Note: Lecture 6 will be at 10-12 on Wednesday, February 12 in MP408

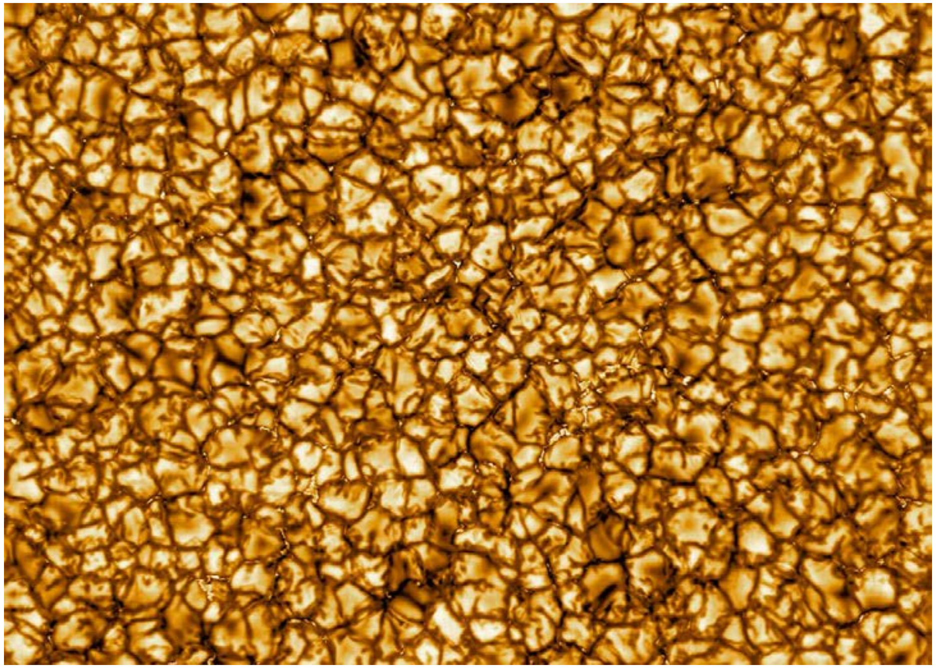
PHY2505S
Atmospheric Radiative Transfer and Remote Sounding

Lecture 5

- Solar and Thermal (Terrestrial) Radiation
- Interaction of Radiation with Gases in the Atmosphere
- Ozone in the Atmosphere & Heating Rates

Highest-resolution image of the Sun ever taken
Credit: NSO/NSF/AURA

- “The world’s most powerful solar telescope has opened its eyes.
- Atop the Haleakala mountain in Hawaii, the 4-metre Daniel K. Inouye Solar Telescope is finally looking at the Sun. …
- New images released on 29 January show patterns of superheated gas churning on the Sun’s surface. Bright ‘cells’ represent the plasma rising from deeper within the star, while darker borders between the cells indicate where plasma is cooling and sinking.
- The Inouye Solar Telescope eclipses what had been the world’s largest solar telescope, a 1.6-metre facility at Big Bear Solar Observatory in southern California. Scientists say that the dramatic upgrade will transform solar physics for decades. …
- The telescope’s huge mirror can study objects as small as 35 kilometres across, from a distance of 150 million kilometres.”



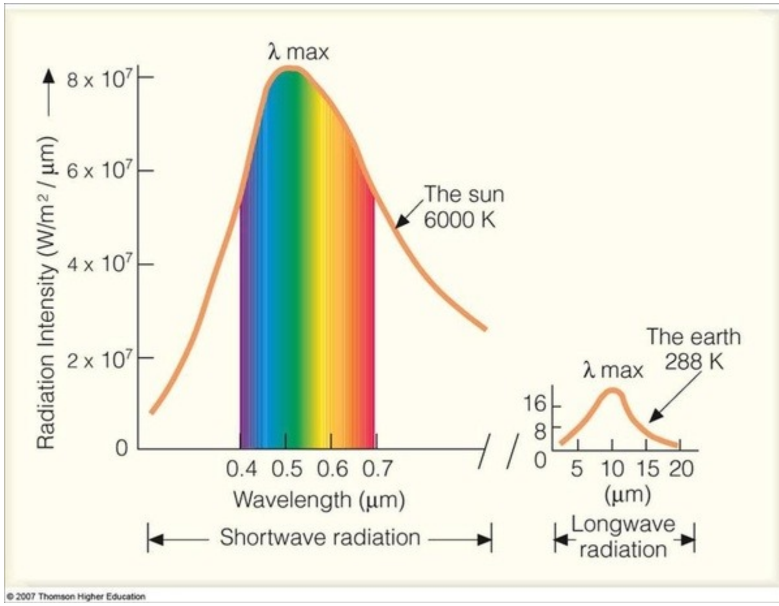
“Bright ‘cells’ represent plasma rising from deeper within the star, while darker borders between the cells indicate where the plasma is cooling and sinking. (NSO/NSF/AURA)”

https://www.nature.com/articles/d41586-020-00224-z

Radiation and Earth

Solar and Terrestrial Radiation

- Solar flux density or irradiance
  - → peaks at visible λ, near 0.48 μm or 11,500 cm^{-1}
  - → falls off rapidly at IR λ
  - → known as <u>shortwave</u> radiation
- Earth's irradiance
  - → peaks at IR λ, near 10 μm or 550 cm^{-1}
  - → emits no visible radiance
  - → known as <u>longwave</u> radiation



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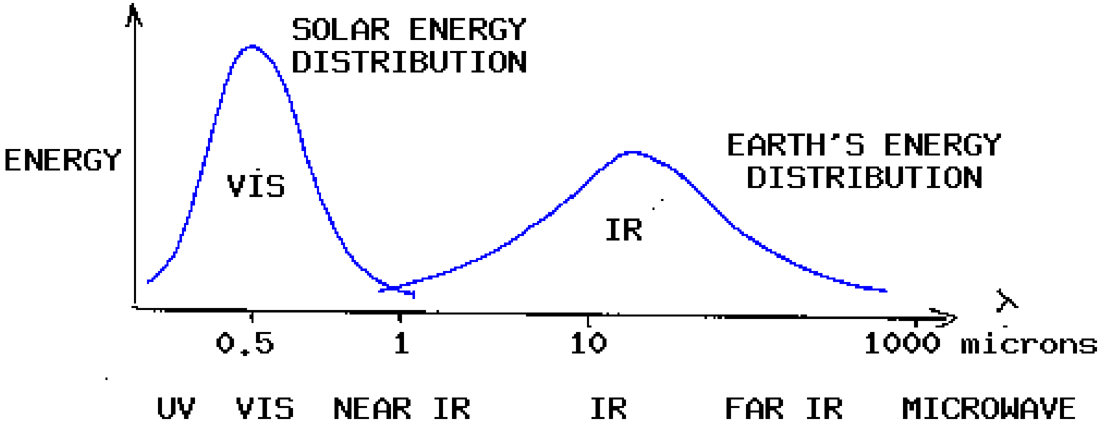
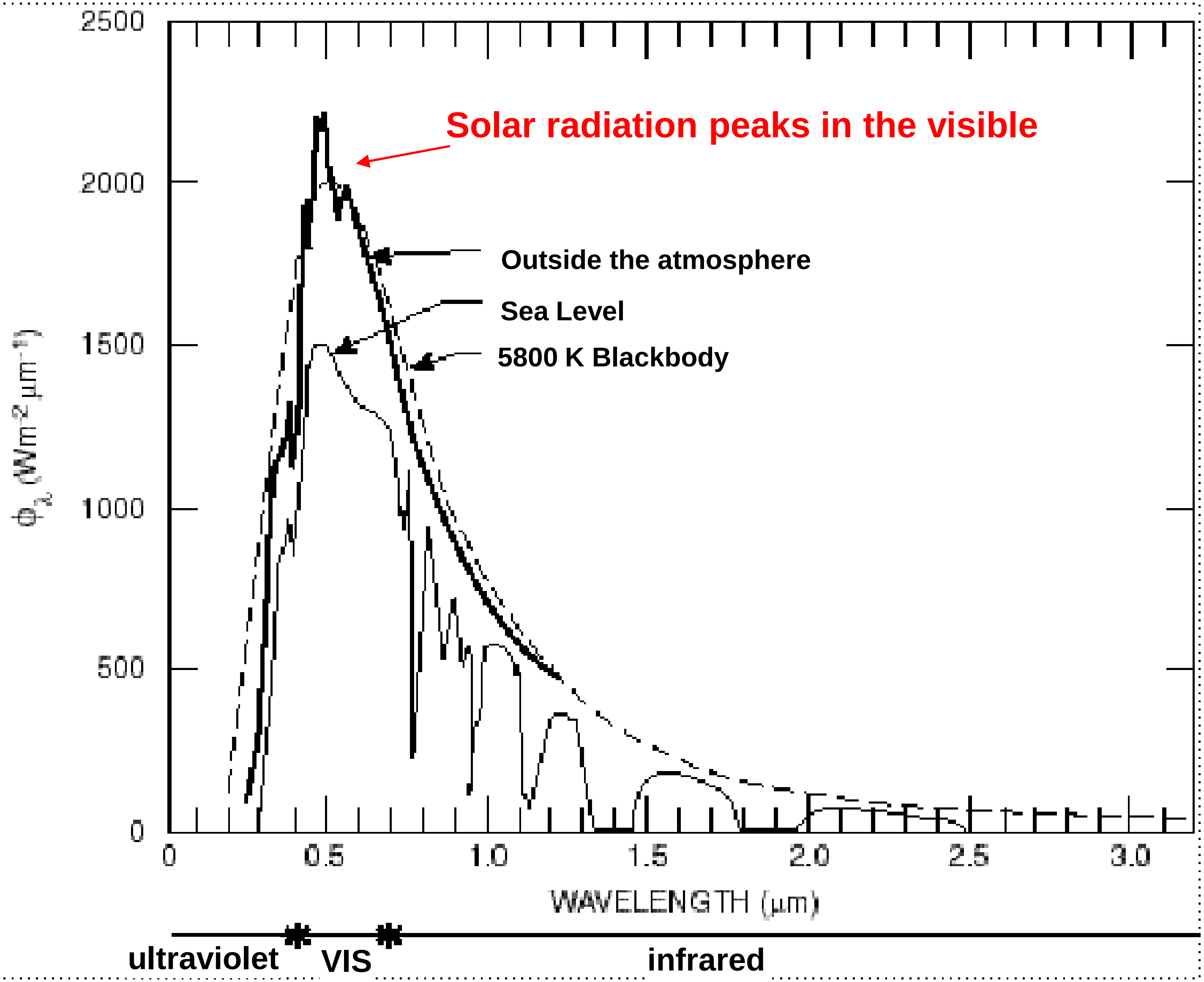


