Radiative Transfer Through the Atmosphere

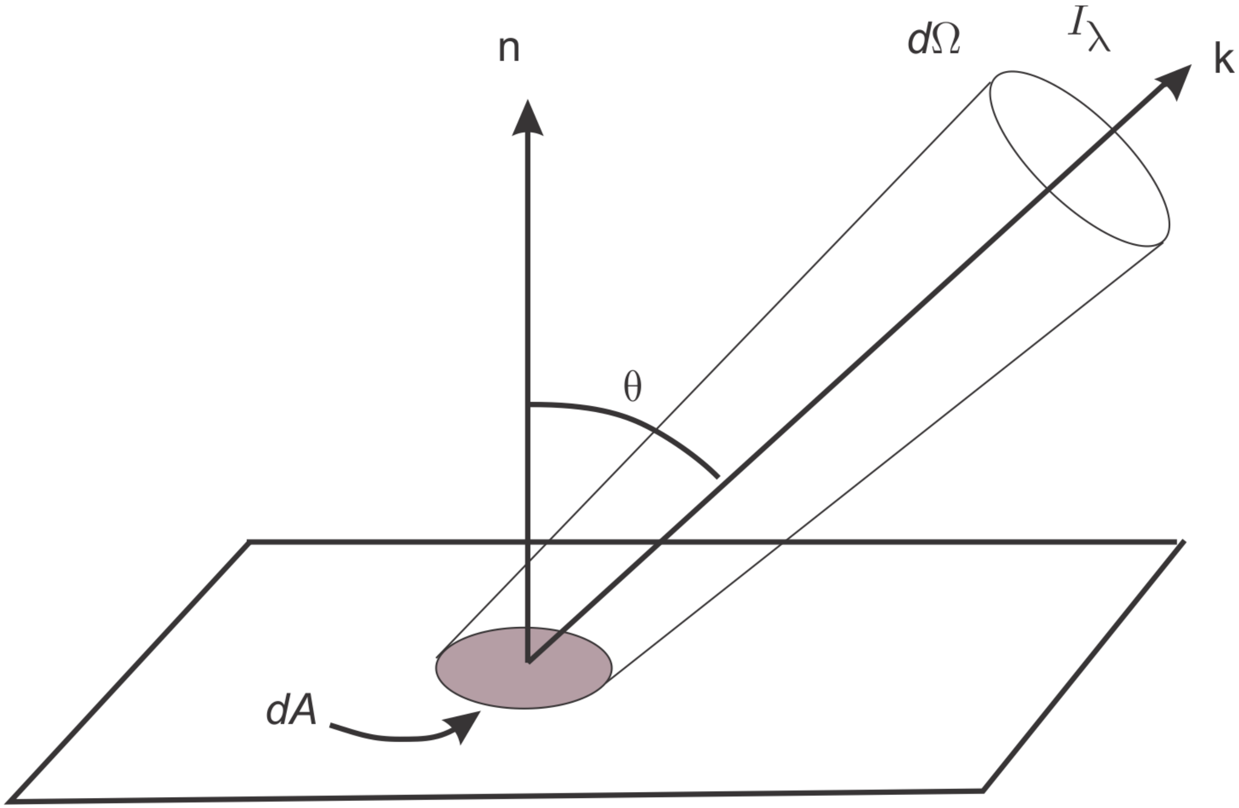
Importance for Climate:

- Shortwave Absorption:
  - Clouds, H_2O, O_3, some CO_2
- Shortwave Reflection:
  - Clouds, surface, atmosphere
- Longwave Absorption:
  - Clouds, H_2O, CO_2, CH_4, N_2O

Program

- Black-body radiation
- Interaction of radiation with gases
- Interaction of radiation with clouds and aerosols

Intensity



$$dE_\lambda = I_\lambda \cos\theta dA d\Omega d\lambda dt$$

I_λ is defined as the amount of energy passing through a surface area dA within a solid angle dΩ per wavelength interval per unit time. Units are $J\, m^{-2} sr^{-1} m^{-1} s^{-1}$

Image credit: *Kerry Emanuel*

Intensity, Flux Density, Total Flux Density, Total Flux

Intensity, Flux Density, Total Flux Density, Total Flux

$$I_\lambda = \frac{dE_\lambda}{\cos\theta \, dA \, d\Omega \, d\lambda \, dt}$$

Intensity

Intensity, Flux Density, Total Flux Density, Total Flux

$$I_\lambda = \frac{dE_\lambda}{\cos\theta\, dA\, d\Omega\, d\lambda\, dt}$$

Intensity

$$F_\lambda = \int_\Omega I_\lambda \cos\theta\, d\Omega$$

Flux density is the normal component of intensity integrated over all solid angles

Intensity, Flux Density, Total Flux Density, Total Flux

$$I_\lambda = \frac{dE_\lambda}{\cos\theta \, dA \, d\Omega \, d\lambda \, dt}$$

Intensity

$$F_\lambda = \int_\Omega I_\lambda \cos\theta \, d\Omega$$

Flux density is the normal component of intensity integrated over all solid angles

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

Total flux density is the flux density integrated over all wavelengths

Intensity, Flux Density, Total Flux Density, Total Flux

$$I_\lambda = \frac{dE_\lambda}{\cos\theta \, dA \, d\Omega \, d\lambda \, dt}$$

Intensity

$$F_\lambda = \int_\Omega I_\lambda \cos\theta \, d\Omega$$

Flux density is the normal component of intensity integrated over all solid angles

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

Total flux density is the flux density integrated over all wavelengths

$$f = \int_A F \, dA$$

Total flux is the integral of the total flux density over area and is the radiant power in Watts

Black-body Radiation

- Planck's Law
- Based on assumption of local thermodynamic equilibrium
  - (Not valid at very high altitudes in atmosphere)

