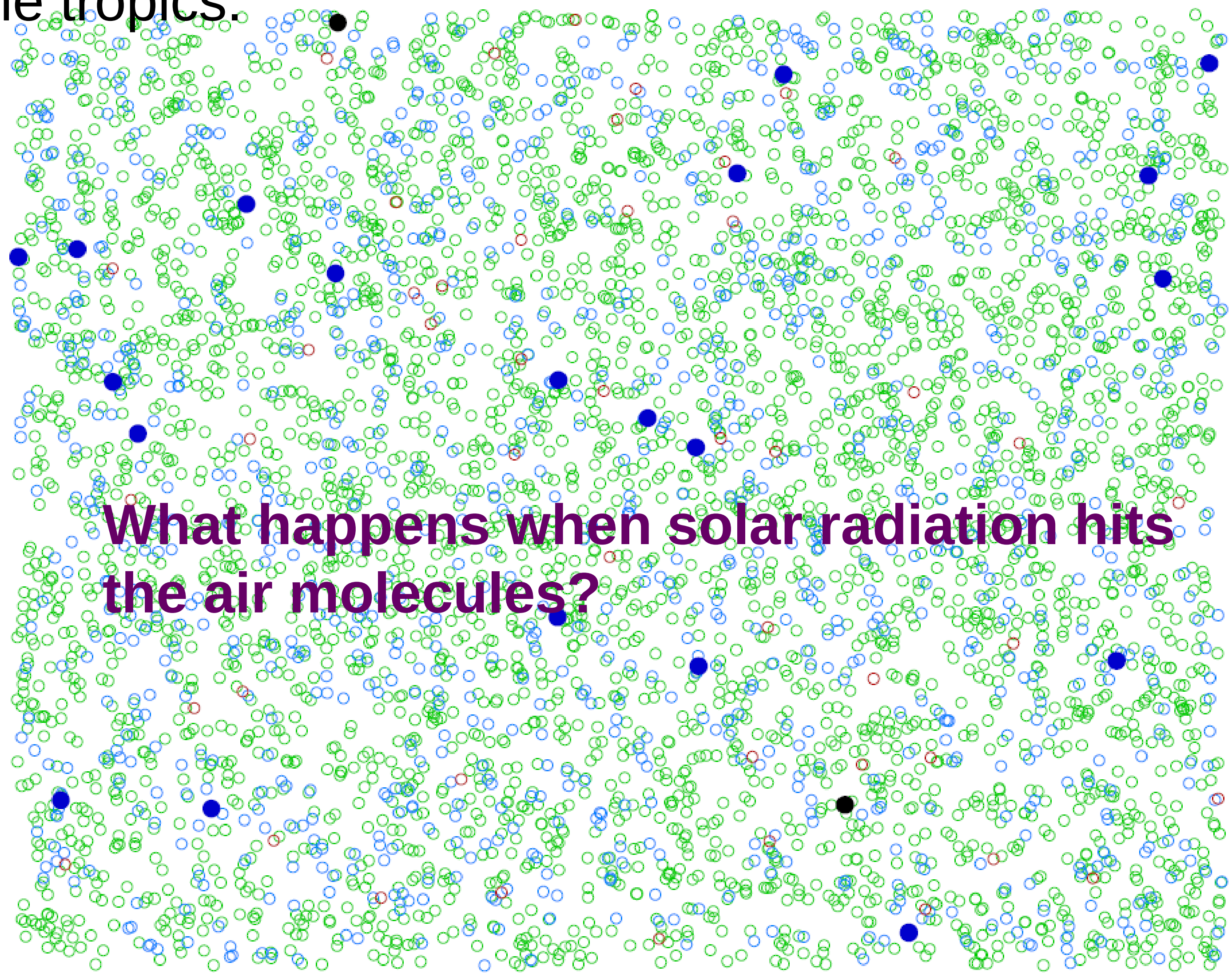
Uranus: (Ts=-200C) gas giant, icy, mostly hydrogen and helium, a bit of methane

$$T = \sqrt[4]{\frac{S_{Ur}(1-\alpha)}{4\sigma}} = \sqrt[4]{\frac{4(1-0.51)}{4\sigma}} = 54^o K = -218^o C$$

The atmosphere is a mixture of molecular Nitrogen and Oxygen, with a bit of Argon, and trace amounts of other gases, like CO_2. Water varies between ~0.4% in very dry air, to ~4% in the tropics.







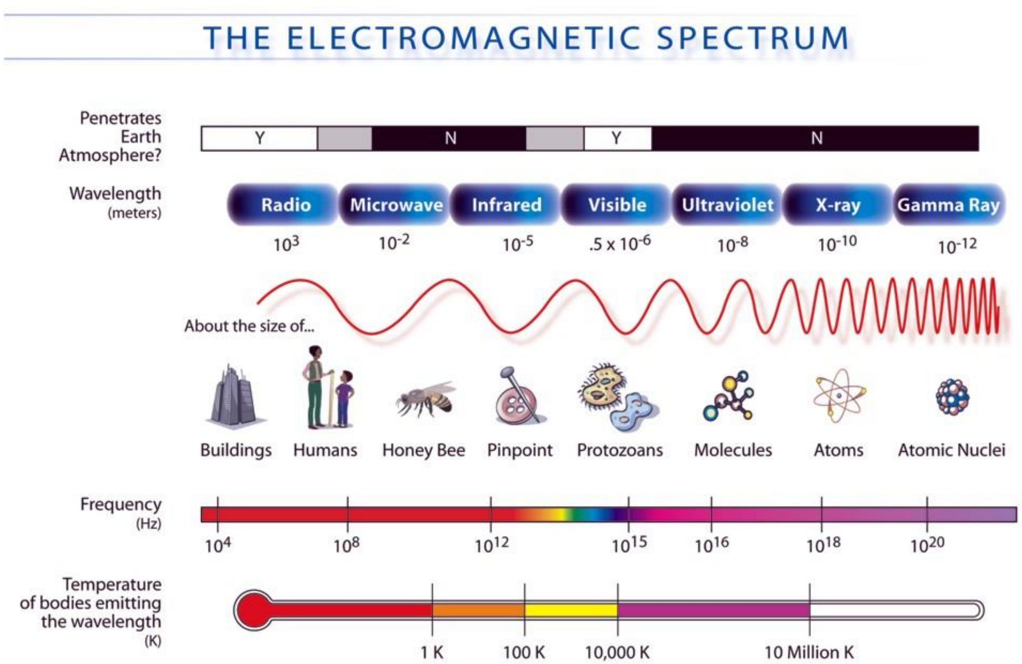
What happens when solar radiation hits the air molecules?

That depends on the type of molecule and radiation

For a given molecule, energy is stored in the bonds between protons and electrons, between atoms, and in the motions of the molecule atoms.

When radiation hits a molecule, it will pass its energy on to the molecule, if the molecule can "contain" this energy

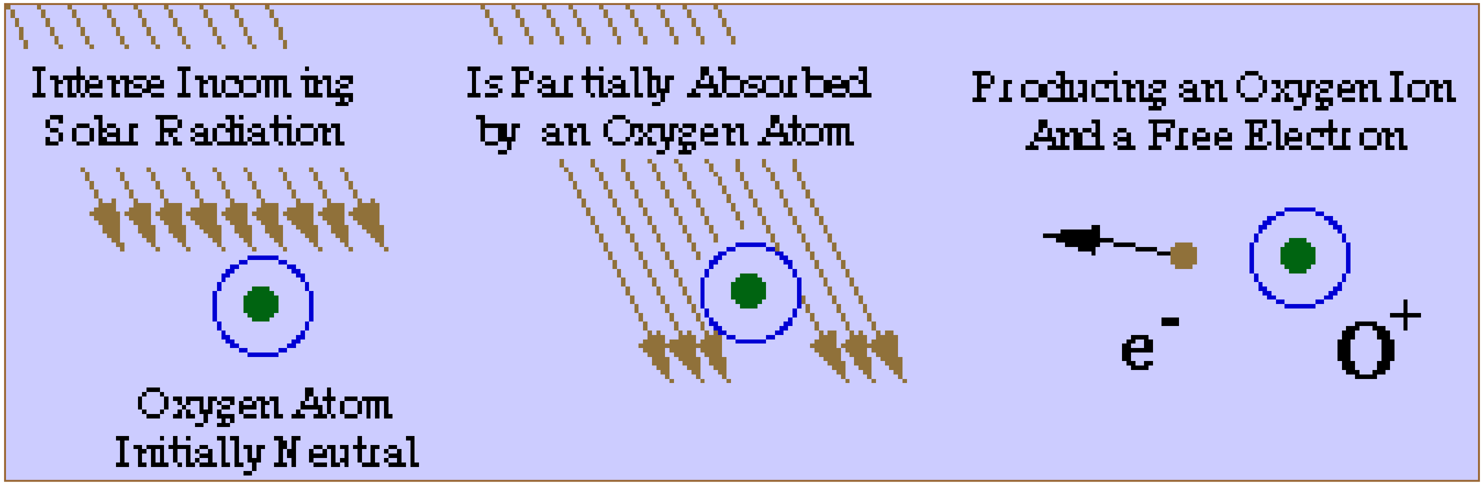
Thus, each mode of energy absorption occurs at a specific band of the solar spectrum. What matters is the wavelength