Solar Radiation Spectrum



Solar radiation peaks in the visible

Outside the atmosphere

Sea Level

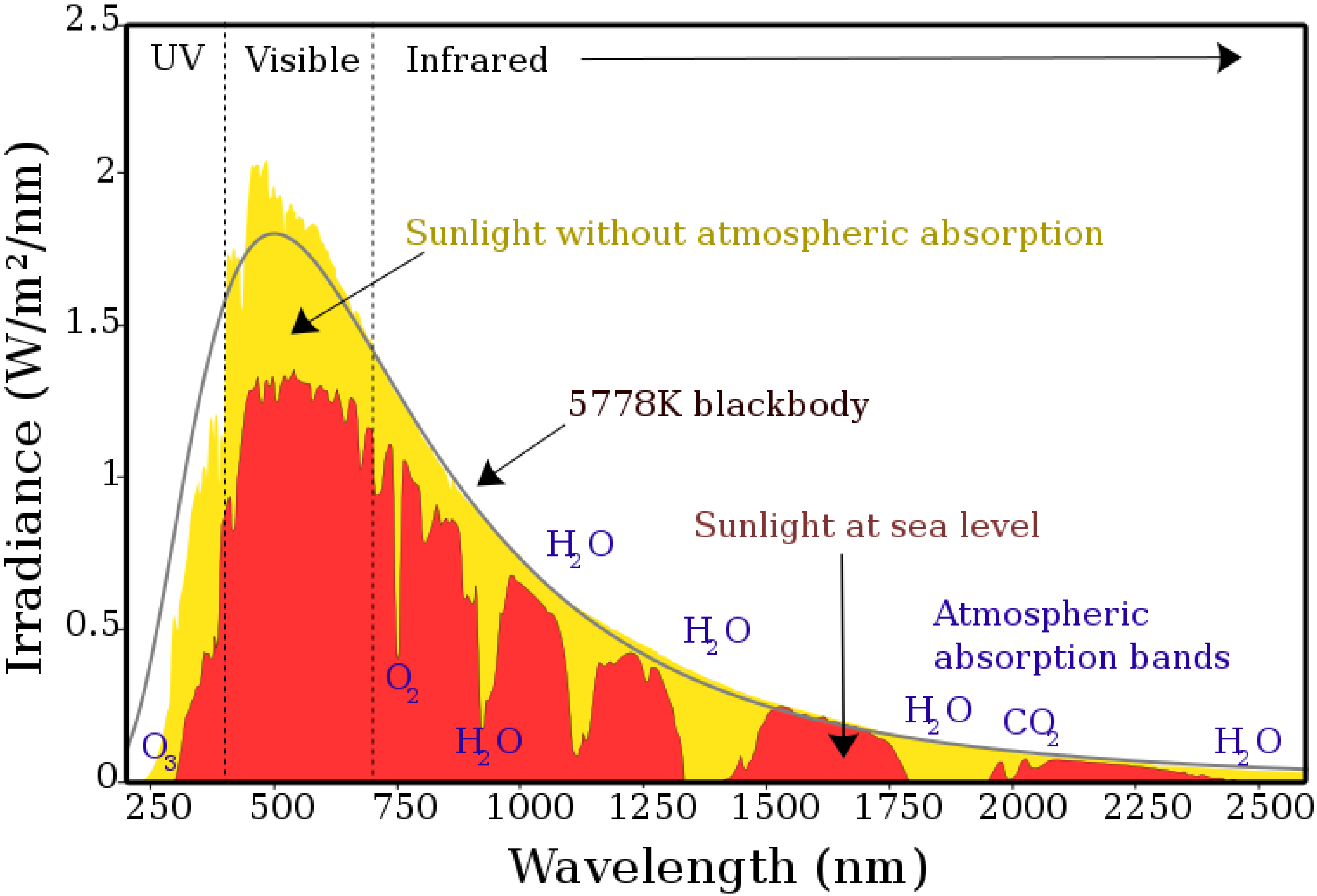
5800 K Blackbody

ultraviolet

VIS

infrared

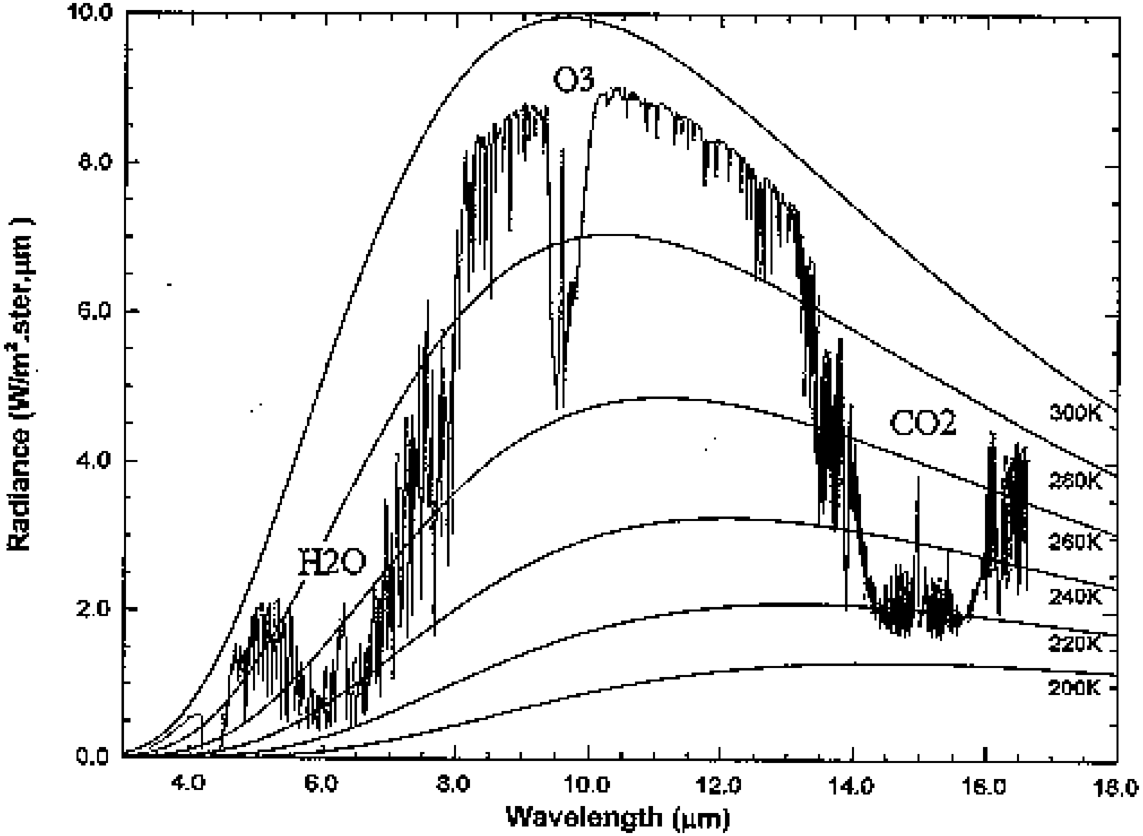
Solar Radiation Spectrum



https://commons.wikimedia.org/wiki/File:Solar_spectrum_en.svg

Thermal (IR) Radiation Spectrum

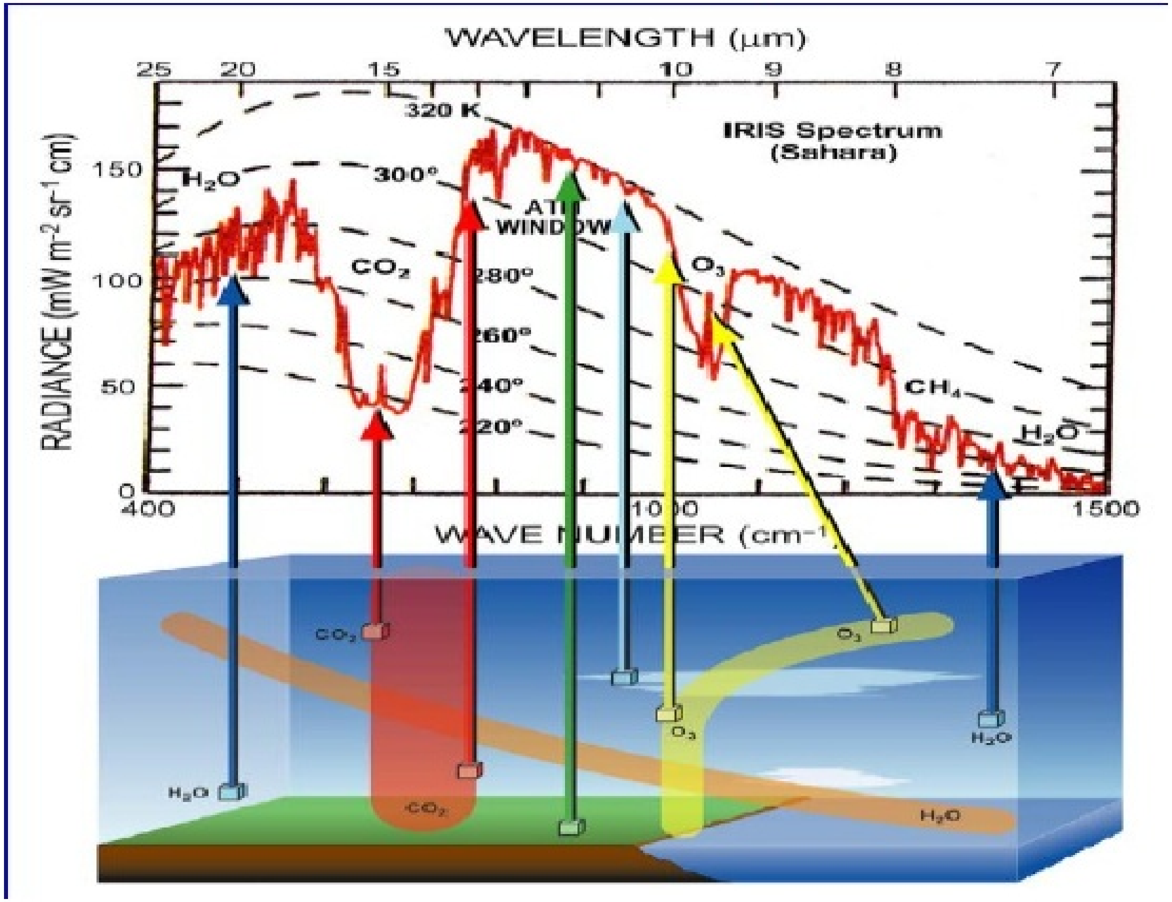
- This figure shows the infrared radiation emitted by the Earth and its atmosphere, with characteristics of Planck emission as well as molecular absorption spectra clearly visible.
- CO_2 is uniformly mixed in the atmosphere, while H_2O and O_3 vary in space and time.



Thermal (IR) Radiation Spectrum

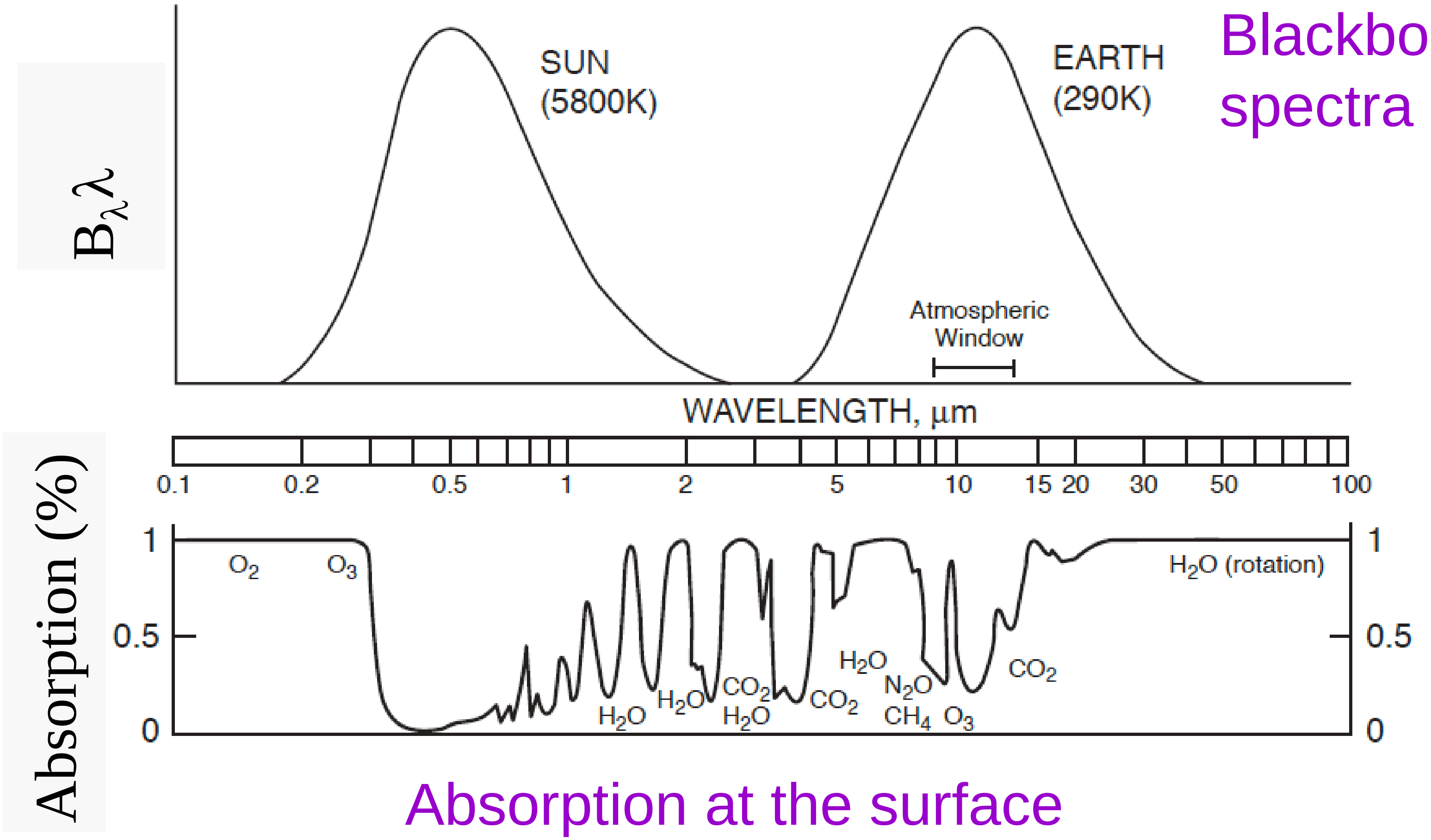
TERRESTRIAL RADIATION SPECTRUM FROM SPACE:

composite of blackbody radiation spectra emitted from different altitudes at different temperatures



https://www.slideshare.net/marcusforpresident2012/hollow-earth-contrails-global-warming-calculations-lecture

Absorption of Radiation by the Atmosphere



Blackbody spectra

Absorption at the surface

Absorption of Solar Radiation

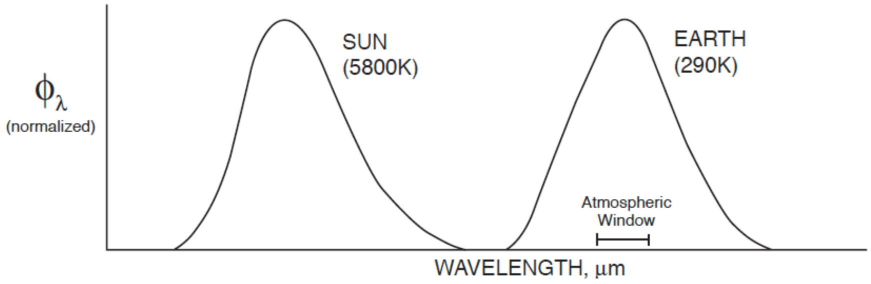
Solar radiation incident on a planet $\left\{ \begin{array}{l} \text{Absorption} \\ \text{Specular reflection} \\ \text{Diffuse reflection} \end{array} \right.$

Miguel Olivares, New York City, Jan 5, 2003.

- The surface and atmosphere of a planet will reflect and scatter some radiation
  - → can see the Earth from "outside"
- The fraction of solar radiation reflected back into space from the planet is called the albedo.
- General definition: (no units) $$A = \frac{M}{E} = \frac{\text{radiant exitance due to reflection}}{\text{irradiance}}$$
- $0 \le A \le 1$, depending upon the surface or planet.
- The fraction of solar radiation absorbed by a planet is $(1 - A)$.

Solar and Terrestrial Radiation Revisited

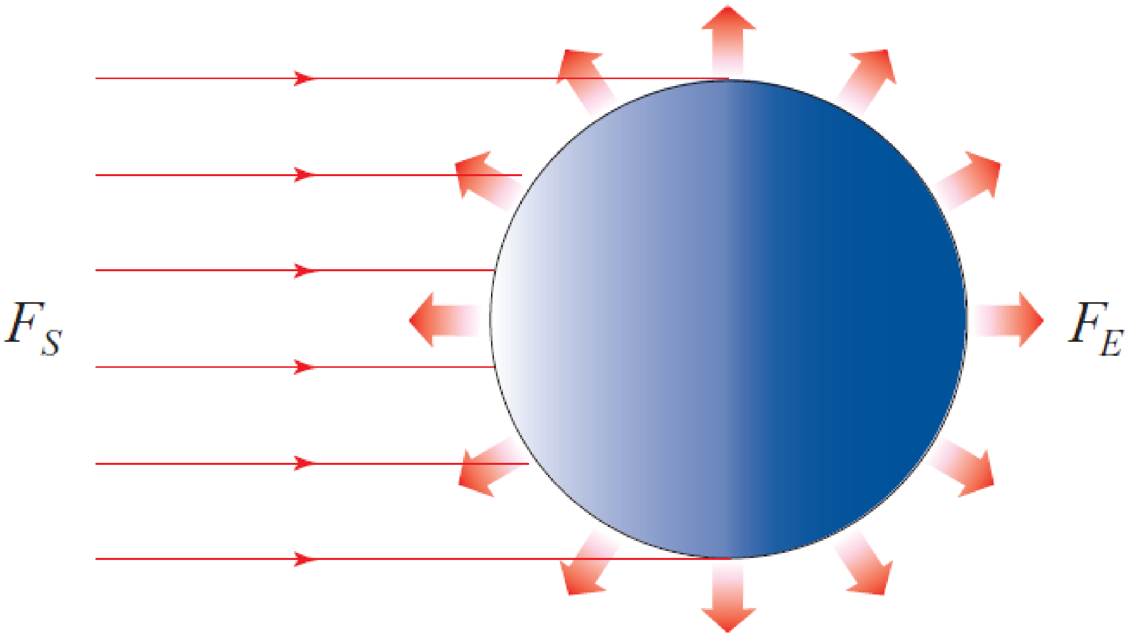
- This "separability" of the radiation equations, which applies for most problems involving planetary atmospheres, is what makes some of these problems tractable.
  - → Link lies in the energy flow equations.



- One consequence of the separability is that the albedo and the emissivity of a body are characteristic of different wavelengths, and thus do not obey Kirchoff's Law directly.
  - → They do obey it when it is stated correctly, i.e., for a particular wavelength or weighted over the full spectrum.
  - → The monochromatic emittance equals the monochromatic absorptance, as we previously stated: $\alpha_\lambda = \varepsilon_\lambda$.
  - → The integrated emittance must also equal the integrated absorptance weighted for surface temperature.

Radiation Balance of Earth

- Over the long-term must be an equilibrium between the solar radiation absorbed by a planet and the thermal radiation it emits.



Wallace and Hobbs, Figure 4.8

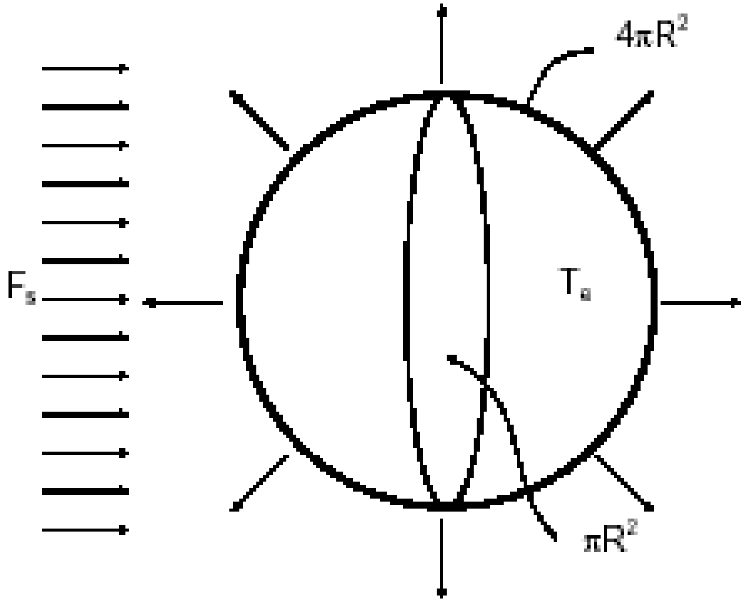


Figure 18: Simple Model of Energy Balance

Radiation Balance of Earth

We can write this balance as:

$$\pi R_E^2 \, I_{sun} \, \Delta\Omega_{sun} \, \alpha_{visible} = 4 \pi R_E^2 \, \varepsilon_{infrared} \, \sigma T_e^4$$

$$\pi R_E^2 \, F_{sun} \, (1 - A) = 4 \pi R_E^2 \, \varepsilon_{infrared} \, \sigma T_e^4$$

Energy from the Sun intercepted by the spherical planet.

Energy emitted by the planet in the infrared.

where we've used:

$F_{sun} = I_{sun} \, \Delta\Omega_{sun}$ and $(1\text{-}A) = \alpha_{visible}$

and A is the albedo or the average amount of solar energy reflected.

$$\boxed{F_{sun} \, (1 - A) = 4 \, \varepsilon_{infrared} \, \sigma T_e^4}$$

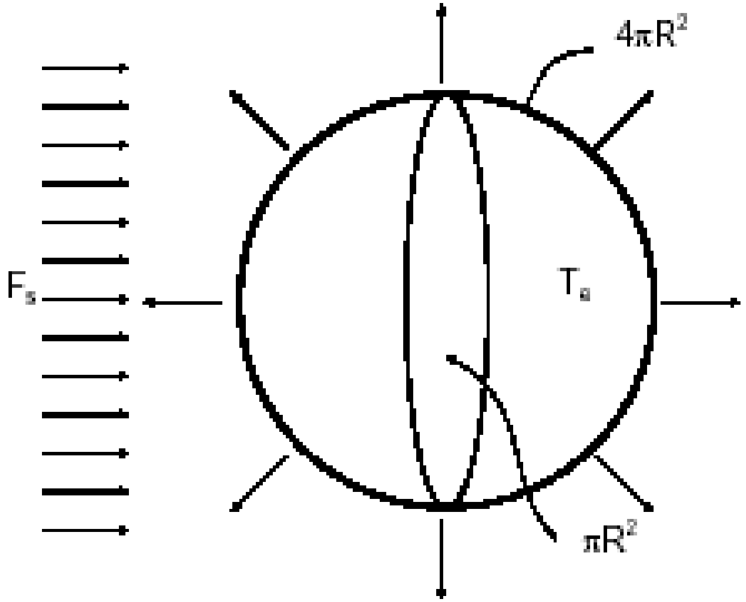


Figure 18: Simple Model of Energy Balance

Radiation Balance of Earth

Let’s plug in some numbers

$$F_{Earth} = \sigma T_e^4 = \left(\frac{1-A}{\varepsilon_{infrared}}\right)\frac{F_s}{4} = \left(\frac{1-0.3}{1}\right)\frac{1368\ \mathrm{Wm}^{-2}}{4} = 239.4\ \mathrm{Wm}^{-2}$$

$$T_e = \sqrt[4]{\frac{F_{Earth}}{\sigma}} = \sqrt[4]{\left(\frac{1-A}{\varepsilon_{infrared}}\right)\frac{F_s}{4\sigma}} = \sqrt[4]{\left(\frac{1-0.3}{1}\right)\frac{1368\ \mathrm{Wm}^{-2}}{4\sigma}} = 255\,\mathrm{K}$$

Application to a Satellite

- Consider a satellite near the Earth's orbit (but not close to Earth, say 180° away, around the orbit).
- Our equilibrium equation becomes:

$\sigma = 5.670\text{x}10^{-8}\ J\ m^{-2}\ K^{-4}\ s^{-1}$

$$T_e^4 = \left(\frac{1-A}{\varepsilon_{\text{infrared}}}\right)\frac{F}{4\sigma} = \left(\frac{\alpha_{\text{visible}}}{\varepsilon_{\text{infrared}}}\right)\frac{F}{4\sigma} = \left(\frac{\alpha_{\text{visible}}}{\varepsilon_{\text{infrared}}}\right)\frac{1370}{4\sigma} = \left(\frac{\alpha_{\text{visible}}}{\varepsilon_{\text{infrared}}}\right)279^4$$

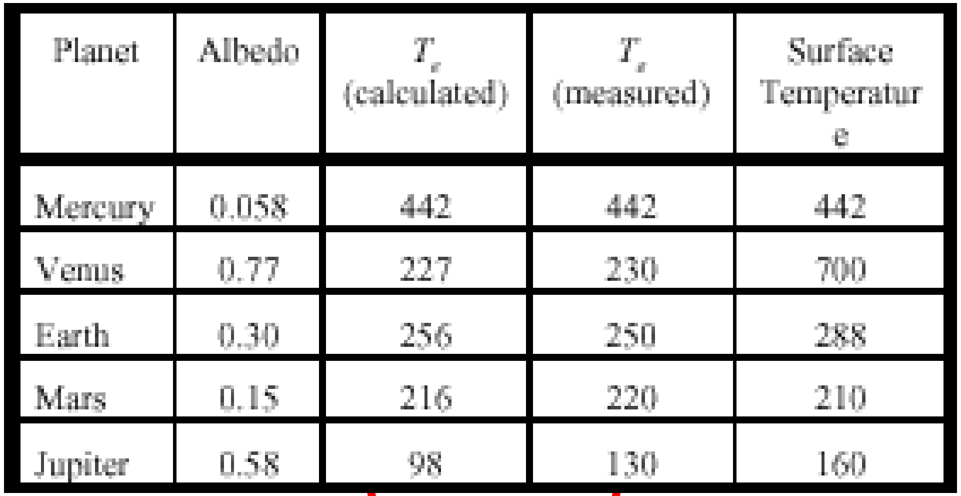
- So the equilibrium temperature of a black (invisible) satellite is about 279 K – about room temperature (for $\alpha_{\text{visible}} \approx \varepsilon_{\text{infrared}}$).
- The equilibrium temperature of a satellite out of sunlight is only 3 K.
  - → Satellites can experience a severe thermal stress as they orbit Earth!
- To reduce a satellite's temperature, need a surface that reflects some solar radiation AND emits well in the IR.
  - → e.g., paint with α_{visible} ~ 0.5 and $\varepsilon_{\text{infrared}}$ ~ 0.95 will give T_e ~ 238 K
  - → Note: a shiny surface in the visible (reflectivity~0.9, α_{visible}~0.1) may have reflectivity of 0.99 ($\varepsilon_{\text{infrared}}$~0.01) in the IR, giving 500 K!

Application to Planets

- For planets, the equilibrium temperature is given by:

$$T_e^4 = \left(\frac{\alpha_{\text{visible}}}{\varepsilon_{\text{infrared}}} \right) \frac{F}{4\sigma}$$

- This is called the <u>effective radiating temperature</u> of the planet.
  - → Can be calculated using an observed value of albedo and the known solar flux for the planet's orbital distance from the Sun.
  - → Can be measured by monitoring the infrared radiation from the planet.
  - → If the planet has no thermal activity of its own then these two should agree.



Planet	Albedo	T_e (calculated)	T_e (measured)	Surface Temperature
Mercury	0.058	442	442	442
Venus	0.77	227	230	700
Earth	0.30	256	250	288
Mars	0.15	216	220	210
Jupiter	0.58	98	130	160

Thermal source?

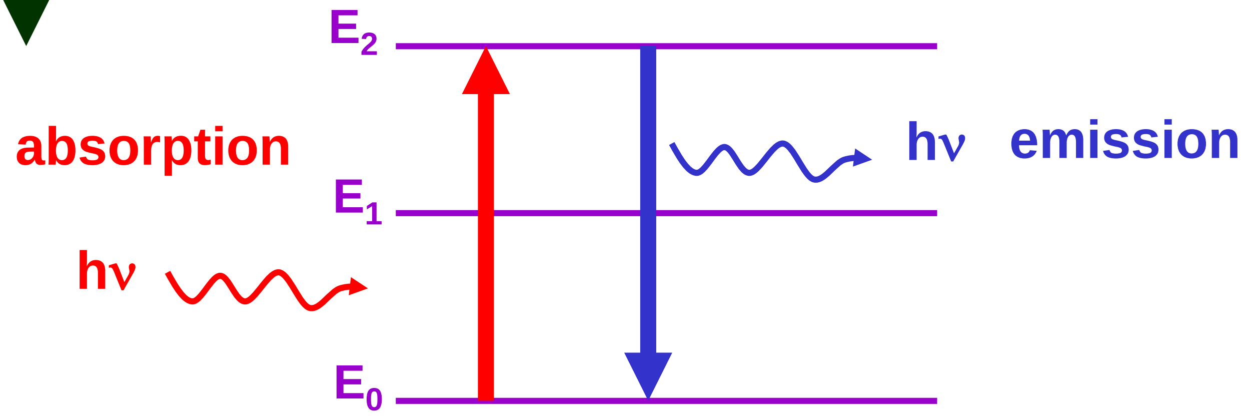
Atmosphere!

Interaction of Radiation with Gases in the Atmosphere

- Now let’s look at the processes by which energy can be absorbed in planetary atmospheres - spectroscopy.
- These processes are related to the atomic and molecular properties of the gases in the atmosphere.

Rotation
Vibration
Electronic transitions
Photodissociation
Photoionization

Types of transitions in the internal energy of the molecules, in order of increasing energy

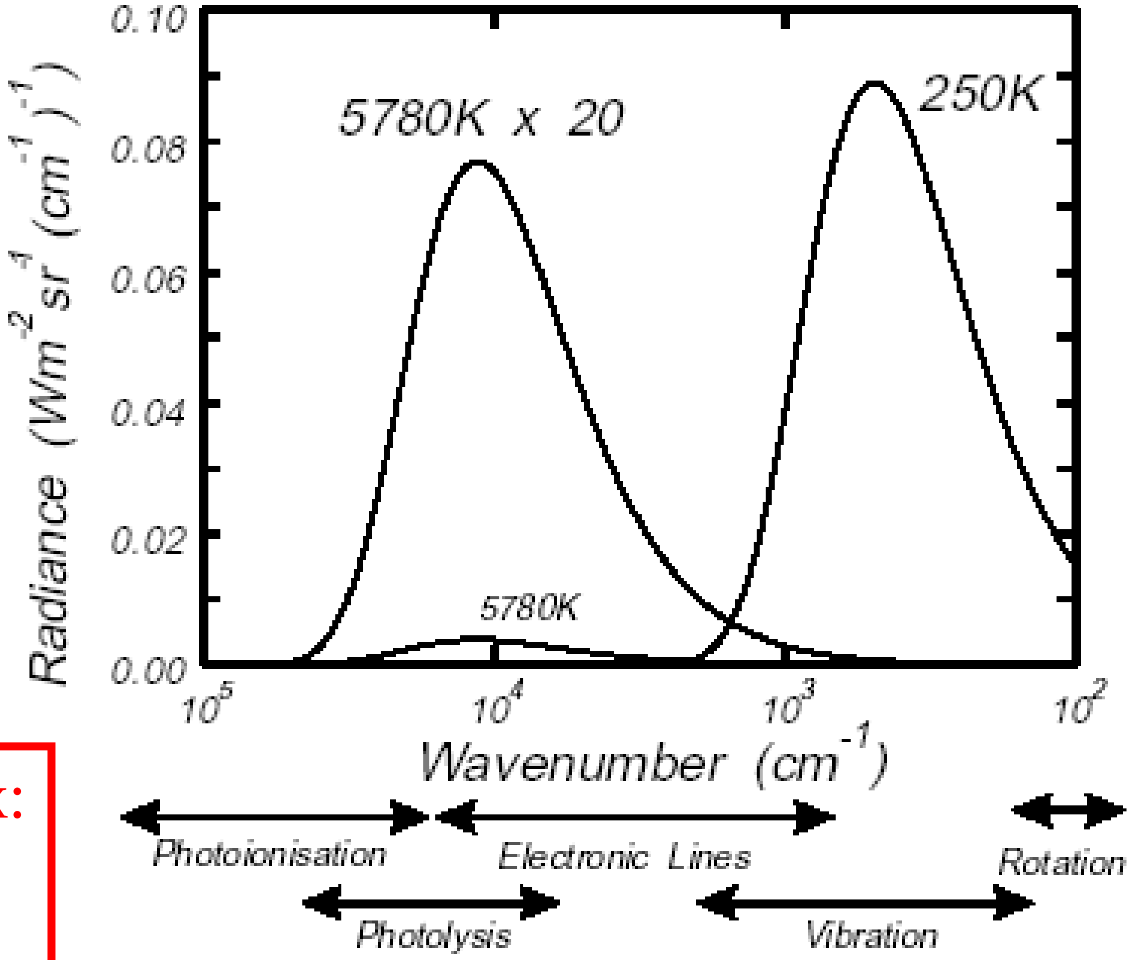


Processes Causing Absorption

1. Rotation of a molecule (the simplest)
   - → Requires little energy
   - → Quantization of angular momentum generates line spectra in the far infrared and microwave
2. Vibration of a molecule
   - → Requires more energy
   - → Absorption spectra (lines) are in the near-infrared and mid-infrared
   - → Usually mixed with rotation lines in vibration-rotation spectra
3. Excitation of atoms or electrons in a molecule that cause dissociation of ionization of electronic transitions
   - → Requires higher energy radiation
   - → Produces ultraviolet and visible spectra (broadband, not lines)

Interaction of Radiation with Gases in the Atmosphere

- Solar interactions – mostly type 3 in the UV-visible
  - Photoionization – extreme UV strips electrons from atoms
  - Photodissociation – UV breaks apart molecules
  - Electronic (orbital)
- Thermal IR interactions
  - Electronic (orbital)
  - Vibration
  - Rotation



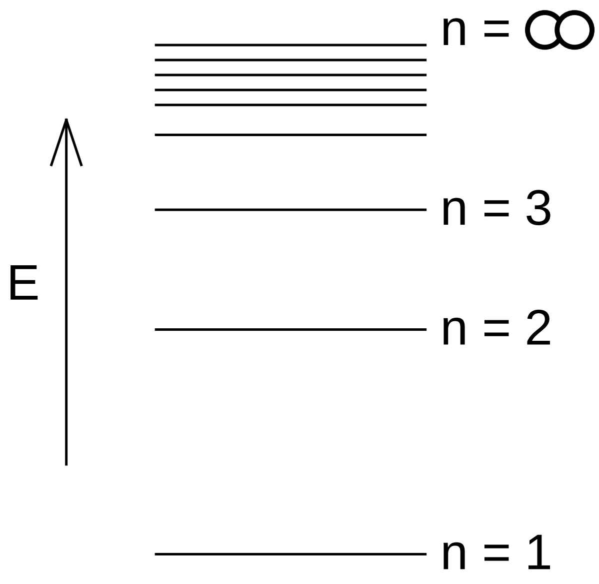
Born-Oppenheimer Approx:
Energy of a gas molecule

$$E = E_{elec} + E_{vib} + E_{rot} + E_{trans}$$

Energy Diagrams

Bohr frequency condition:

- When an atom changes its energy by ΔE, the difference is carried away as a photon of frequency ν, where: $\Delta E = h\,\nu$
- Radiation is absorbed and emitted by atoms only at certain wavenumbers, so only certain energy states of atoms are permitted.