$$B_\lambda(T) = \frac{2hc^2}{\lambda^5 \left[e^{hc/\lambda kT} - 1 \right]}$$

$$k = Boltzmann's\ constant$$

$$h = Planck's\ constant$$

$$\lambda = wavelength$$

$$c = speed\ of\ light$$

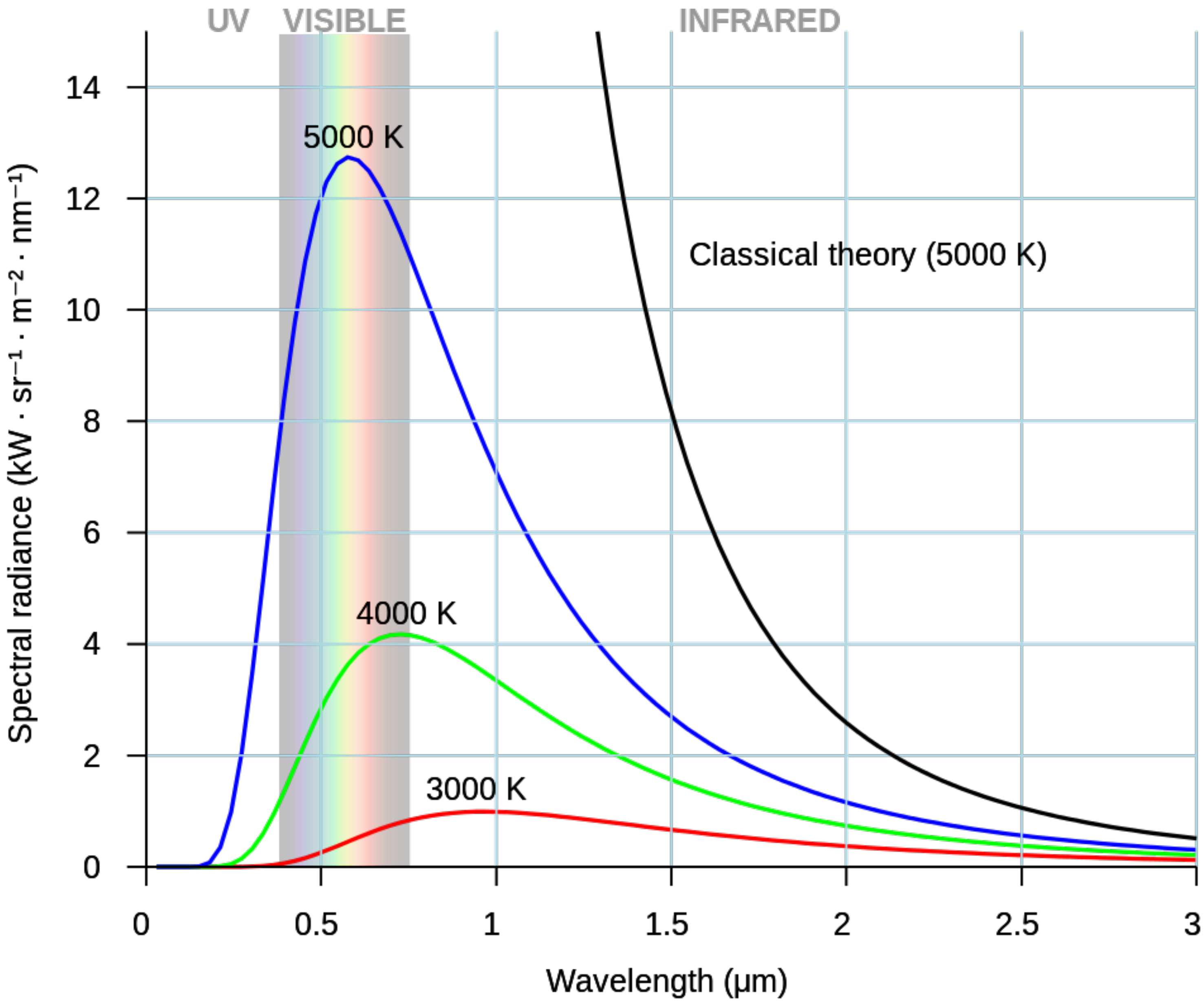


Image credit: *Darth Kule*

Wien's Displacement Law

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

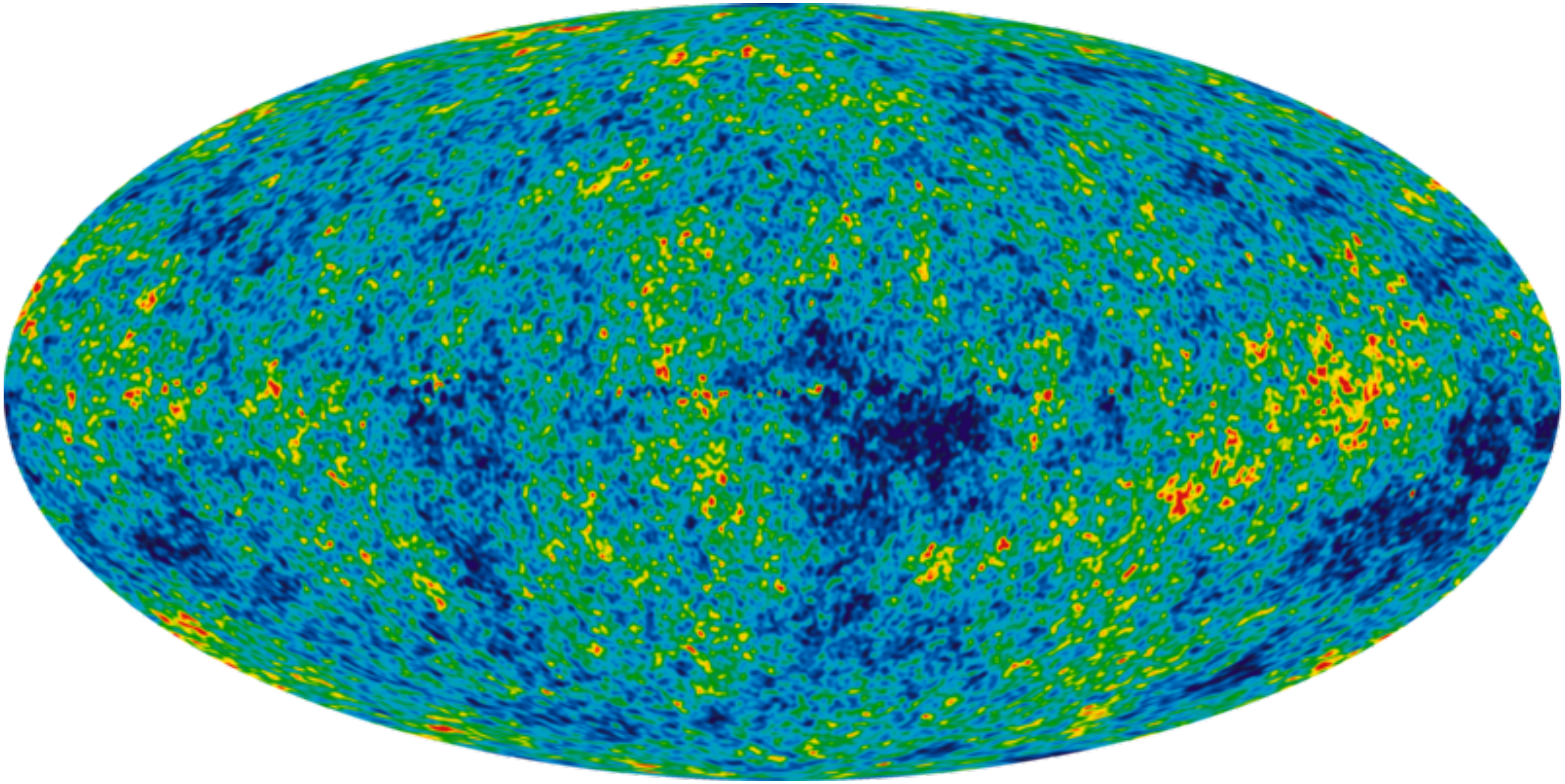
λ_{max} = Wavelength of maximum emission