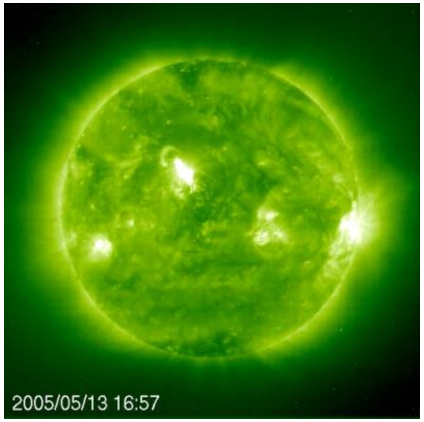
$$\nu = \frac{\Delta E}{h}$$

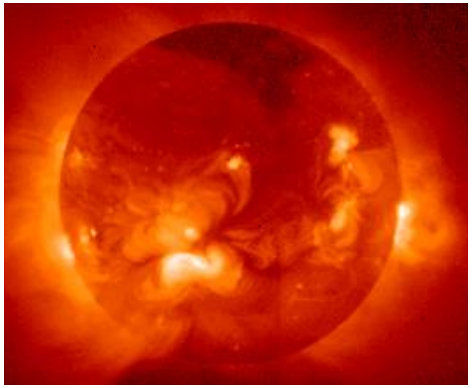
Gamma and X ray radiation, and the most energetic UV radiation can break the bond between the molecule and its electrons, causing **ionization**:

For example: ionization of $O_2 \rightarrow O_2^+$, $N_2 \rightarrow N_2^+$ $O \rightarrow O^+$



Extreme UV image





Xray image

Ionization Energy: after an electron 'jumps' out of the atom/molecule, we are left with an ionized particle. This molecule can now absorb more radiation than otherwise allowed, and it carries this excess energy with it as kinetic energy. There is therefore an 'ionization continuum' (region of continuous absorption) on the high frequency (high energy) side of the ionization frequency.

Occurs in extreme UV:

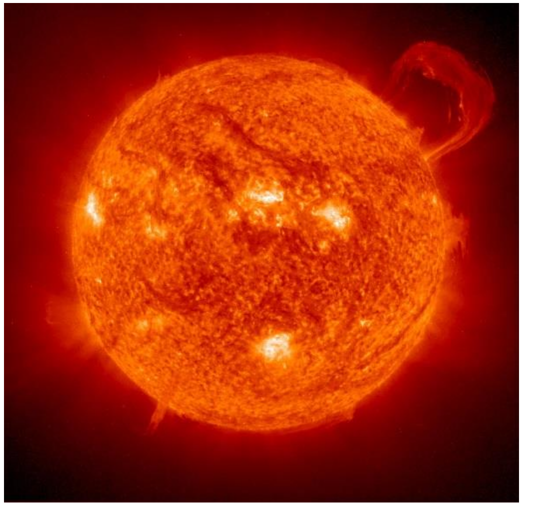
$N_2 \Rightarrow N_2^+$ (700 A) [1 A = 10^{-4} μm]

$O \Rightarrow O^+$ (850 A)

$O_2 \Rightarrow O_2^+$ (1110 A)

All occur, in general, above 100 km altitude For this reason the *ionosphere* occurs above 100 km.

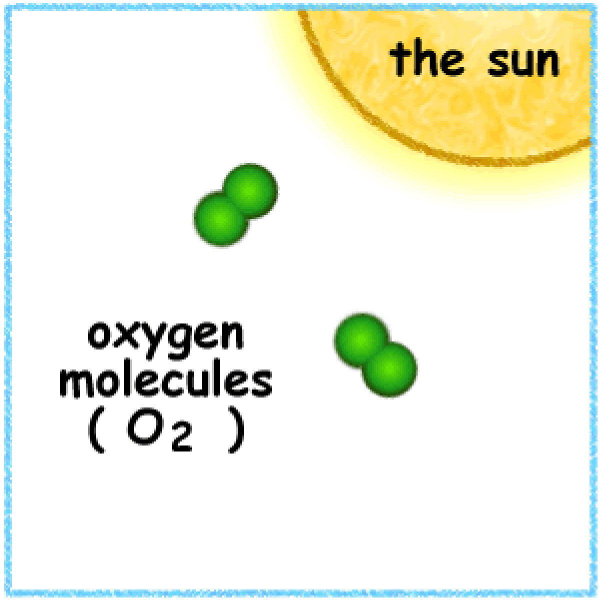
UV radiation can break apart the molecules - **dissociation**



For example, breakup of O_2:

$O_2 + UV = O + O$

$O + O_2 \rightarrow O_3$

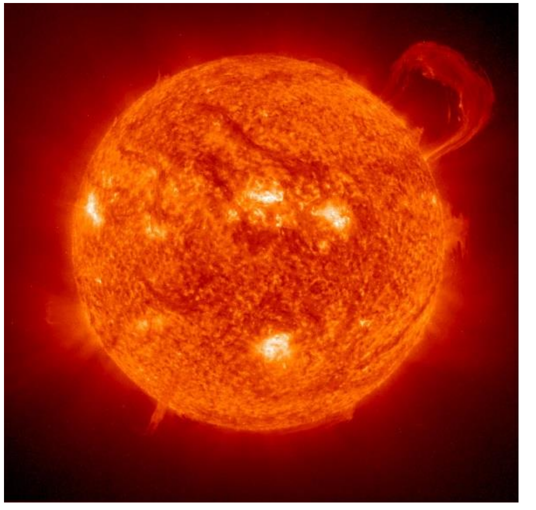


This process occurs when the vibrational energy between the molecules gets too large.

The molecular bond energy is released into molecular motions- temperature rises

Occurs for ($\lambda < 0.24\ \mu m$)

Less energetic UV radiation will break apart Ozone (O_3):