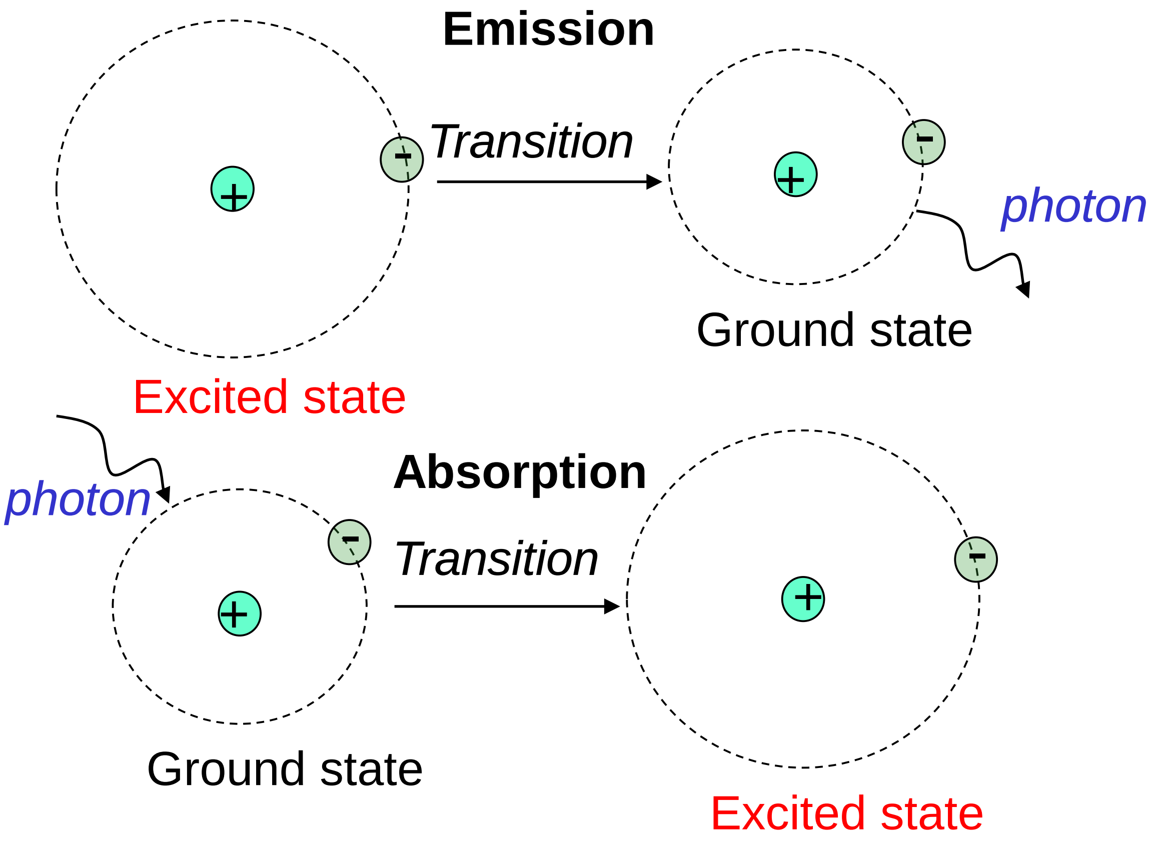


Term diagram for hydrogen

An <u>energy</u> or <u>term diagram</u> shows the allowed energy levels of a system.

- Energy is on the y axis.
- For every allowed energy level there is a line.
- The only allowed transitions move energy from one line to another.

The Spectrum of Hydrogen



Emission

Transition

photon

Ground state

Excited state

Absorption

photon

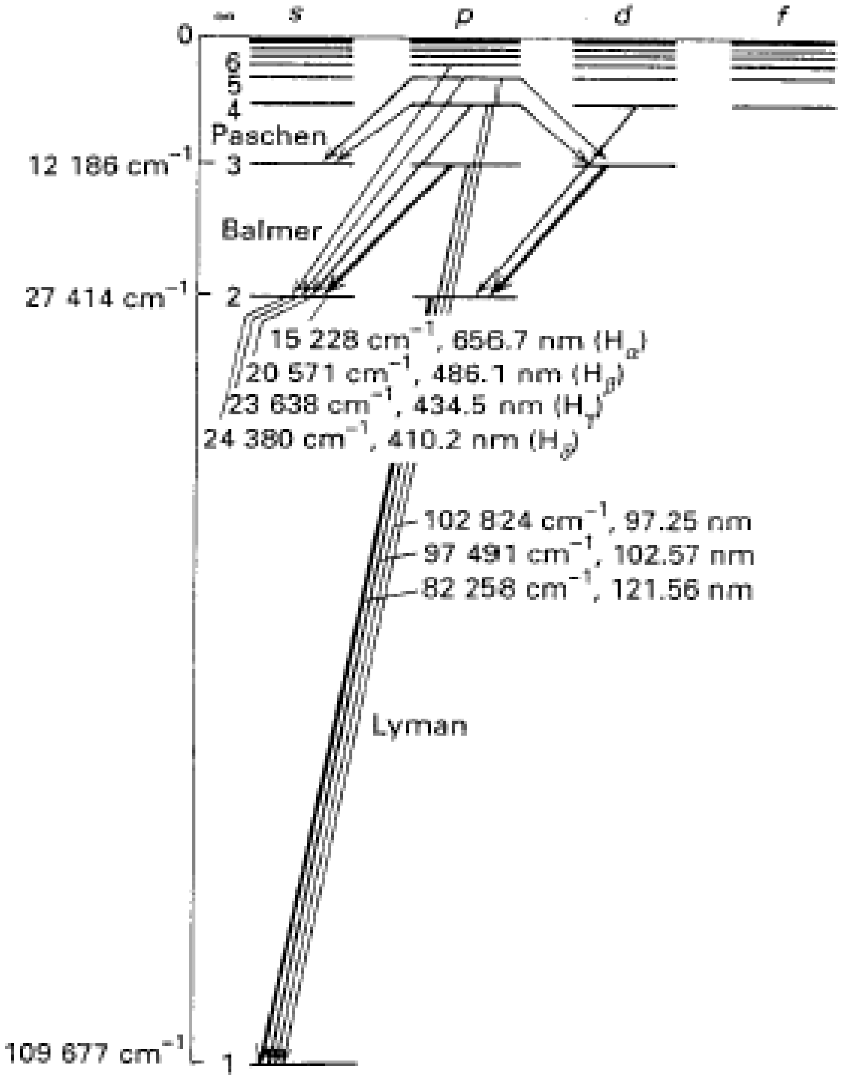
Transition

Ground state

Excited state

Emission and absorption for a hydrogen atom that is composed of one proton and one electron. The radius of the circular orbit is given by $n^2 \times 0.53$ Å, where n is the quantum number and 1Å = 10^{-8} cm.

The Spectrum of Hydrogen



Energy diagram of the hydrogen atom.

The electronic spectrum of hydrogen - the Bohr atom

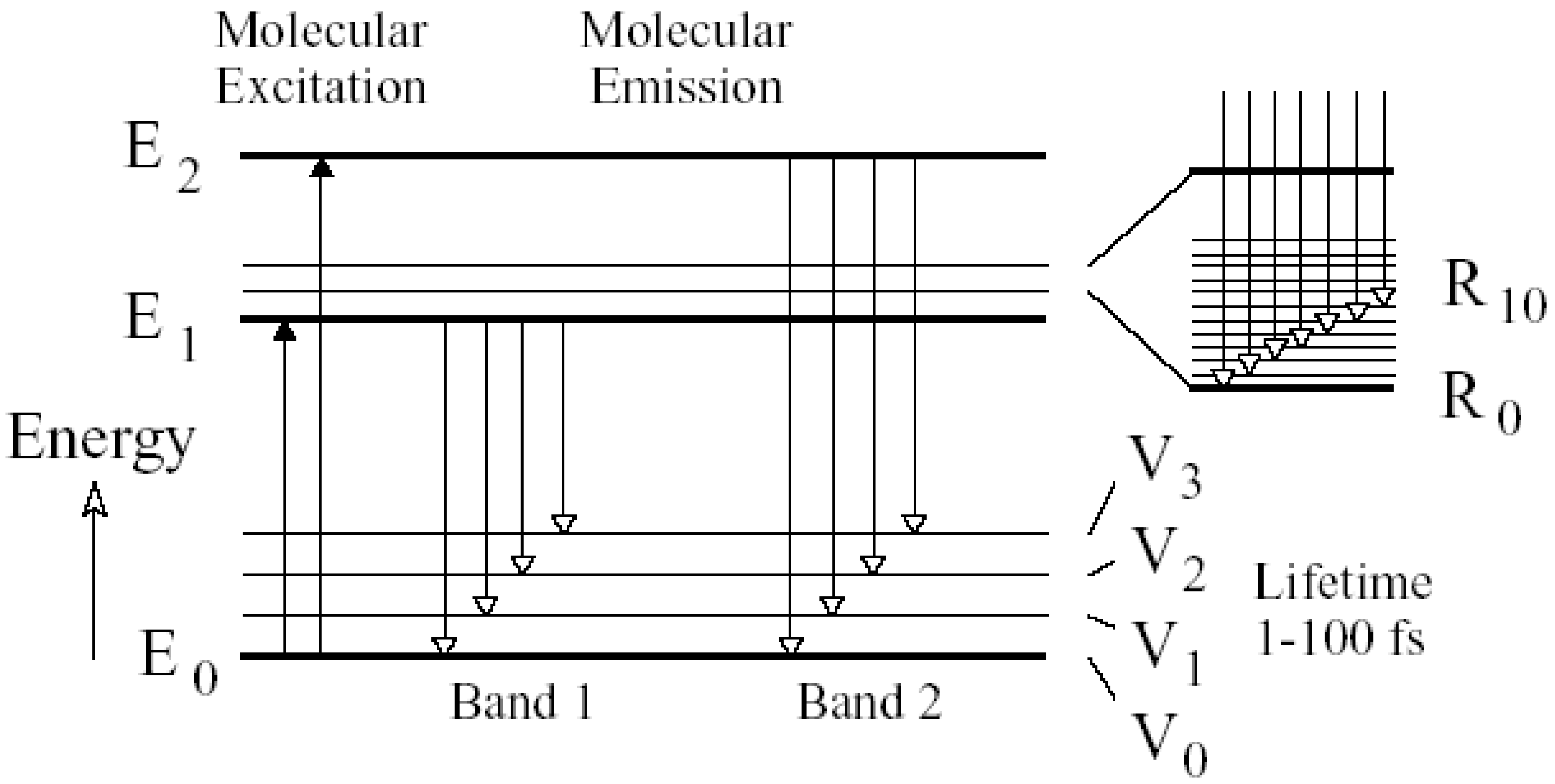
- http://mutuslab.cs.uwindsor.ca/schurko/molspec/animations/bird_concordia/HydrogenSpectrum.htm

Atomic emission spectra:

- http://mutuslab.cs.uwindsor.ca/schurko/molspec/animations/shockwave_animations/atomicspectraa.swf

Band Spectra of Molecules

Molecule:

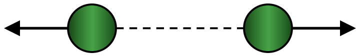


vibrational and rotational transitions - **band** emission spectra

http://www.cem.msu.edu/~cem333/Week02.pdf

Absorption in Earth’s Atmosphere - 1

- Earth’s atmosphere - mainly N_2 and O_2.



- These two molecules are spectrally “dull”!
  - → Have only photoionization, photodissociation, and atomic-like lines.
  - → All of these are at high energies that involve interaction with short-wave UV radiation to produce atomic oxygen, ozone, and atomic nitrogen which in turn interact with UV.

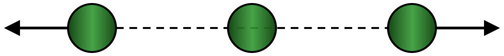
- The two O or N nuclei can only move towards and away from each other during vibration.
  - → They have one vibrational mode due to the symmetrical charge distribution, and so lack a permanent dipole moment.
  - → As a result, they have little radiative activity in the visible and IR.