$$b = 2.9 \times 10^{-3}\ K\ m$$

Pāhoehoe Lava, Hawaii

Image credit: *Hawaii Volcano Observatory*

Image credit: *NASA/IPAC*



9 year image of background cosmic radiation

Image credit: *NASA/WMAP Science Team*

Comparison of Black-body Curves of Earth and Sun

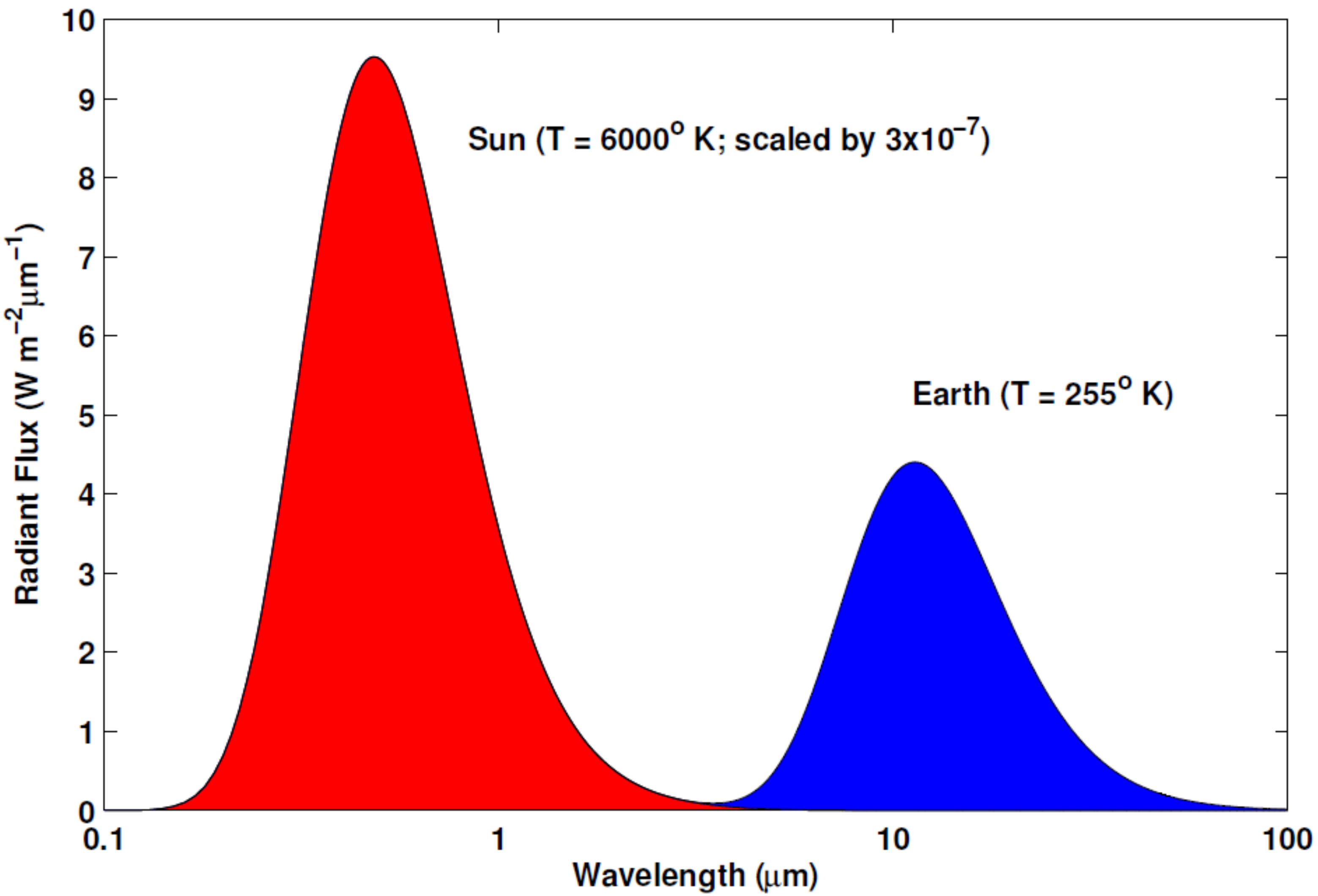


Image credit: *Kerry Emanuel*

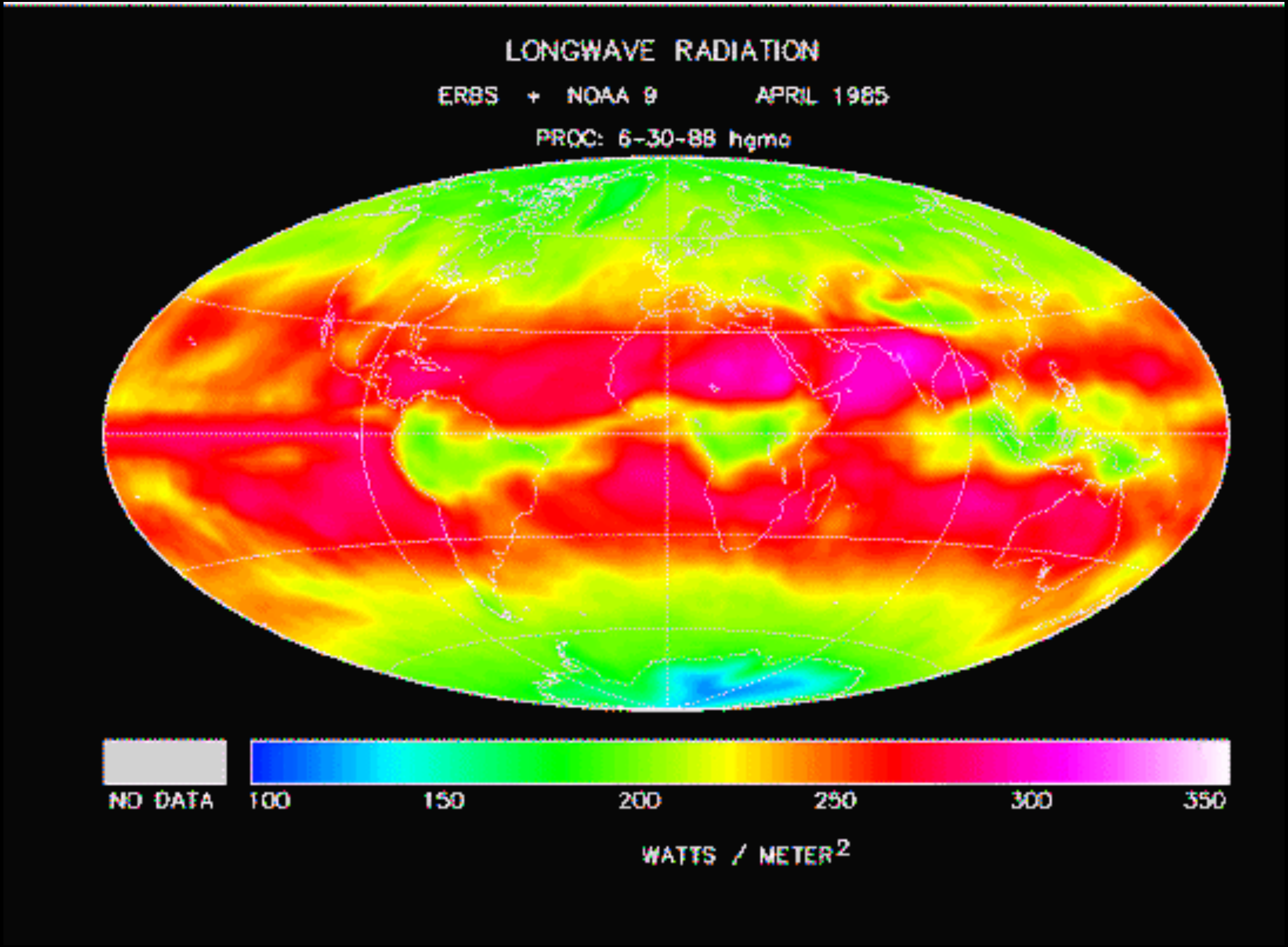


Image credit: *NASA*

The **Stefan-Boltzmann** Law is the integral of the Planck function over all frequencies and all angles in a hemisphere:

$$\pi \int_0^\infty B_\upsilon(T)\,d\upsilon = \sigma T^4$$

$$\sigma \equiv \frac{2\pi^5 k^4}{15 c^2 h^3} \quad \textit{Stefan - Boltzmann constant}$$