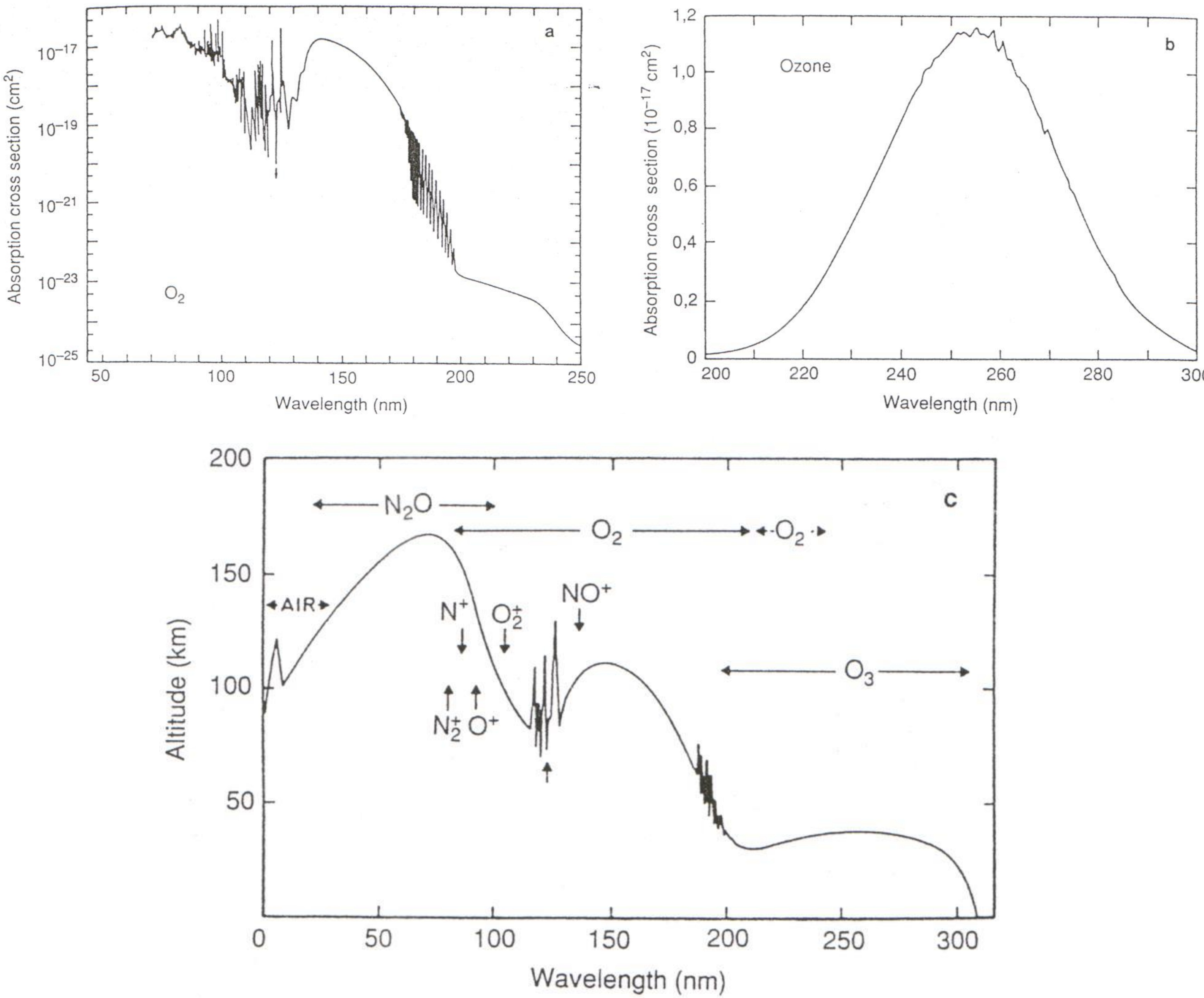


$O_3 + UV = O_2 + O$

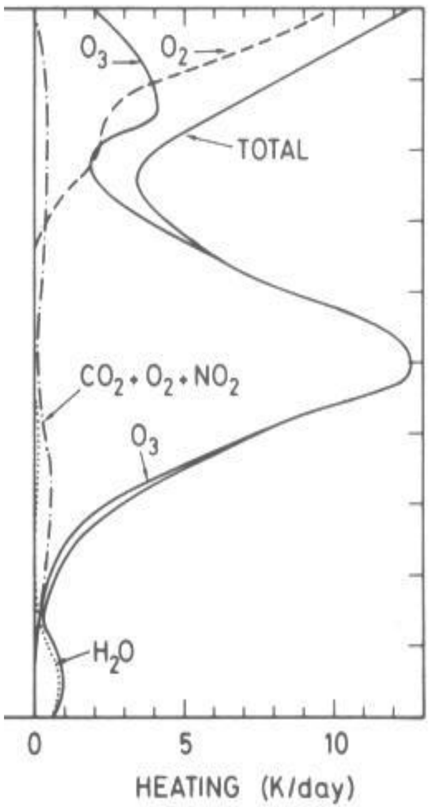
$O_3 + O \rightarrow 2O_2$

Again, this process heats the atmosphere

Occurs for wavelengths of (0.25-0.3 μm), above 12 km, and mostly between 30-50km defining the *ozone layer.*


a
O2
Absorption cross section (cm2)
10−17
10−19
10−21
10−23
10−25
50
100
150
200
250
Wavelength (nm)
b
Ozone
Absorption cross section (10−17 cm2)
1,2
1,0
0,8
0,6
0,4
0,2
0
200
220
240
260
280
300
Wavelength (nm)
c
N2O
O2
O2
AIR
N+
O2+
NO+
N2+
O+
O3
Altitude (km)
200
150
100
50
0
50
100
150
200
250
300
Wavelength (nm)

SW Heating **LW Cooling**



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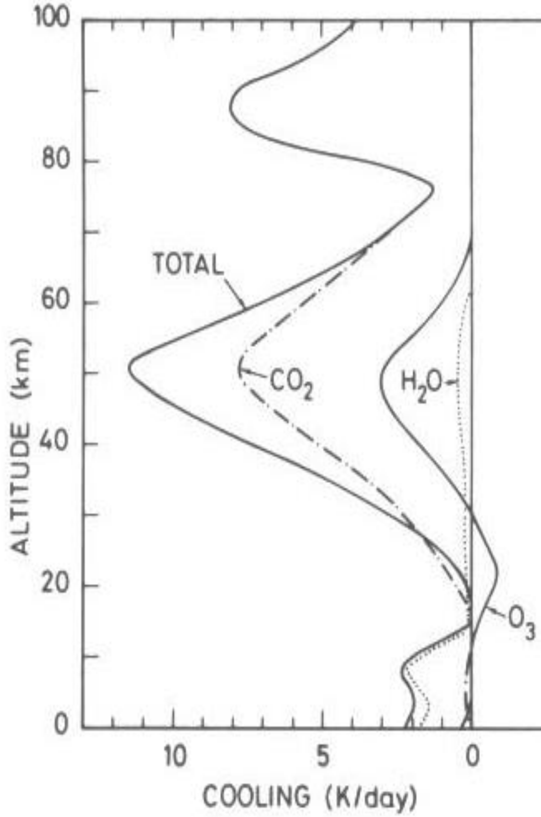

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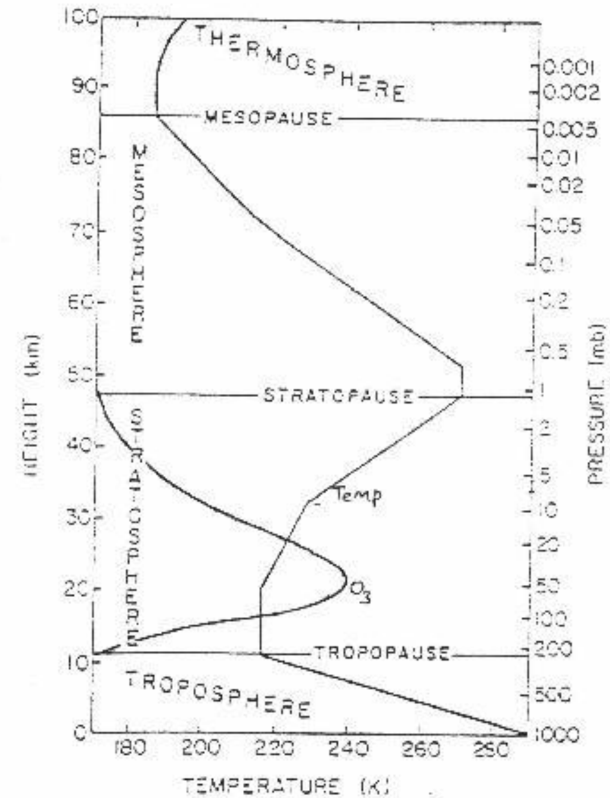
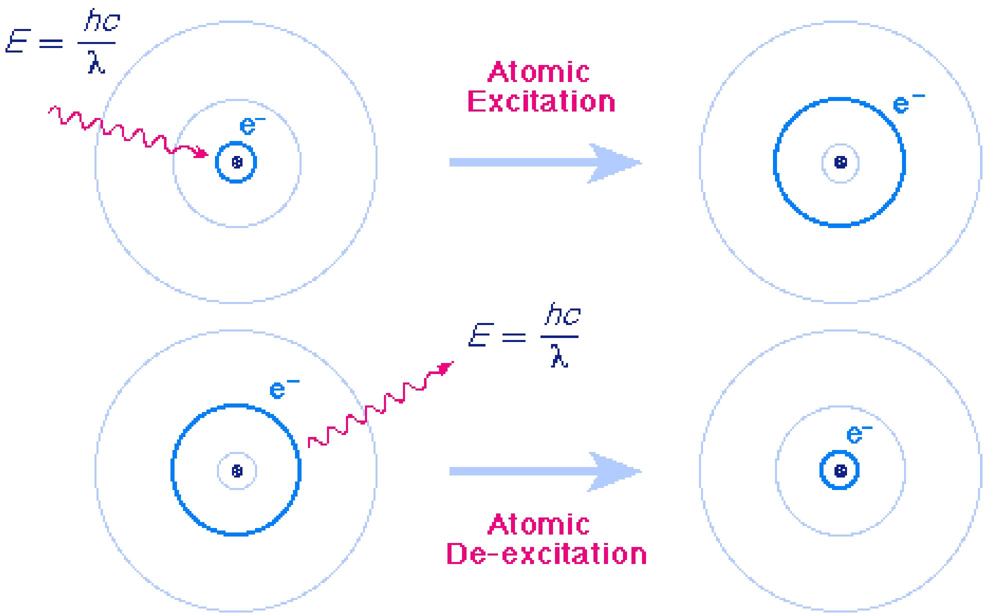


Electronic Transitions: when electrons "jump" to higher energy levels due to absorption by the atoms/molecules. Requires specific energy values corresponding to the next energetic levels. Emissions result when the molecule/atom reverts spontaneously back to the lower level.