Absorption in Earth's Atmosphere - 2

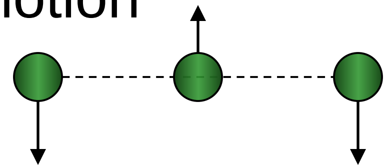
- Earth's atmosphere also contains CO_2, N_2O, which are triatomic molecules having a linear symmetrical configuration.
- These molecules do have IR spectra.

3 vibrational modes

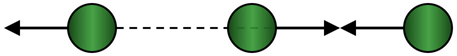
ν1 → symmetric stretch



ν2 → bending motion



ν3 → antisymmetric stretch



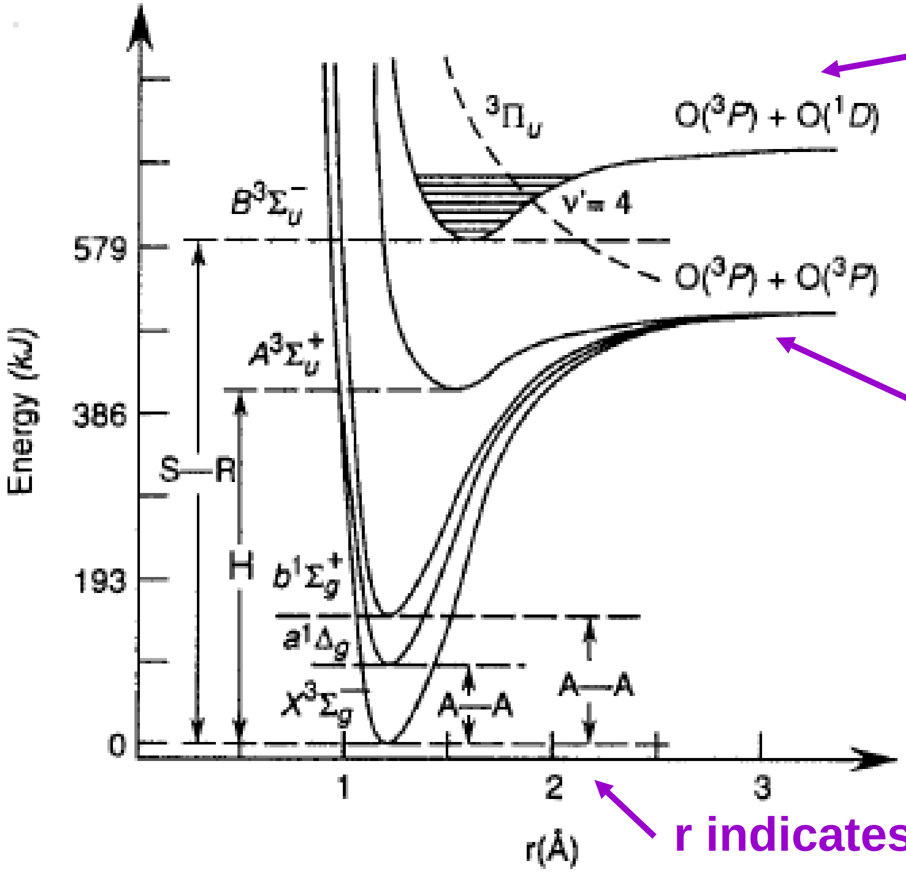
See animation at http://chemmac1.usc.edu/bruno/java/Vibrate.html

Absorption in Earth's Atmosphere - 3

Let's return to molecular oxygen - what can happen?

- The dissociation potential is the energy necessary to photodissociate (or separate) a molecule into atoms
- The sign and magnitude of the force between two atoms in a molecule such as O_2 depend on:
  - → The distance between the two nuclei
  - → Their electronic configuration
- This force is illustrated in a potential energy curve
- The ground state represents the maximum stability at the minimum energy

Potential Energy Curves for O_2



Herzberg:

$200 < \lambda < 240$ nm

$O_2 + h\nu \rightarrow O(^3P) + O(^1D)$

$\lambda < 320$ nm is source of heating of stratosphere

Schumann-Runge:

$\lambda < 200$ nm

$O_2 + h\nu \rightarrow O(^3P) + O(^3P)$

r indicates the separation between the O nuclei

FIGURE 4.1 Potential energy curves for ground and first four excited states of O_2. S–R = Schumann–Runge system, H = Herzberg continuum, A–A = atmospheric bands (adapted from Gaydon, 1968).

B. J. Finlayson-Pitts, 2000

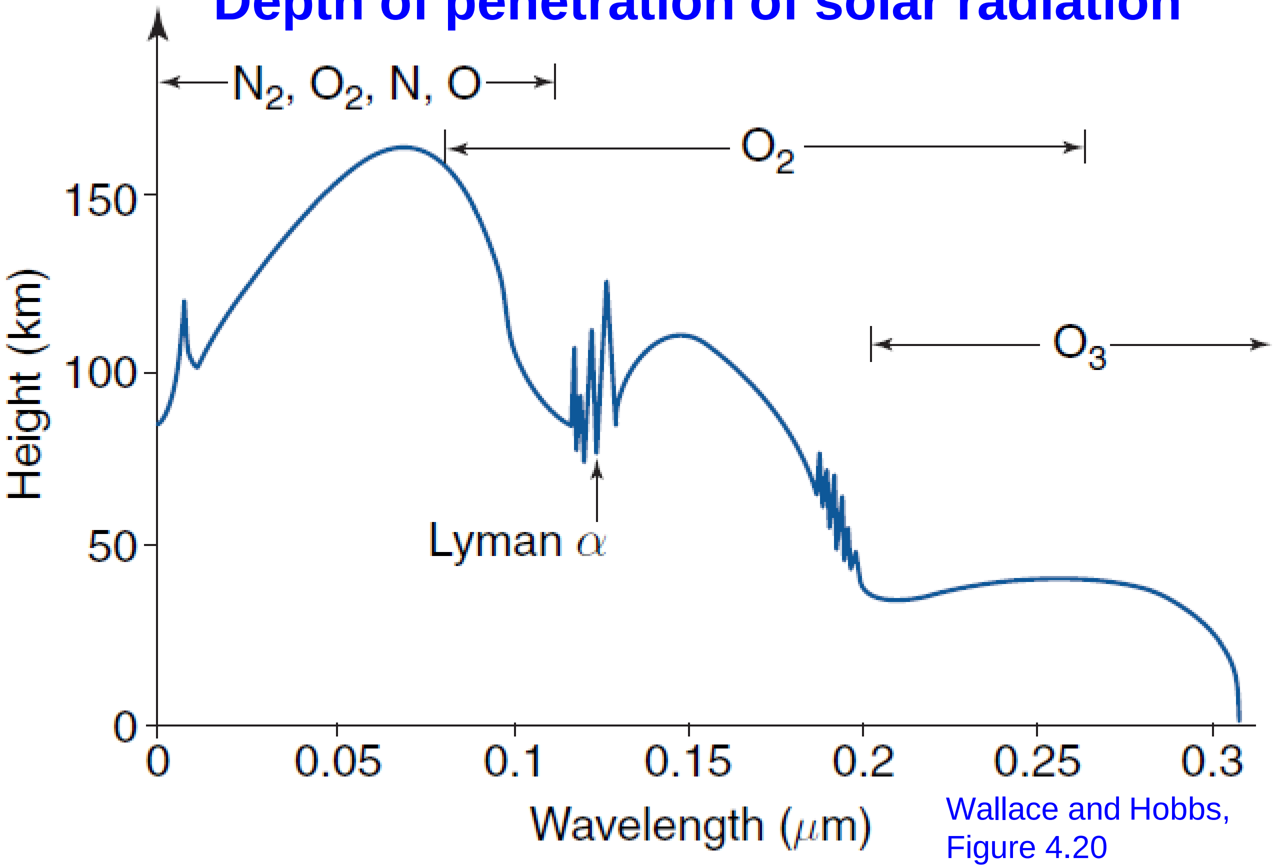
$O(^3P)$ is the O atom in the ground-level triplet state and is highly reactive due to two unpaired electrons

$O(^1D)$ is the O atom in an excited singlet state and is rapidly stabilized to $O(^3P)$ by collision with N_2 or O_2

Absorption by O_2 - 1

This figure shows the height in the atmosphere at which the solar flux density is reduced by a factor of e, so where the optical depth is 1 (= ln F_o/F)

Depth of penetration of solar radiation

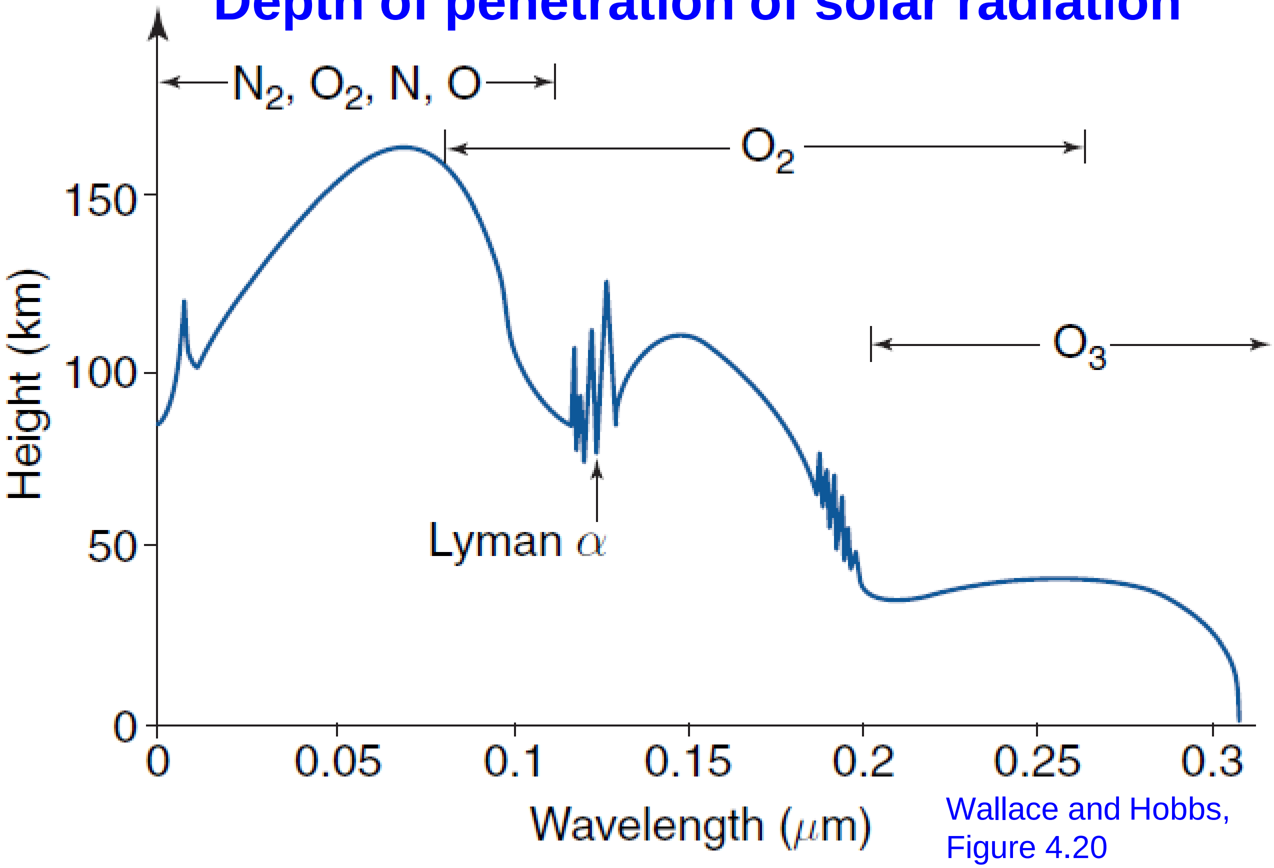


Wallace and Hobbs, Figure 4.20

Absorption by O_2 - 2

- For $\lambda \leq 330$ nm, no solar radiation reaches the ground (implications for the long method of measuring the solar constant…)
- The shortest λ are absorbed at the highest altitudes by O_2, O, N_2, N
- O_2 absorbs from ~85 to 200 nm, photolyzed to produce O
- O_3 absorbs for λ > 200 nm, producing the surface cut-off