Emission and Absorption Spectra

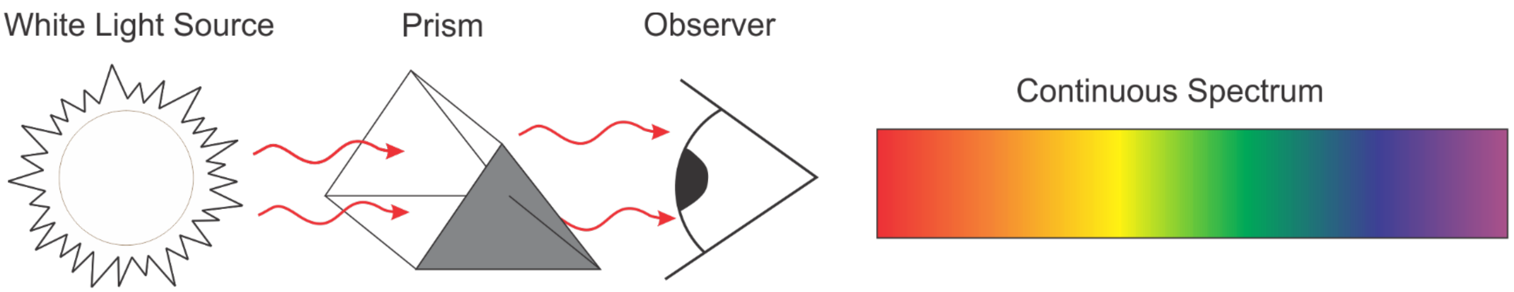


Image source*: Kerry Emanuel*

Emission and Absorption Spectra

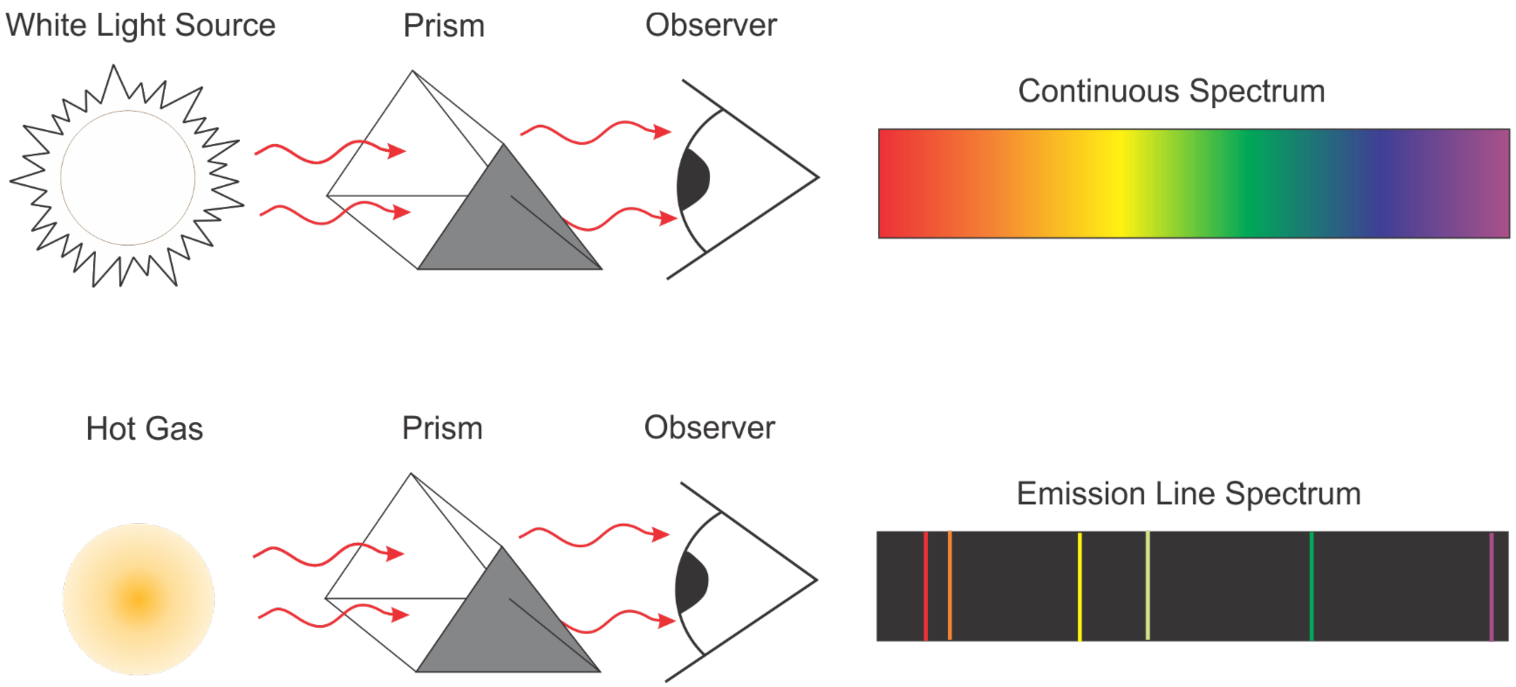


Image source*: Kerry Emanuel*

Emission and Absorption Spectra

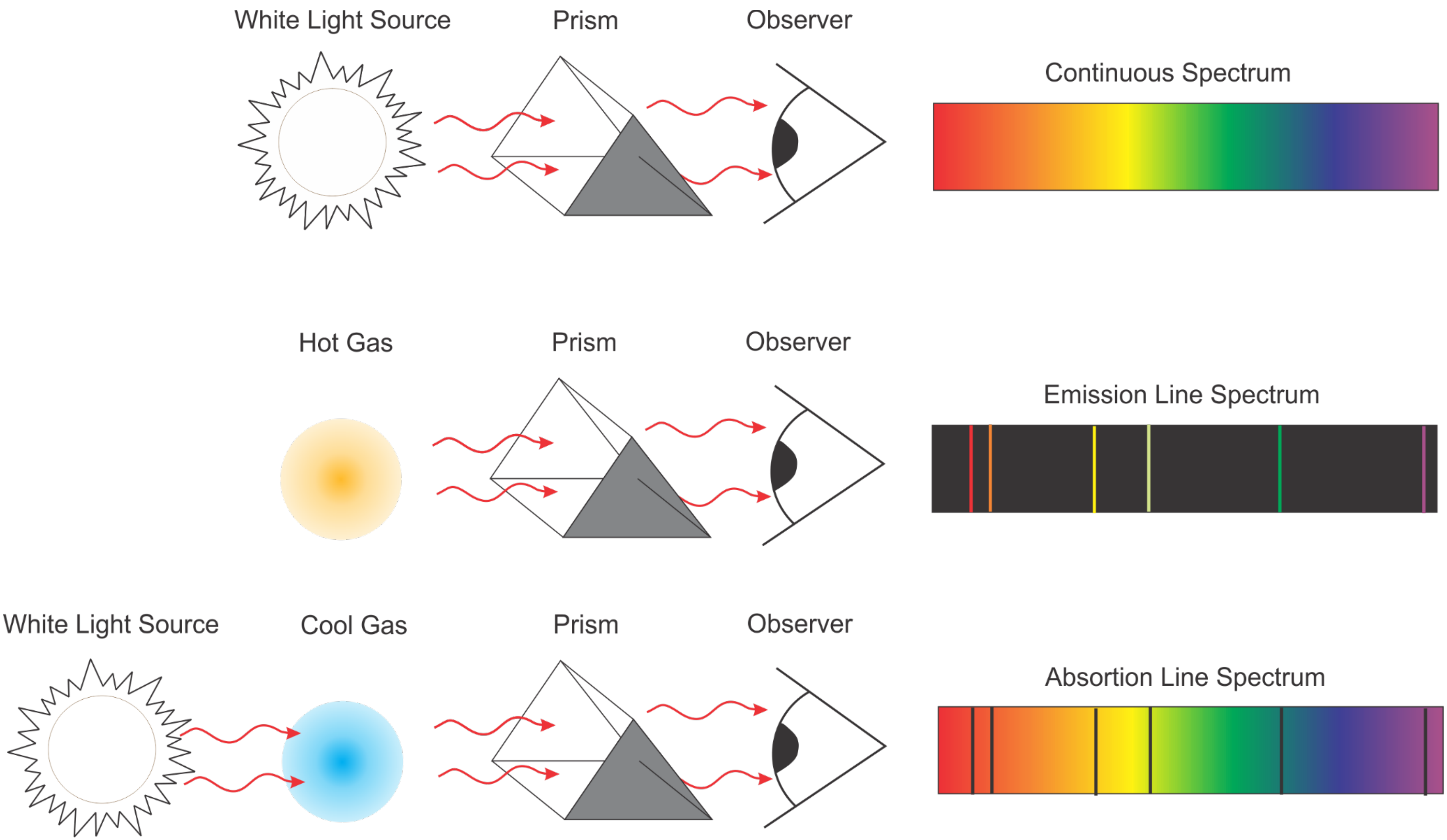
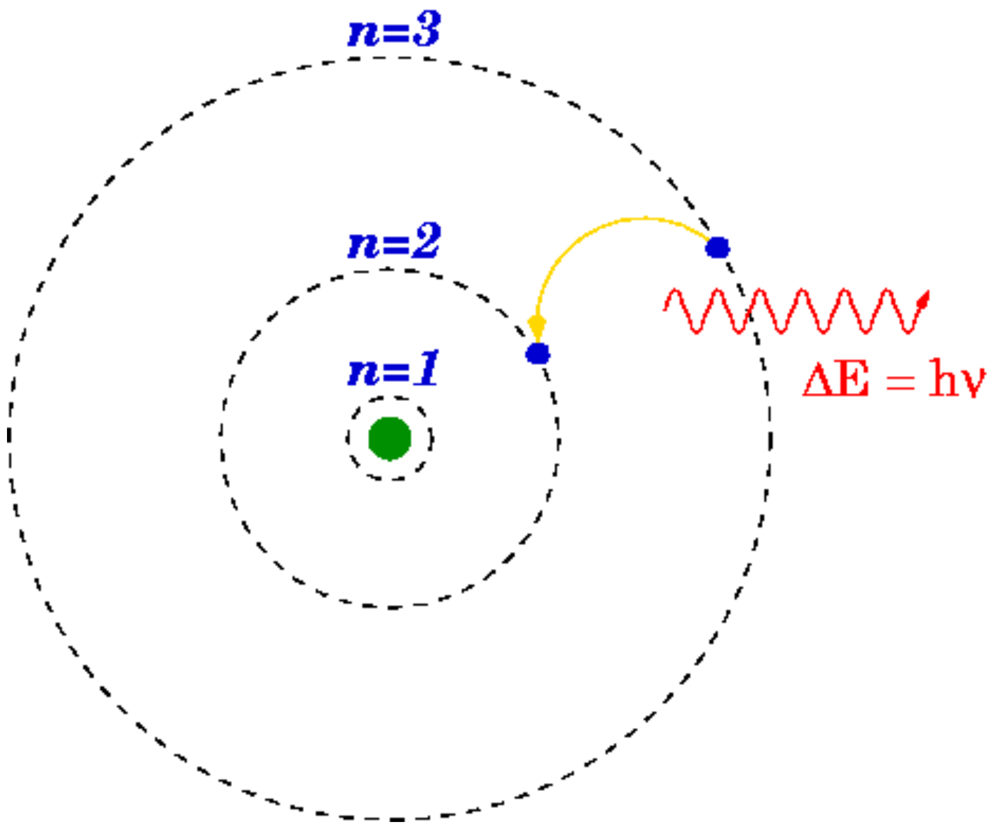


Image source*: Kerry Emanuel*

Absorption and Emission in a Gas

Electronic Transitions



Electric transition in the quantum energy states of an atom resulting in the emission of a photon

Image credit: *Willow*, Wikipedia

Electronic Transitions

$$\textit{Photon energy} \quad E_{\upsilon} = \hbar\upsilon$$

$$\textit{Atomic energy levels} \quad E_{\upsilon} = n\hbar\upsilon, \;\; n = 0, 1, 2, 3\ldots$$

$$\hbar \equiv h / 2\pi$$

An isolated atom can absorb only those photons whose energy is equal to the difference between two atomic energy levels. Mostly involves ultraviolet and visible parts of solar spectrum.