This a weak effect which occurs in the near UV and visible:

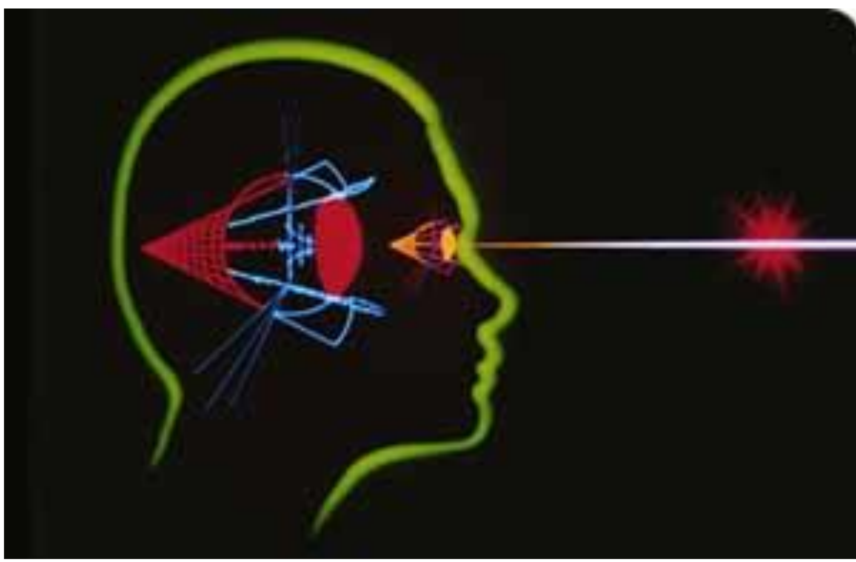
O_3 absorption (0.3-0.35 μm, 0.6 μm) at 20-50 km

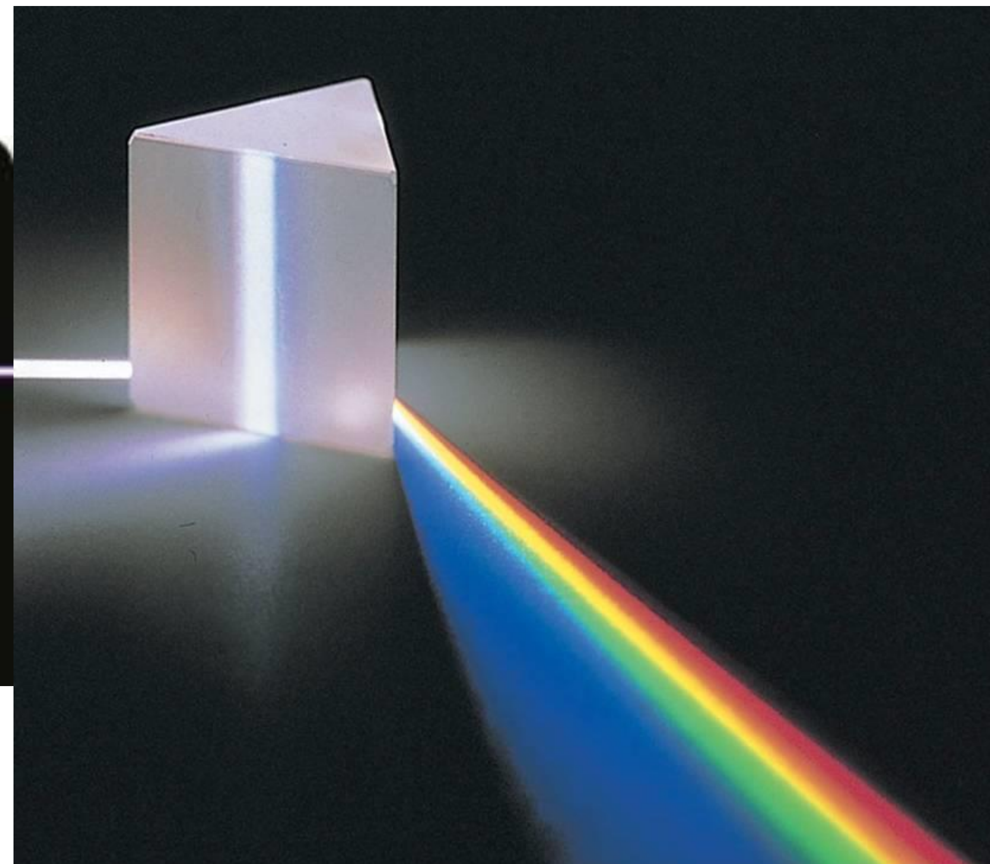
H_2O absorption (0.3-1 μm) near surface.

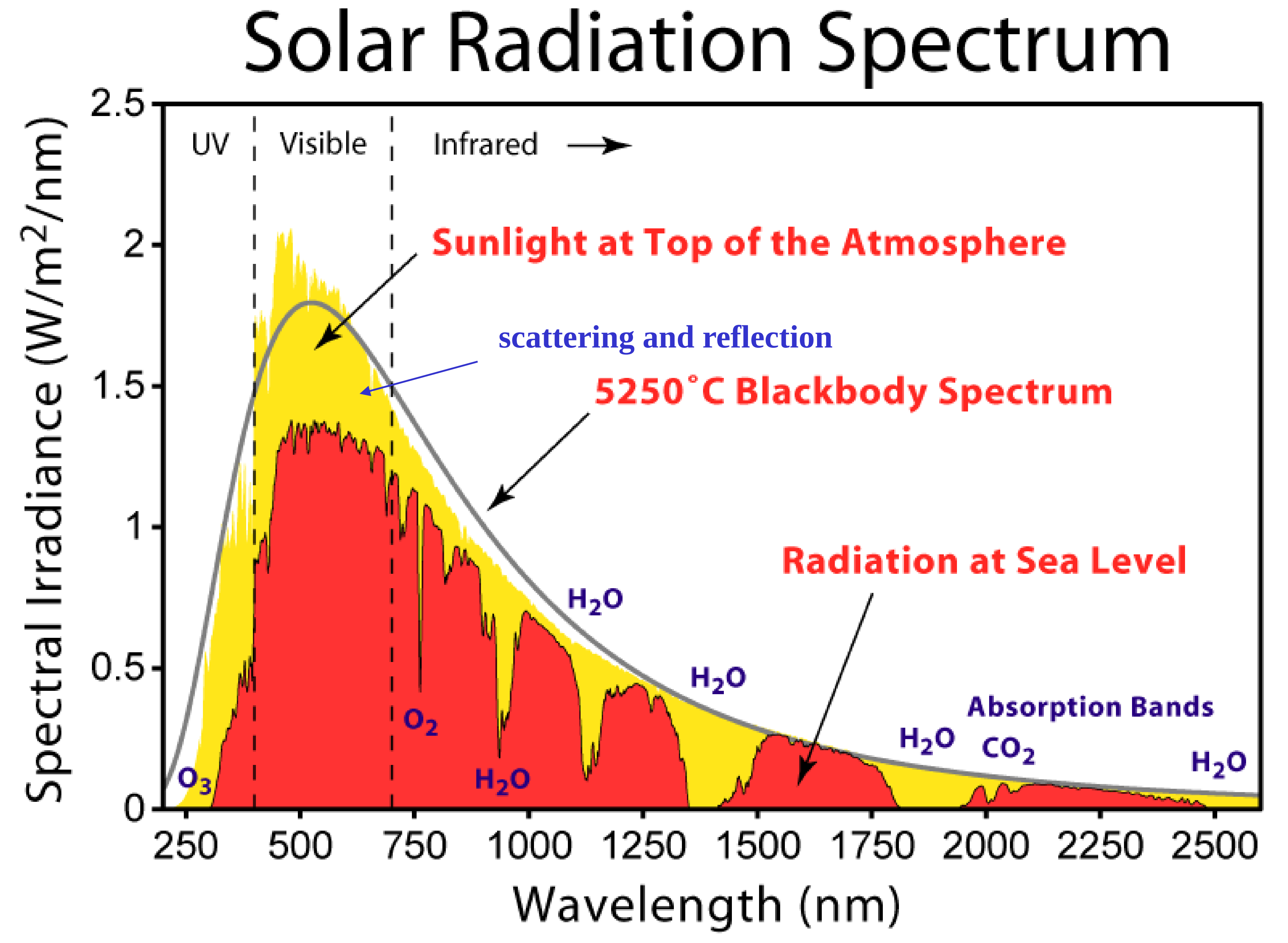


Overall, visible light interacts the least with air molecules.

Our eyes developed to make use of this, to see things on earth.






Solar Radiation Spectrum
Spectral Irradiance (W/m²/nm)
Wavelength (nm)
2.5
2
1.5
1
0.5
0
250
500
750
1000
1250
1500
1750
2000
2250
2500
UV
Visible
Infrared
Sunlight at Top of the Atmosphere
scattering and reflection
5250˚C Blackbody Spectrum
Radiation at Sea Level
Absorption Bands
O_3
O_2
H_2O
H_2O
H_2O
H_2O
CO_2
H_2O

The less energetic radiation absorption occurs in the IR range which has part in the solar and part in the terrestrial spectrum