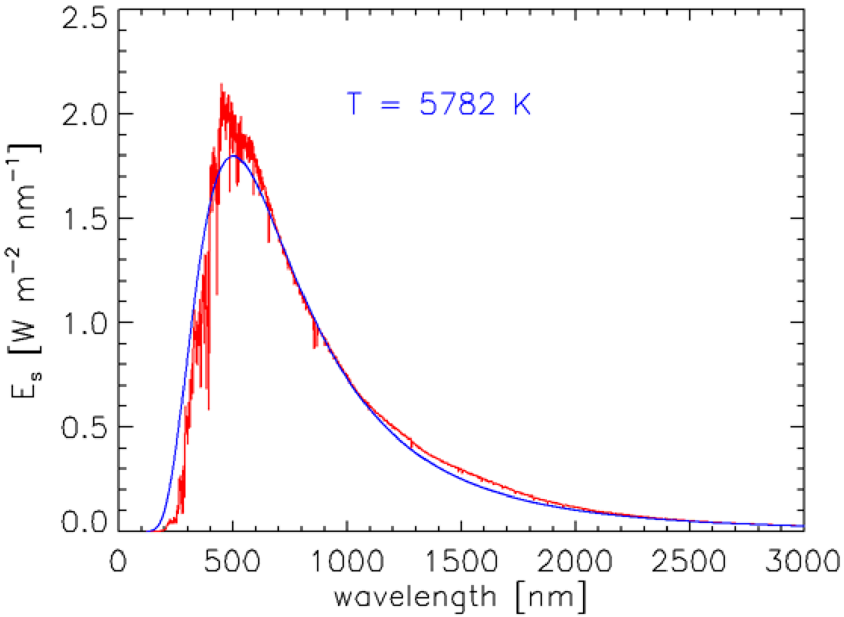
Depth of penetration of solar radiation

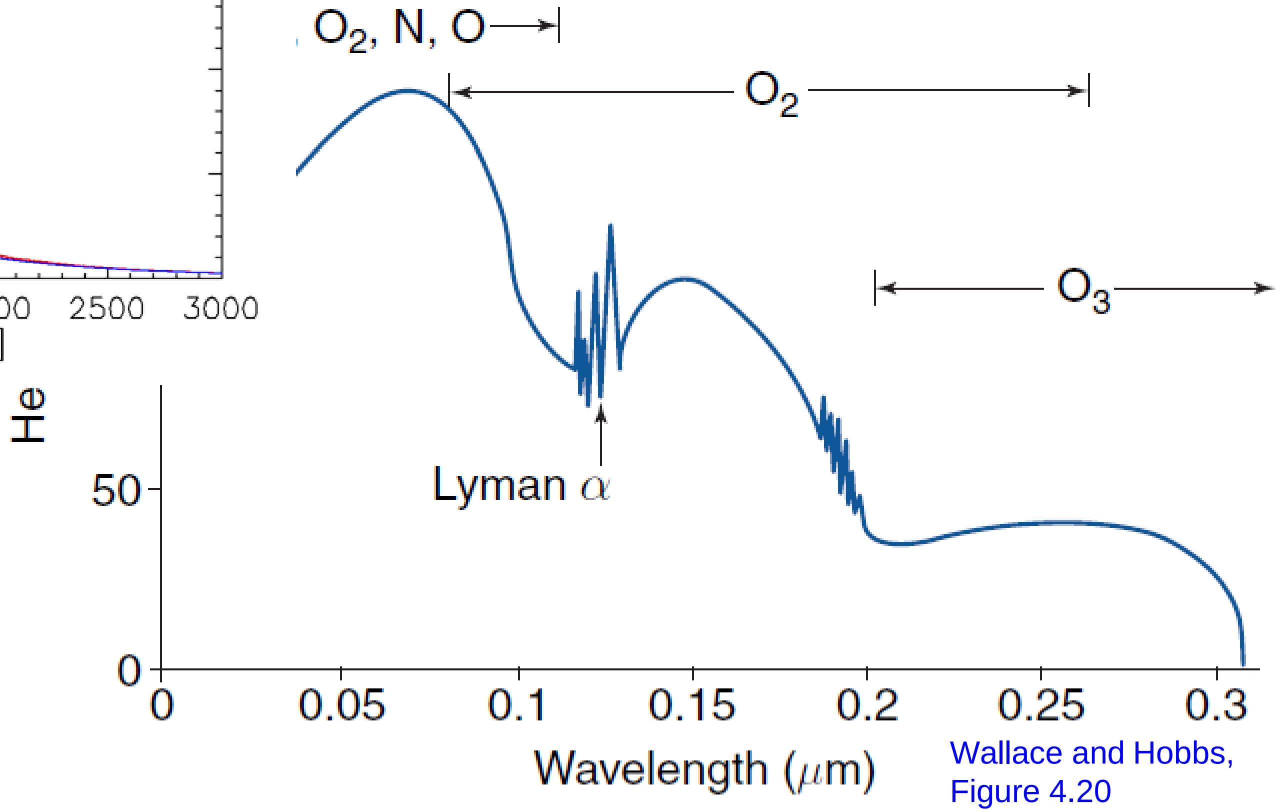


Wallace and Hobbs, Figure 4.20

Absorption by O_2 - 3

Compare with a plot of the solar spectrum





Wallace and Hobbs, Figure 4.20

There is little solar radiation < 150 nm, so absorption in the far UV contributes little to the energy balance of Earth (although important in aurora, airglow, and ionosphere).

Absorption by O_2 - 4

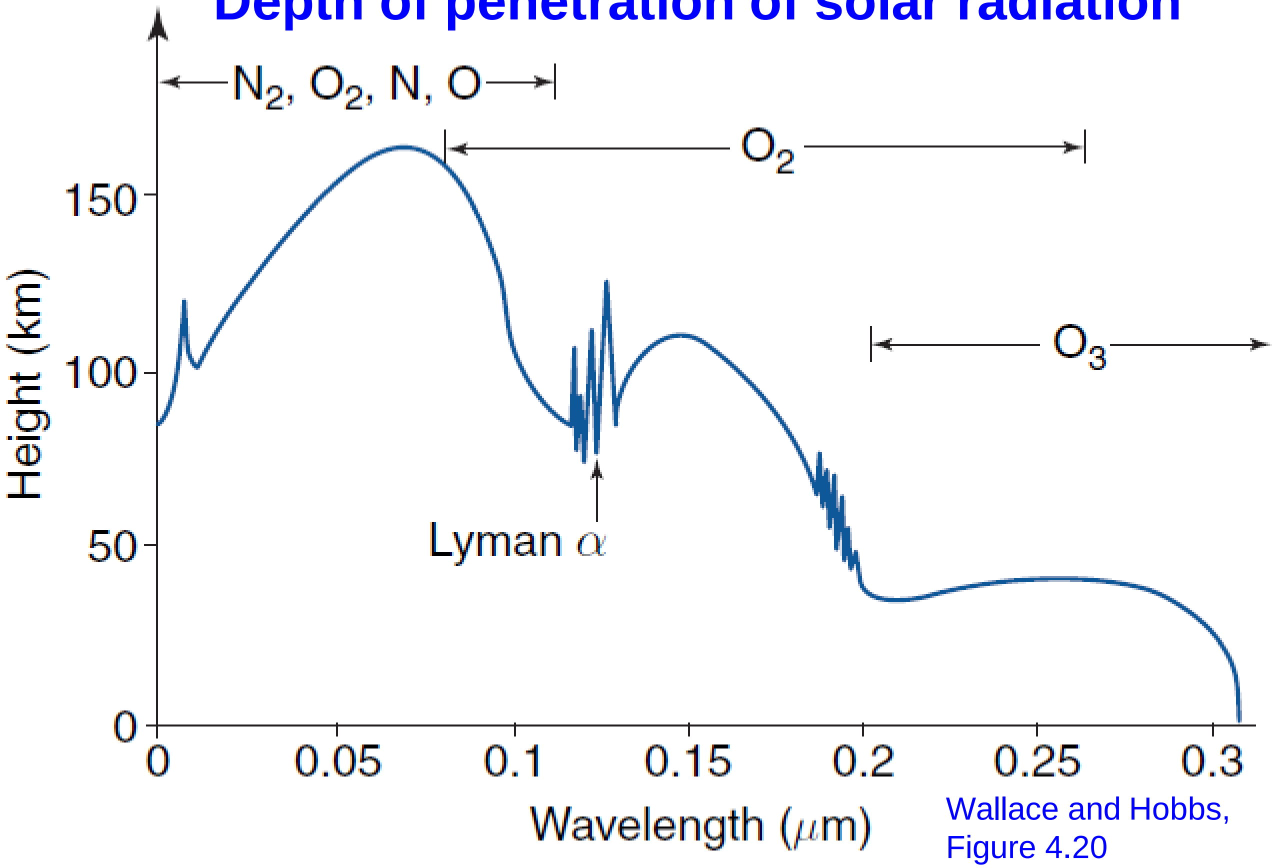
$O_2 + h\nu \rightarrow O + O$
$\lambda < 240$ nm
$O + O_2 + M \rightarrow O_3 + M$

Source of ozone (O_3) in the stratosphere

M (any molecule) carries away the extra energy

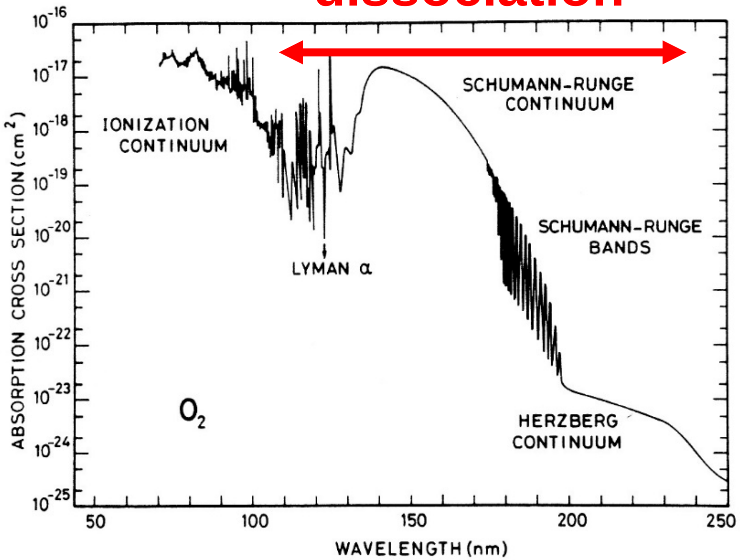
$O_3 + h\nu \rightarrow O_2 + O$
$\lambda < 310$ nm