Molecules have additional energy levels:

Rotational and Vibrational Transitions

Simple homonuclear diatomic molecule (e.g. N_2, O_2):

No electric dipole moment (difference between center of mass and center of charge):

→ No interaction with electromagnetic radiation

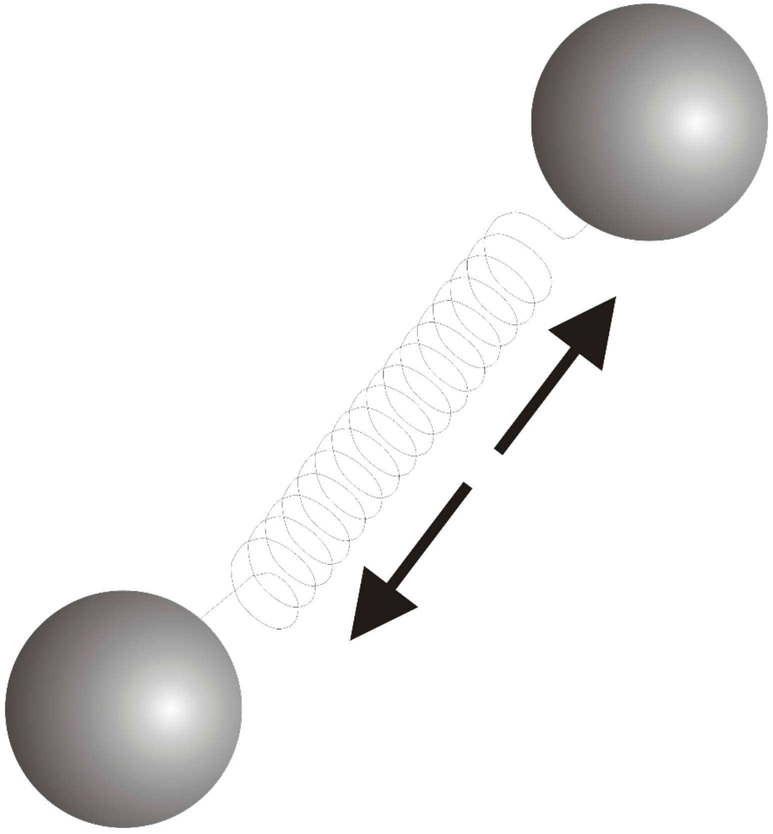


Image credit: *Kerry Emanuel*

Rotational and Vibrational Transitions

Heteronuclear diatomic molecule (e.g. CO):