Slide 1: Electromagnetic Spectra of Solar and Terrestrial Radiation

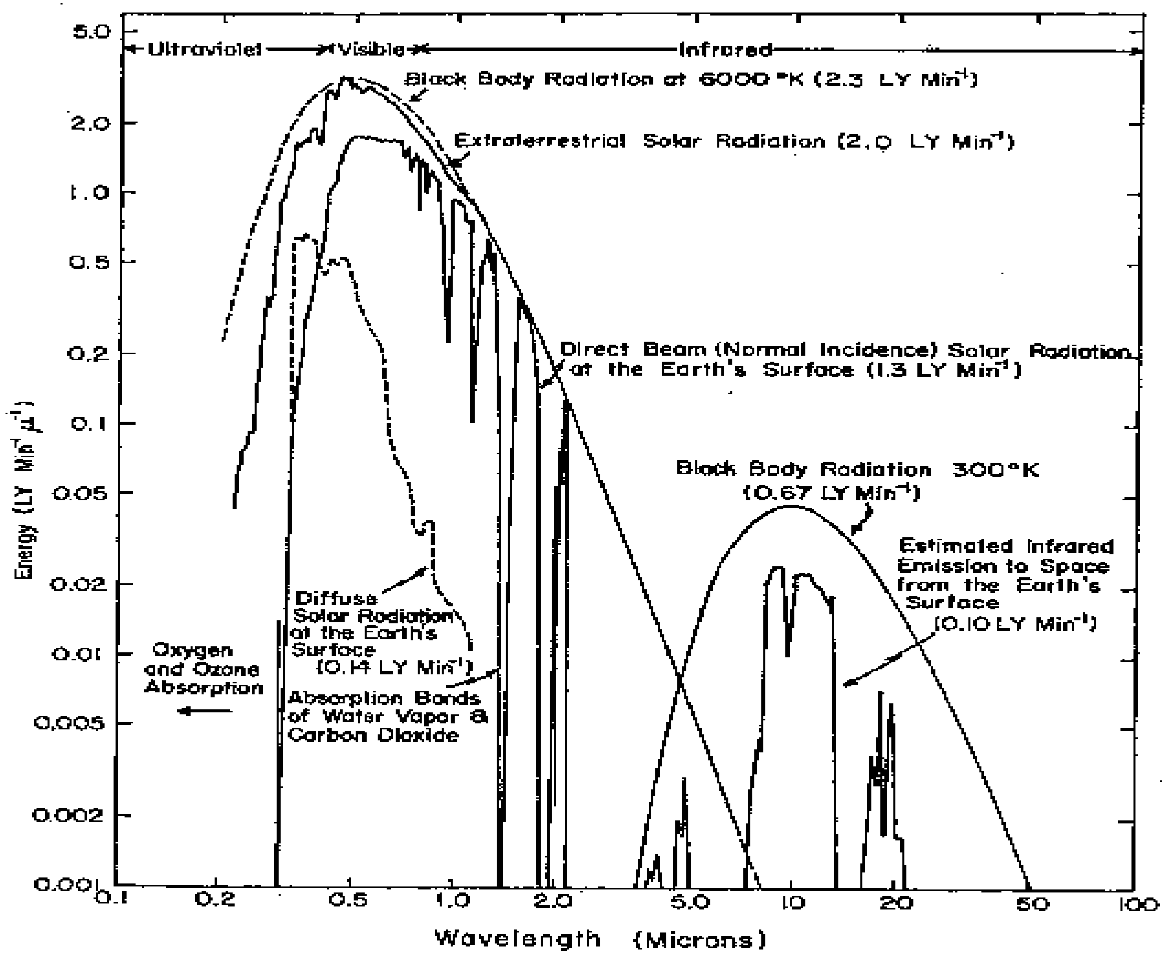


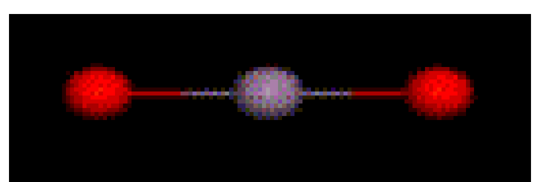
FIG. 6.—Electromagnetic spectra of solar and terrestrial radiation. The black body radiation at 6,000° K is reduced by the square of the ratio of the sun's radius to the average distance between the sun and the earth in order to give the flux that would be incident on the top of the atmosphere.

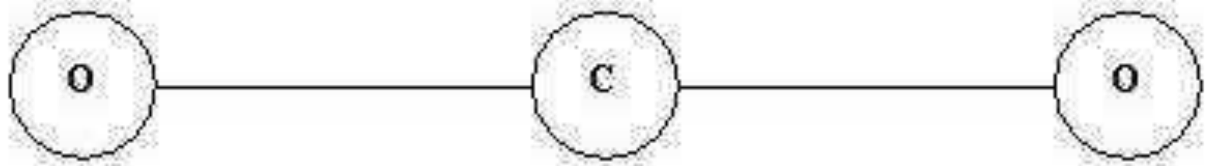
Vibrational Energy:

Potential energy varies with the distance in the molecule, relative to the equilibrium position r_o. Atoms/molecules oscillate about this mean position and can assume discrete vibrational energy states.

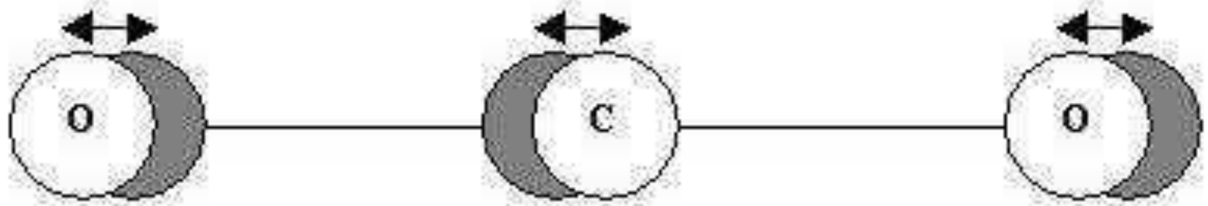
At atmospheric temperatures, most molecules are in the lowest energy state.

IR radiation gets can excite the vibrational modes when it is absorbed.

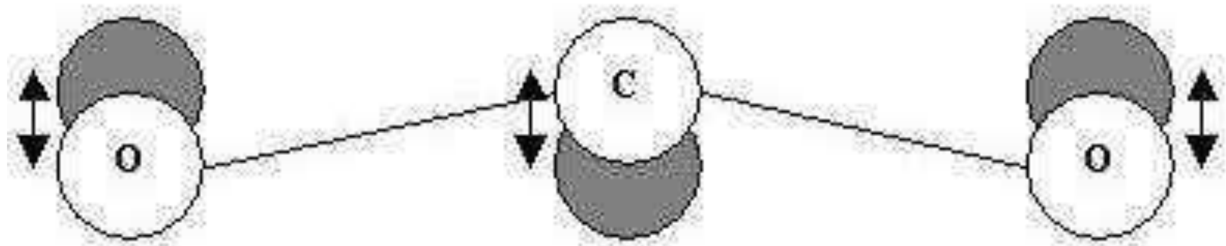




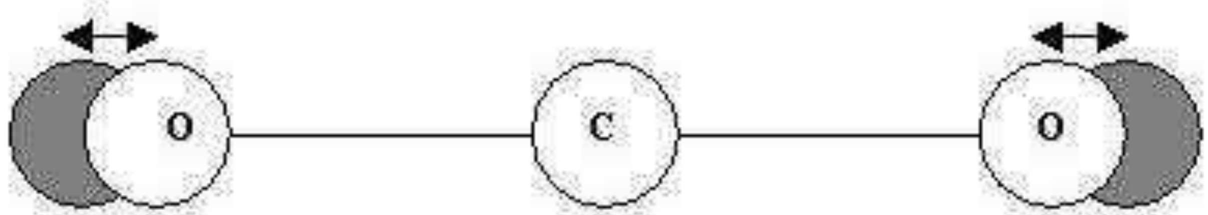
Molecular structure of Carbon Dioxide



The asymmetric stretch mode



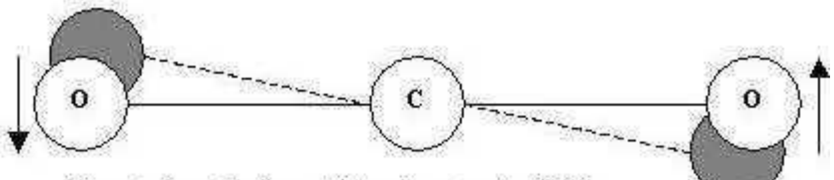
The bending mode



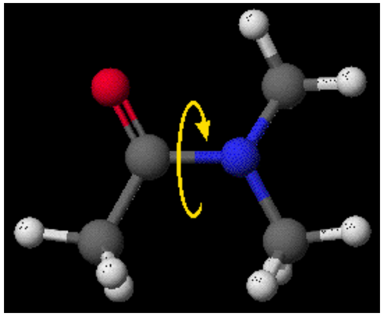
The symmetric stretch mode

Rotational Energy:
Energy levels are associated with the rotation of molecules as a whole about its center of mass. There are only small differences between energy levels.