Depth of penetration of solar radiation

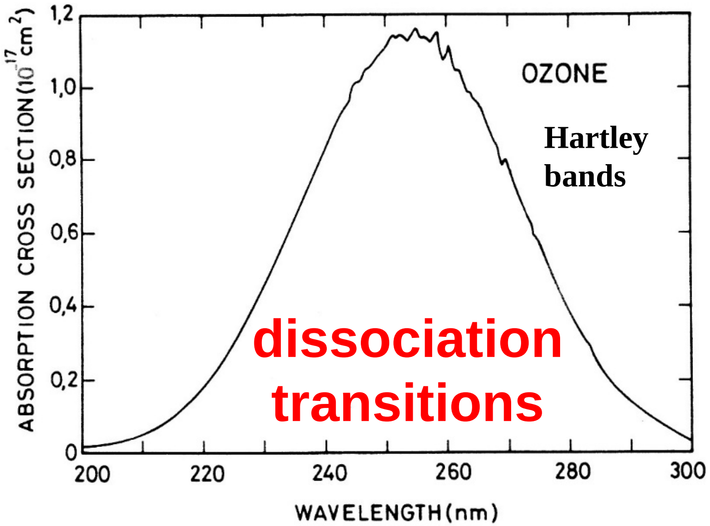


Wallace and Hobbs, Figure 4.20

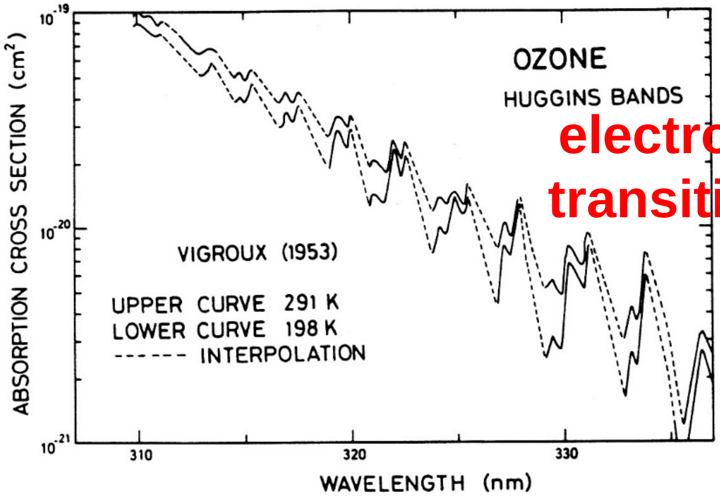
O_2 and O_3 Absorption Cross Sections



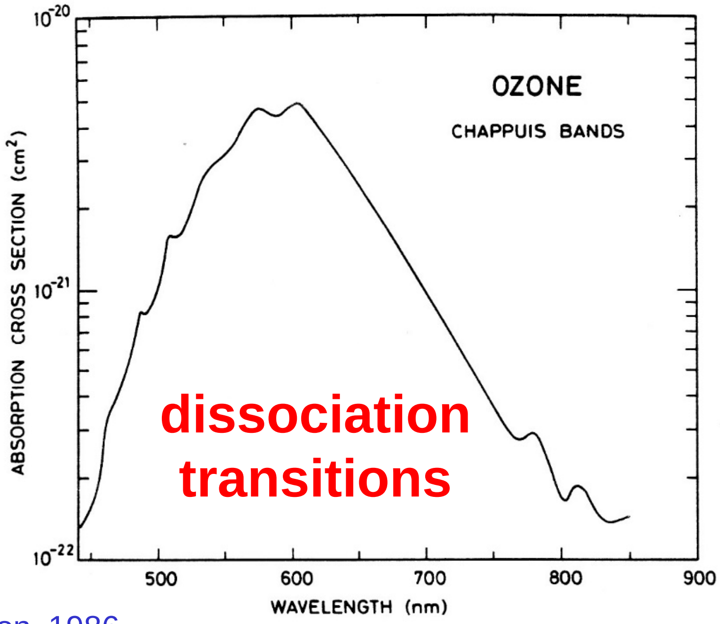
dissociation



dissociation transitions



electronic transitions



dissociation transitions

Brasseur and Solomon, 1986

Spectrum of Solar Radiation vs. Altitude

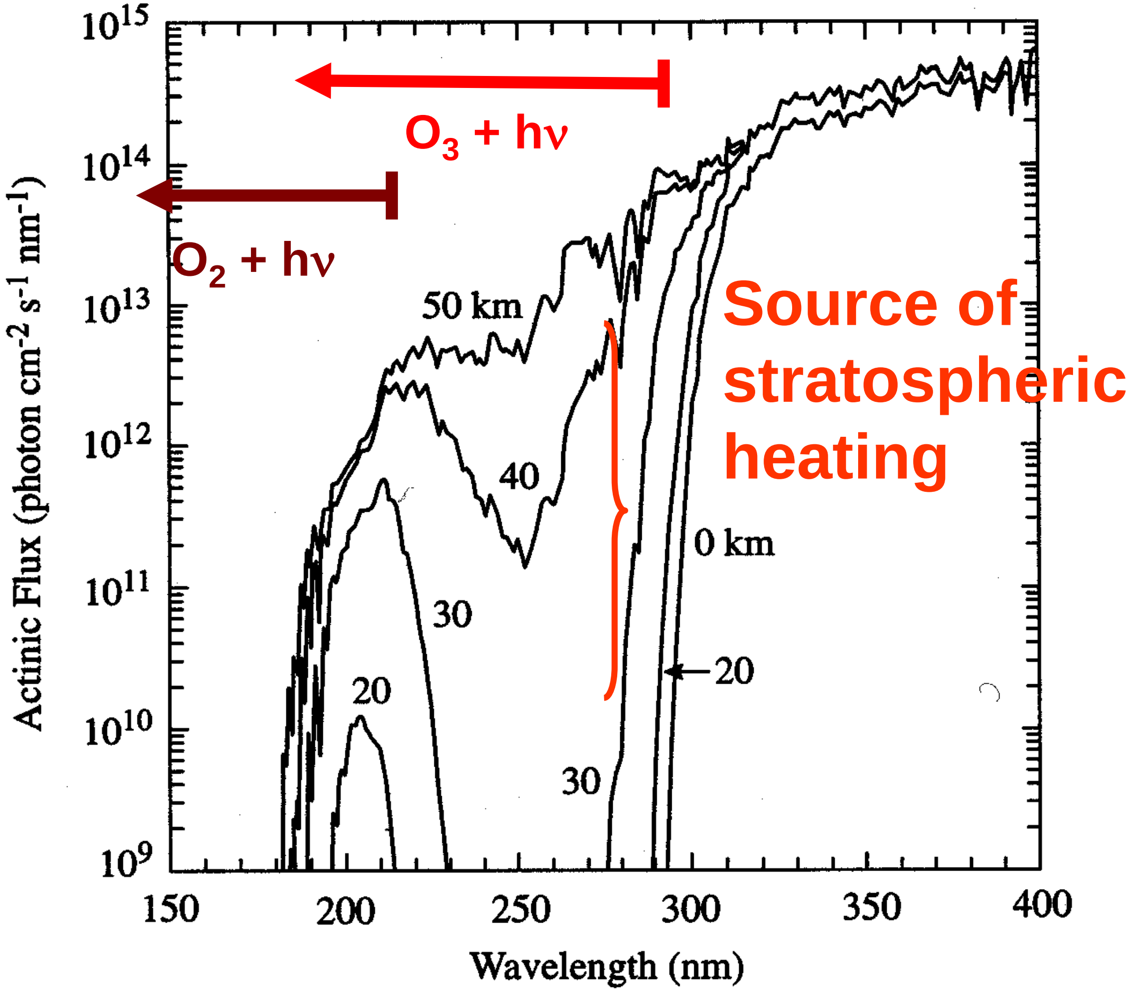


Fig. 10-2 Solar actinic flux at different altitudes, for typical atmospheric conditions and a 30° solar zenith angle. From DeMore, W. B., et al. *Chemical Kinetics and Photochemical Data for Use in Stratospheric Modeling*. JPL Publication 97-4. Pasadena, Calif.: Jet Propulsion Lab, 1997.

Absorption of Solar Radiation

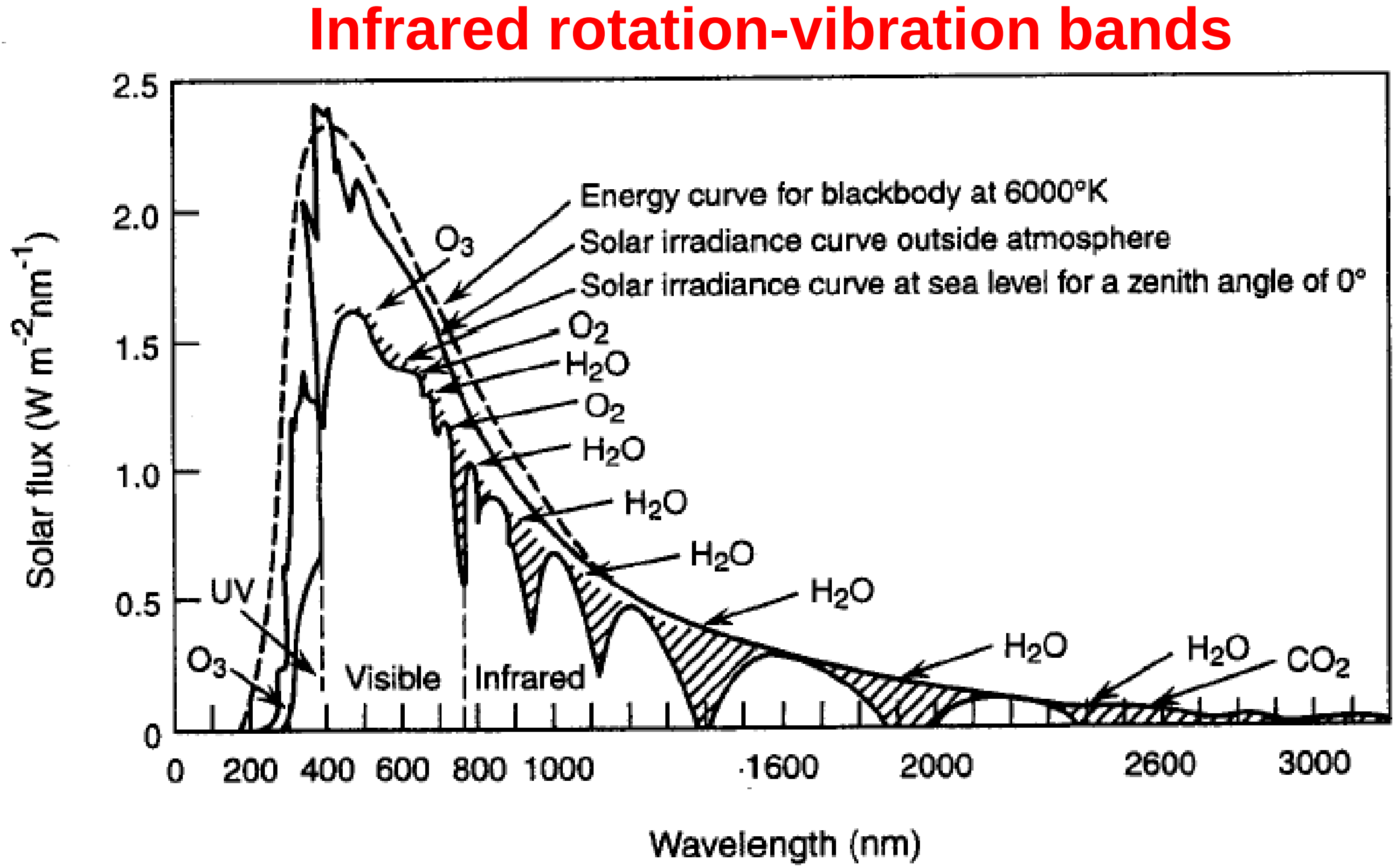


FIGURE 14.1 Solar flux outside the atmosphere and at sea level, respectively. The emission of a blackbody at 6000 K is also shown for comparison. The species responsible for light absorption in the various regions (O_3, H_2O, etc.) are also shown (adapted from Howard *et al.*, 1960).

Solar Absorption – A Summary

Interactions between solar radiation and the atmosphere:

- Photoionization and photodissociation in the upper atmosphere
- Atmospheric scattering
- Absorption in the lower atmosphere
  - → In the ultraviolet, where ozone strongly absorbs
  - → At the red end of the solar spectrum, primarily due to absorption by water which is concentrated in the troposphere
  - → Absorption in the infrared by greenhouse gases

Ozone in the Atmosphere & Heating Rates