Electric dipole moment, rotational modes

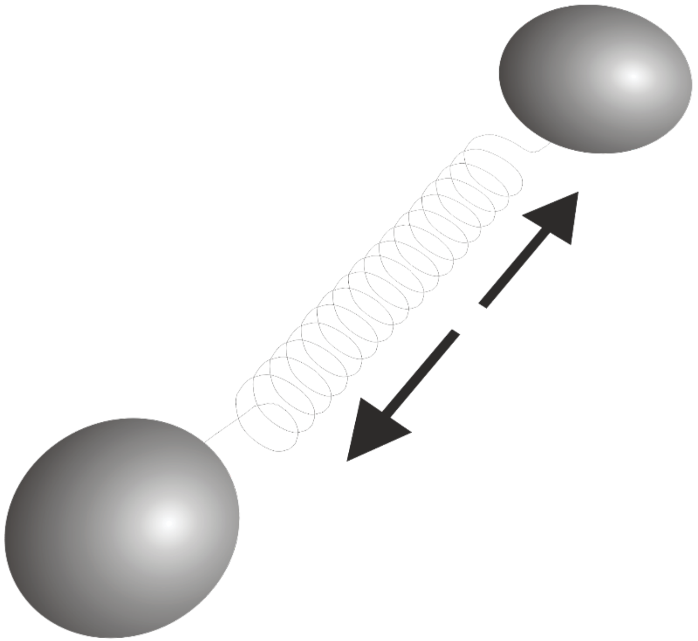


Image credit: *Kerry Emanuel*

Energy level diagram for rotational-vibrational transitions

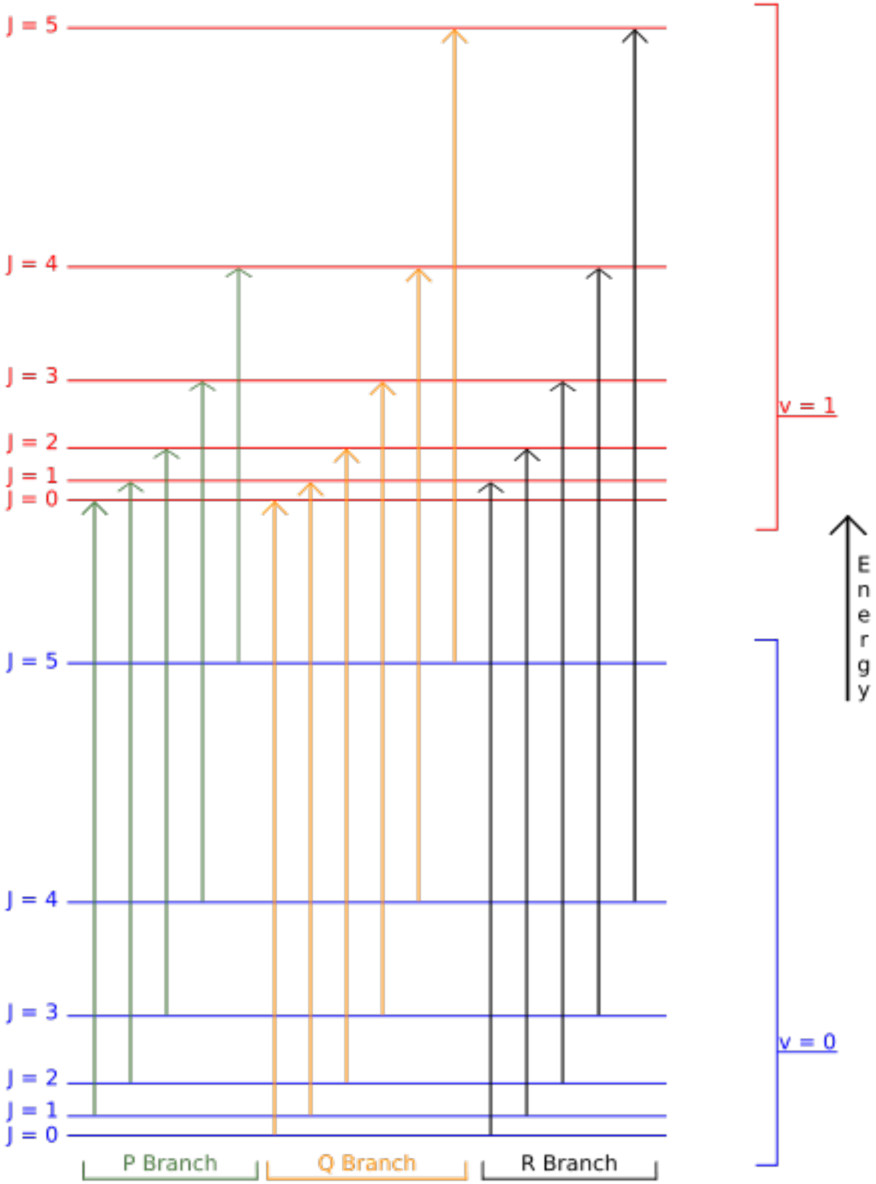


Image credit: *David-i98*, Wikipedia

Polyatomic Molecules

3N-6 vibrational modes and numerous rotational and rotational-vibrational modes

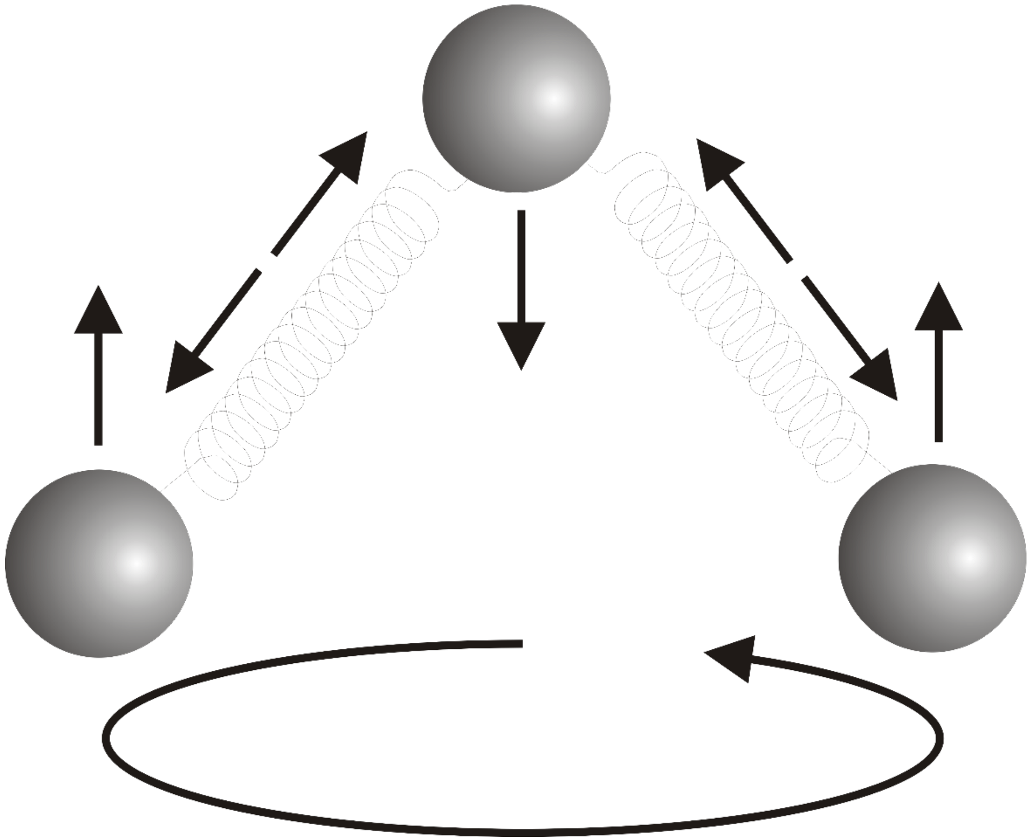
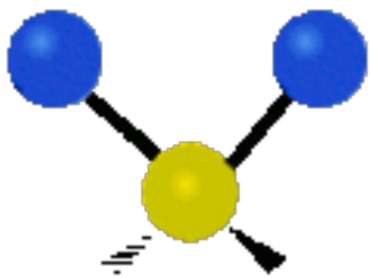
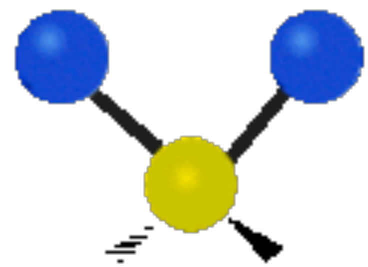


Image credit: *Kerry Emanuel*

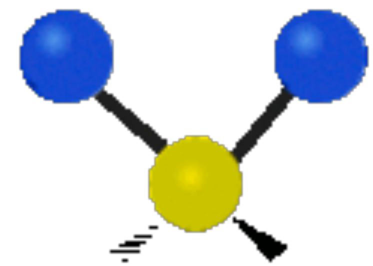
The three fundamental modes of a water molecule



v_1,O-H symmetric stretching
3657 cm^{-1} (2.734 μm)



v_2, H-O-H bending
1595 cm^{-1} (6.269 μm)



v_3, O-H asymmetric stretching
3756 cm^{-1} (2.662 μm)

Image credit: *Tiago Becerra Paolini*, Wikipedia

Water infrared absorption coefficient

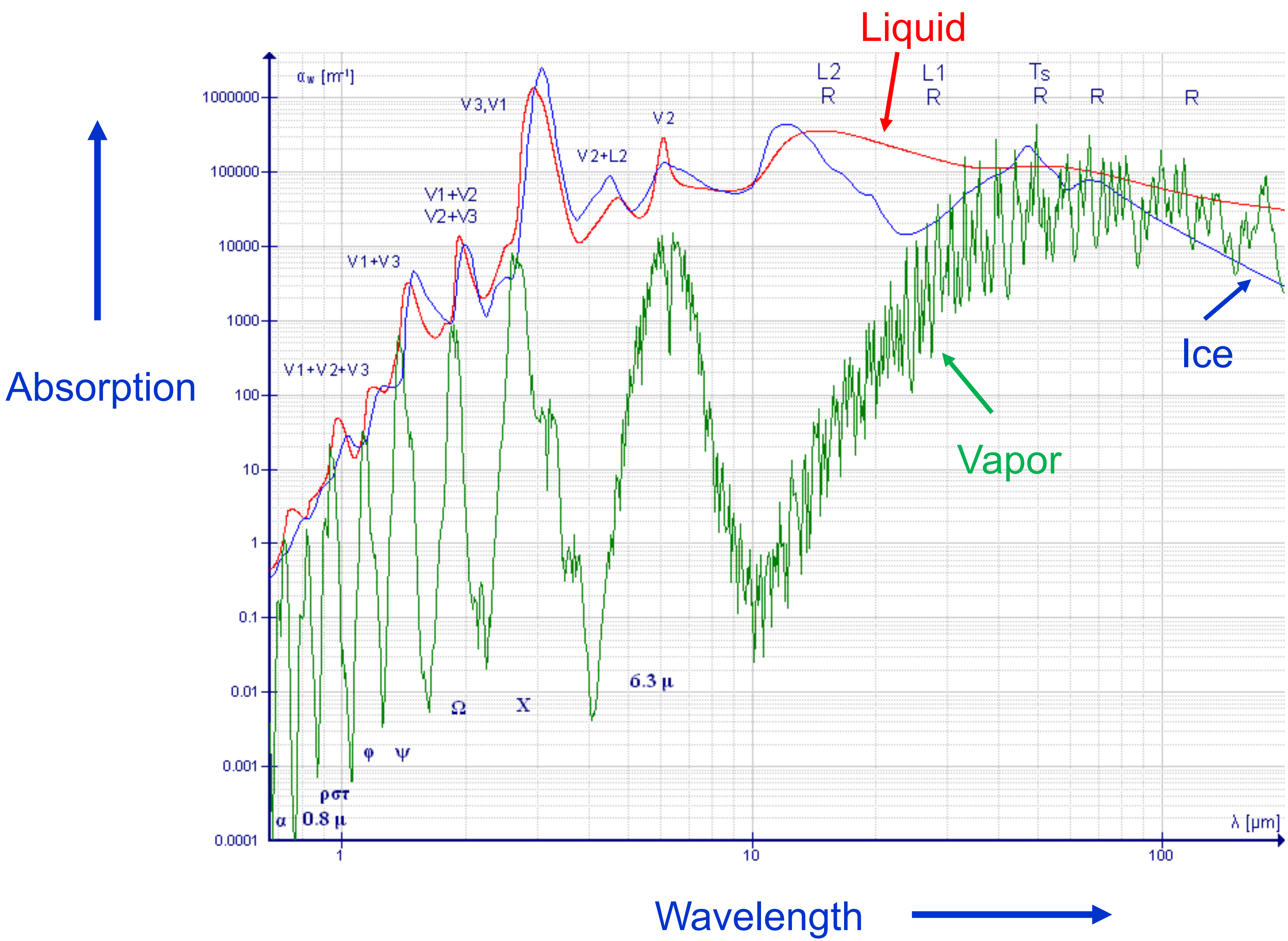


Image credit: *Darekk2*, Wikipedia

Kirchoff's Law

$$a_\lambda = \varepsilon_\lambda$$

Absorptivity = Emissivity

For molecules in a gas:

$$E_{total} = E_{atomic} + E_{vibrational} + E_{rotational} + E_{translational}$$

- Translational energy is the kinetic energy of molecular motions in a gas, proportional to the gas temperature. Not quantized.
- Molecules in a gas can absorb more frequencies than isolated atoms.
- Collisions between molecules can carry away energy or supply energy to interactions between matter and photons.