Vibrational-rotational bands :
Vibrational energy level transitions are often also accompanied by transitions of the easily excited rotational levels as well



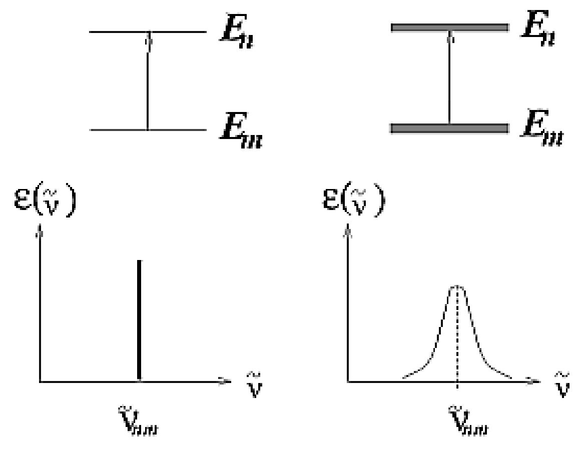
The rotation of a linear triatomic molecule, CO_2



Pressure broadening:

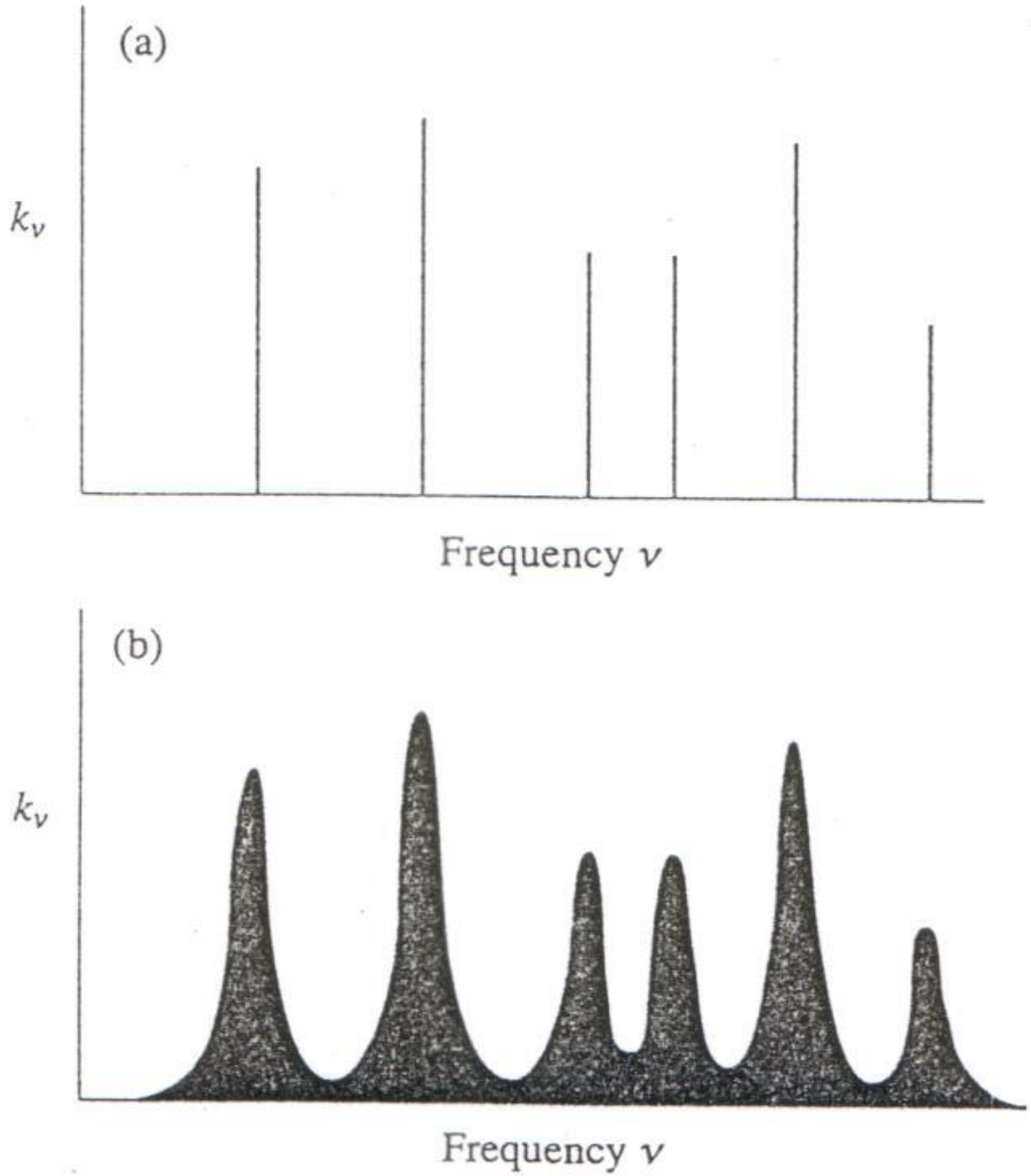
There is a certain "width" to the allowed frequencies of absorption and emission for a specific molecule. Collisions between molecules in the atmosphere adds a little extra energy which can also be lost when reverting back to a lower energy level. Collisions with like molecules are more effective in this regard (the energy is more equally shared). So increasing the atmospheric pressure increases the range of frequencies molecules can absorb and emit – called *pressure broadening*.

Low Pressure



High Pressure

The atoms in solids are so close together that their mutual interactions give multitudes of adjacent quantum states, allowing an essentially continuous absorption and emission with ν



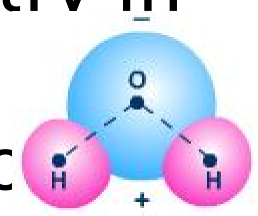
Low pressure

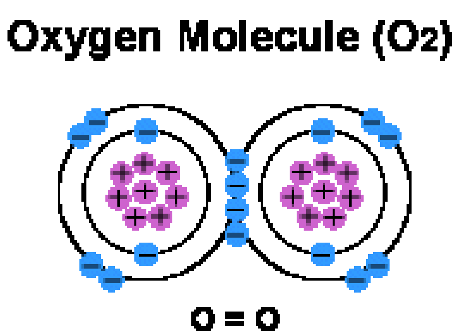
High pressure

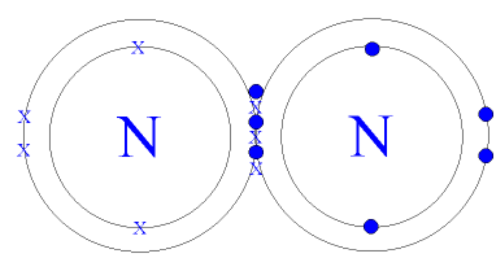
Absorption of electromagnetic radiation requires an electric dipole.

Electric dipoles require some asymmetry in the molecule structure.

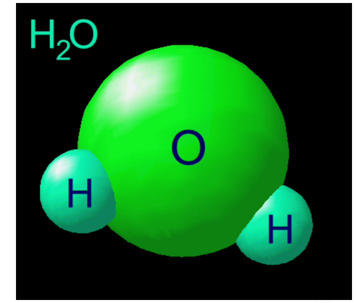
→ O_2, N_2 don't interact with IR radiation



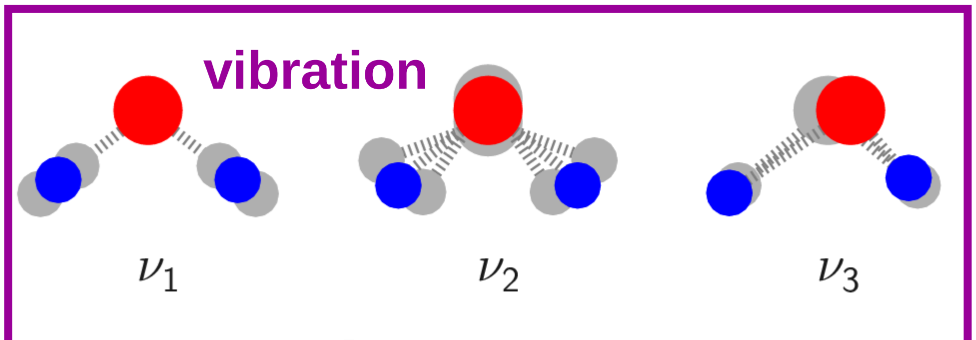


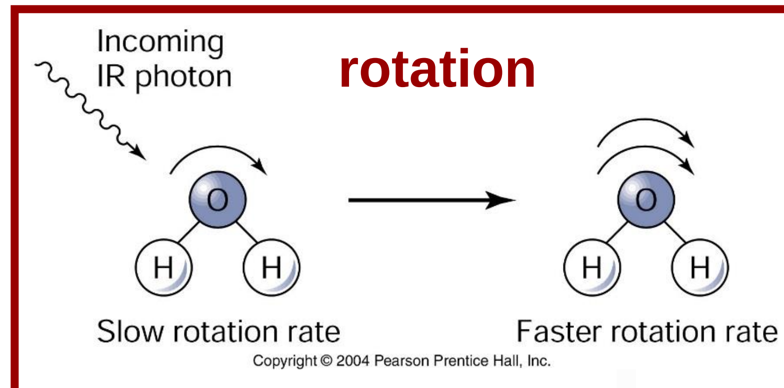


H_2O molecules have a triangular structure, with a dipole.