Natural, Pressure and Doppler Broadening

- **Natural broadening:** Heisenberg's uncertainty principle places a lower bound on actual line width
- **Doppler broadening:** Caused by the fact that the velocity of atoms or molecules relative to the observer follows a Maxwell Distribution, so the effect is dependent on temperature. Produces a Gaussian line shape.
- **Pressure broadening:** Collisions between molecules affect absorption and emission. This effect depends on mostly on pressure, which is proportional to the rate of collisions. The broadening effect is described by a Lorentzian profile in most cases
- There are other broadening mechanisms, but they are less important in our atmosphere

Doppler and Pressure Broadening

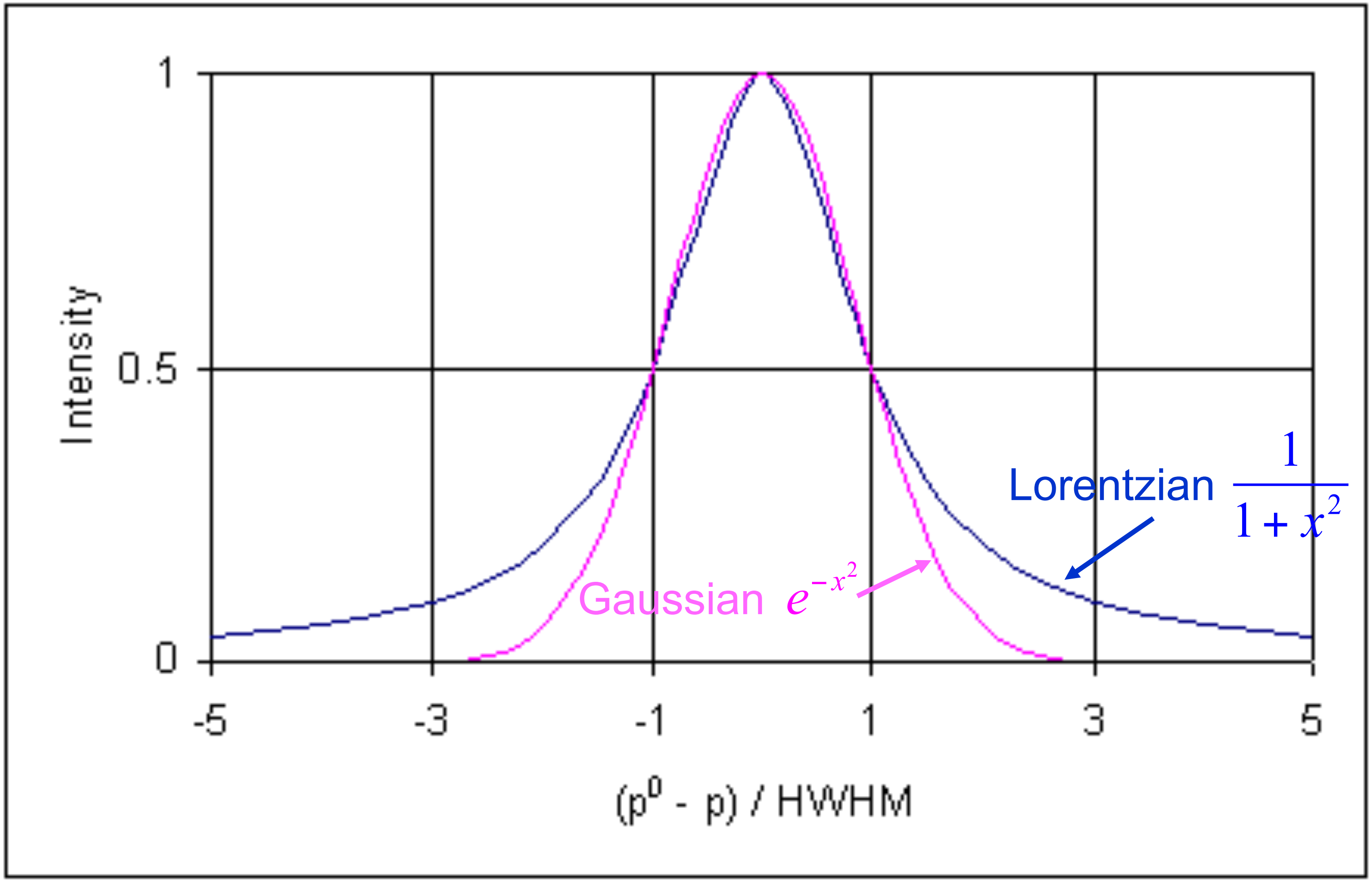


Image credit: *Petergans*, Wikipedia

Principal Atmospheric Absorbers

- H_2O: Bent triatomic, with permanent dipole moment and pure rotational bands as well as rotation-vibration transitions
- O_3: Like water, but also involved in photodissociation
- CO_2: No permanent dipole moment, so no pure rotational transitions, but temporary dipole during vibrational transitions
- Other gases: N_2O, CH_4