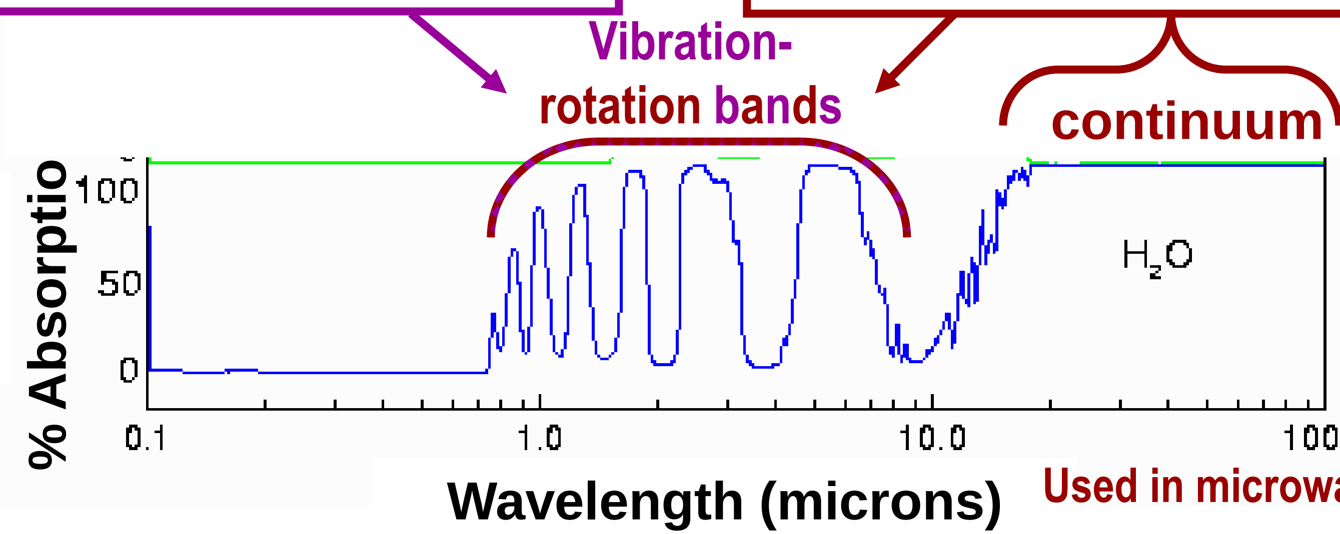


IR is absorbed by exciting **vibrational** and **rotational** energy.



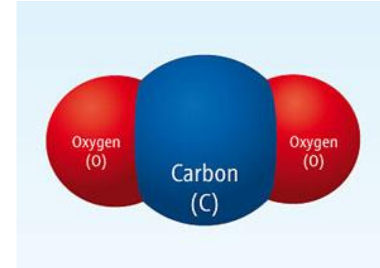


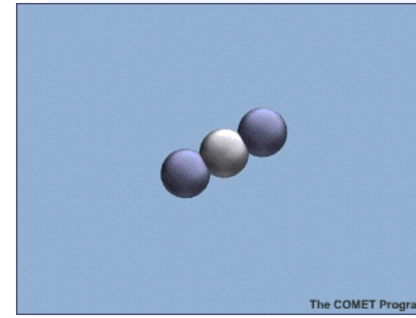
H_2O absorption spectrum



Used in microwave ovens

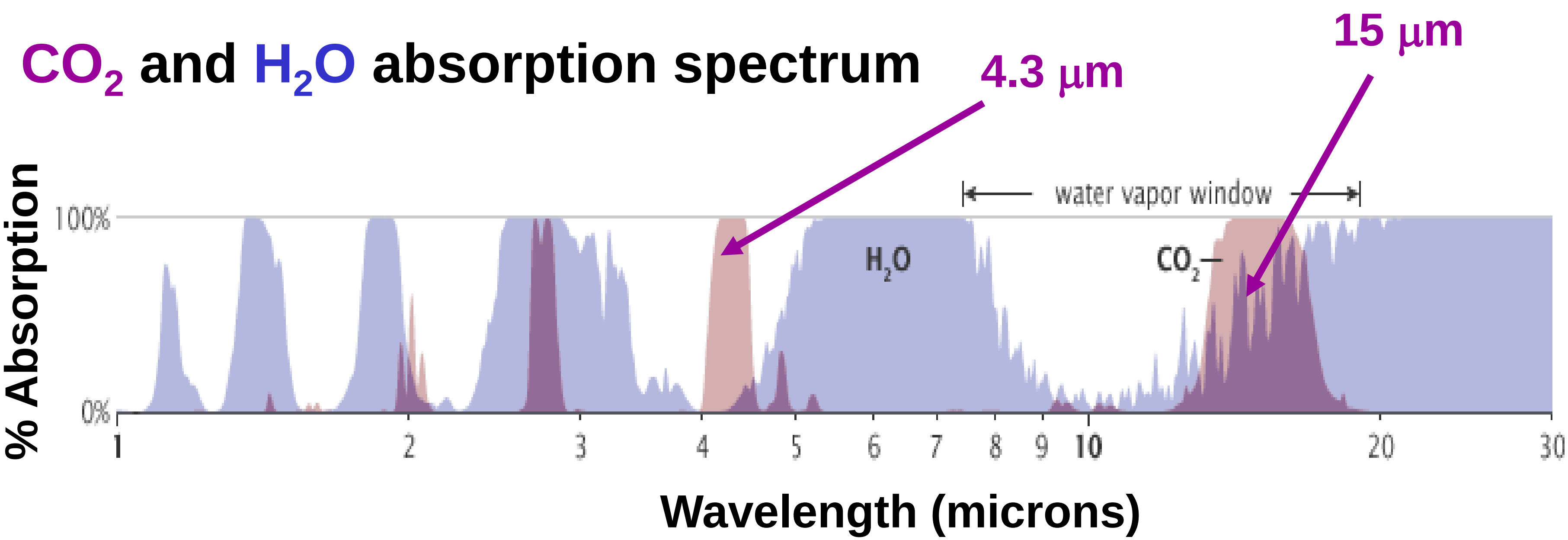
CO_2 molecules have a linear symmetric structure, with no dipole, but when they vibrate, the symmetry breaks, a dipole forms and IR can be absorbed





Some of the CO2 vibration bands lie in the water vapor “windows”

CO_2 and H_2O absorption spectrum



The result is a combination of absorption bands and ranges:

Rotation-vibration bands:

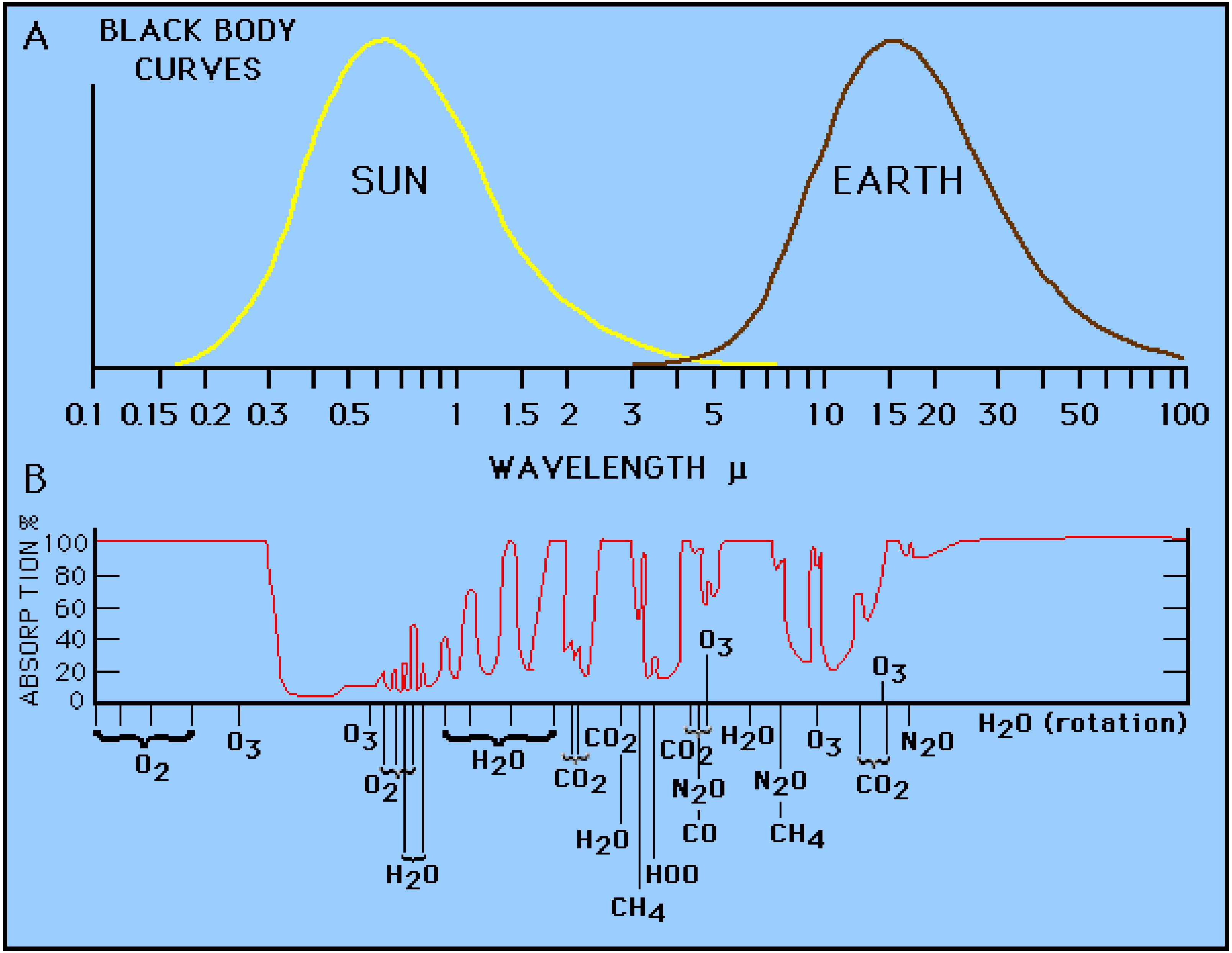
-H_2O moderate absorption in the 1-25 μm range in bands

-Strong H_2O absorption band in the 5.5-7 μm band

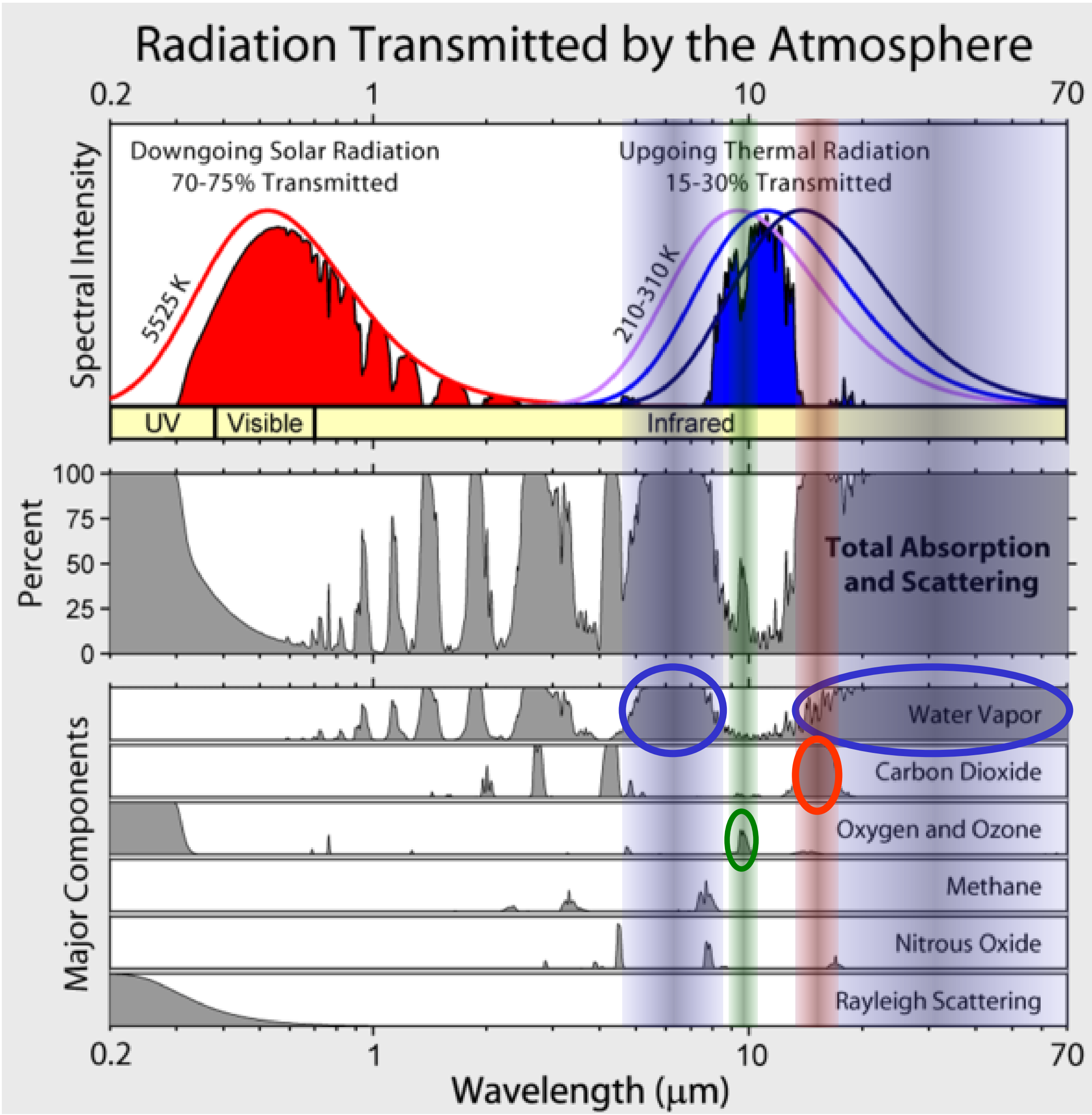
-CO_2 strongly absorbs at 2.7 μm, 4.3 μm and 12-17 μm

-O_3 in the stratosphere has moderate absorption at 4.5 μm, 9.6 μm and 15 μm (heating the stratosphere)

Rotational bands – far infrared: H_2O at > 25 μm


A
BLACK BODY CURVES
SUN
EARTH
0.1 0.15 0.2 0.3 0.5 1 1.5 2 3 5 10 15 20 30 50 100
WAVELENGTH µ
B
ABSORP TION %
100
80
60
40
20
0
O2
O3
O3
O2
H2O
H2O
CO2
CO2
H2O
CH4
HOO
O3
CO2
N2O
CO
H2O
N2O
CH4
O3
O3
CO2
N2O
H2O (rotation)

Other gases also absorb IR: O_3, CH_4, NO



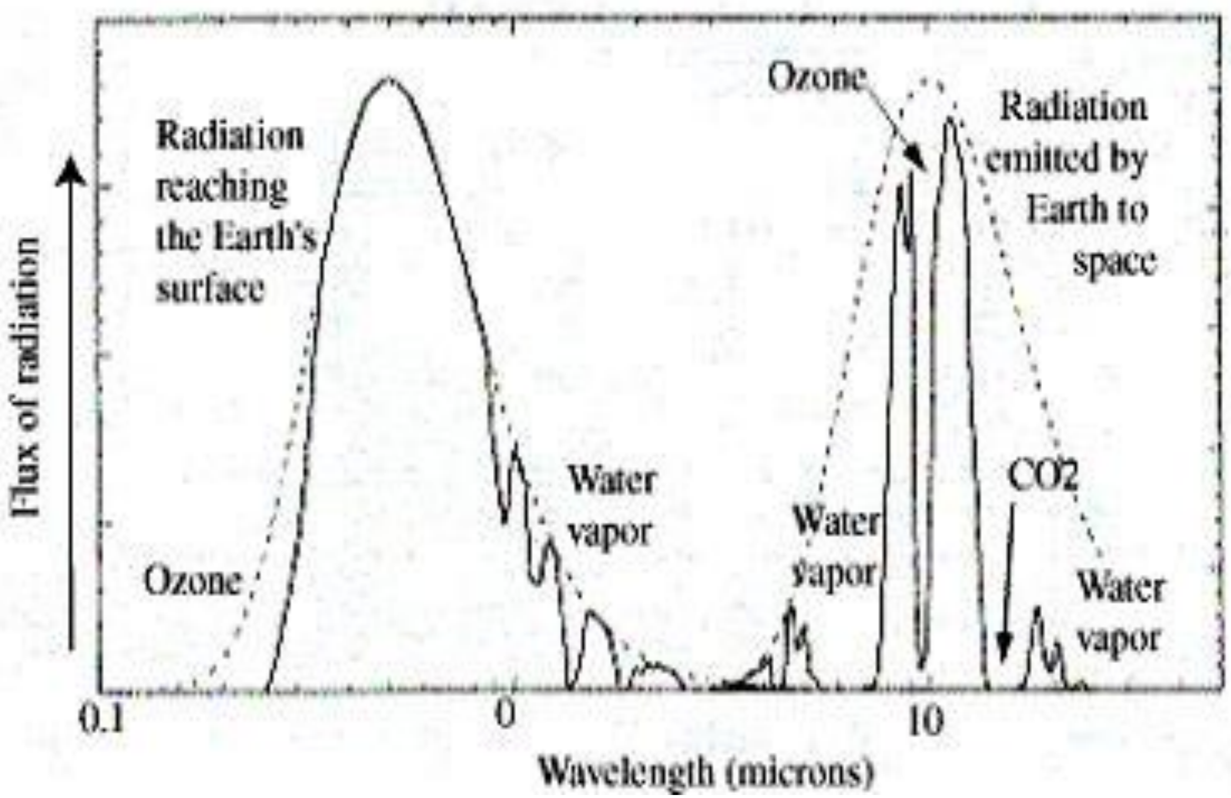
Most important are the absorption peaks which sit on the Earth's peak emission spectrum:

H_2O - 6.3μm

H_2O > 12μm

CO_2 – 15μm

O_3 – 9.6μm



Flux of radiation
Radiation reaching the Earth's surface
Ozone
Water vapor
Ozone
Radiation emitted by Earth to space
Water vapor
CO2
Water vapor
0.1
0
10
Wavelength (microns)