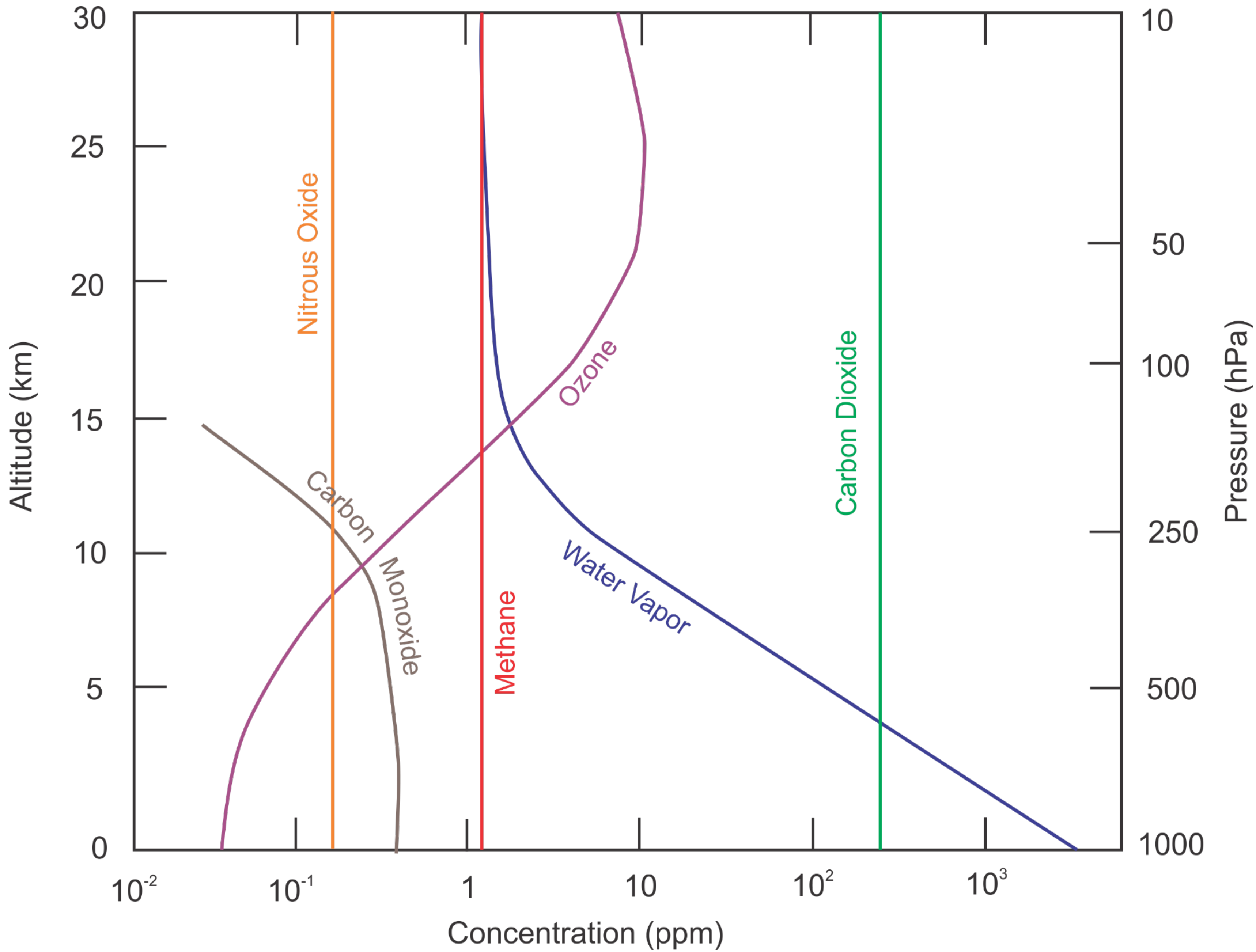


Image credit: *Kerry Emanuel*

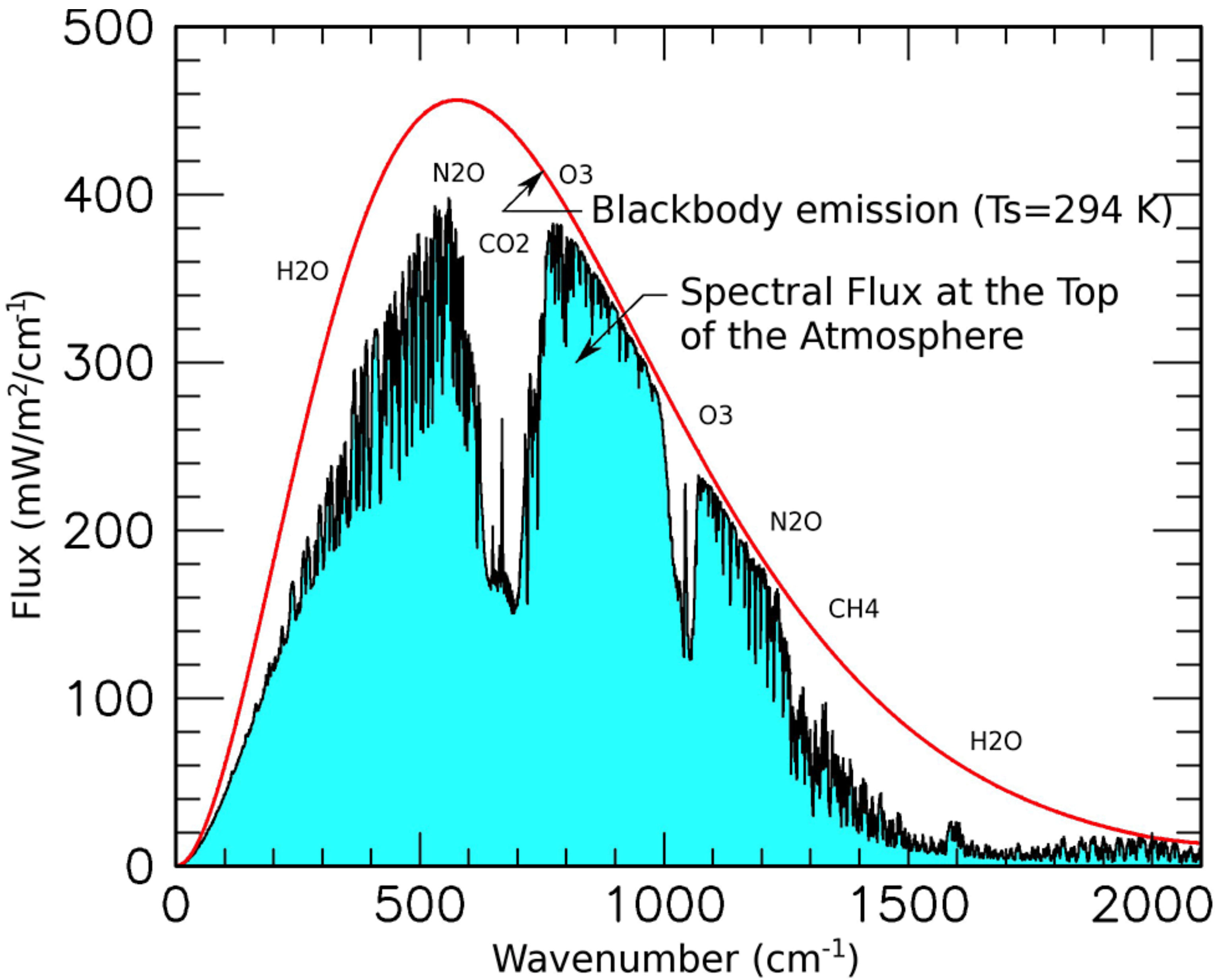


Image credit*: NASA*

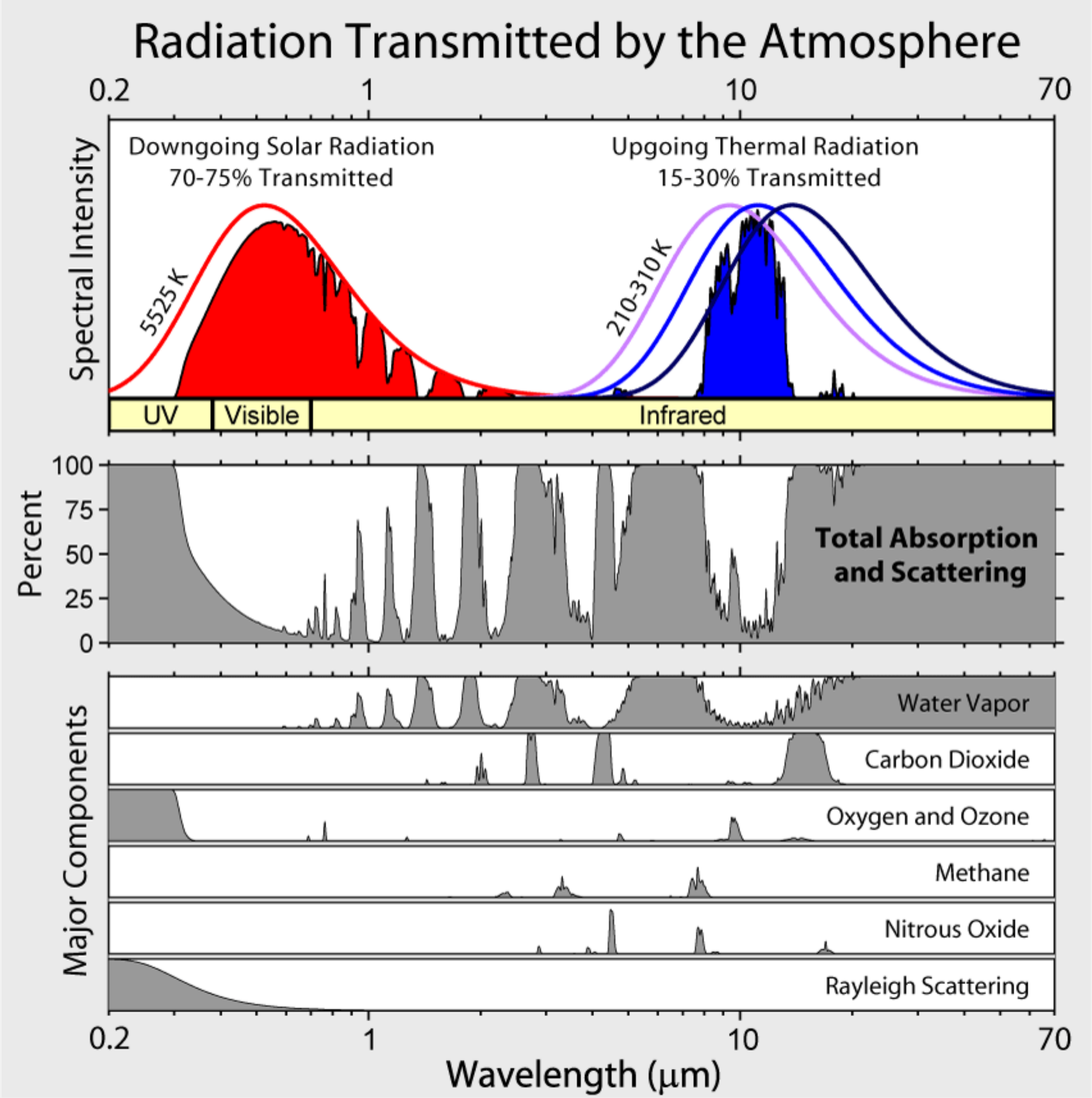


Image credit: *Robert A. Rohde*, Wikipedia

Mean Surface Temperature in the Absence of Greenhouse Gases

Solar constant

$$\sigma T_e^4 = \frac{S_0}{4}\left(1 - a_p\right)$$

Effective emission temperature

Planetary albedo

Effective emission temperatures of three planets

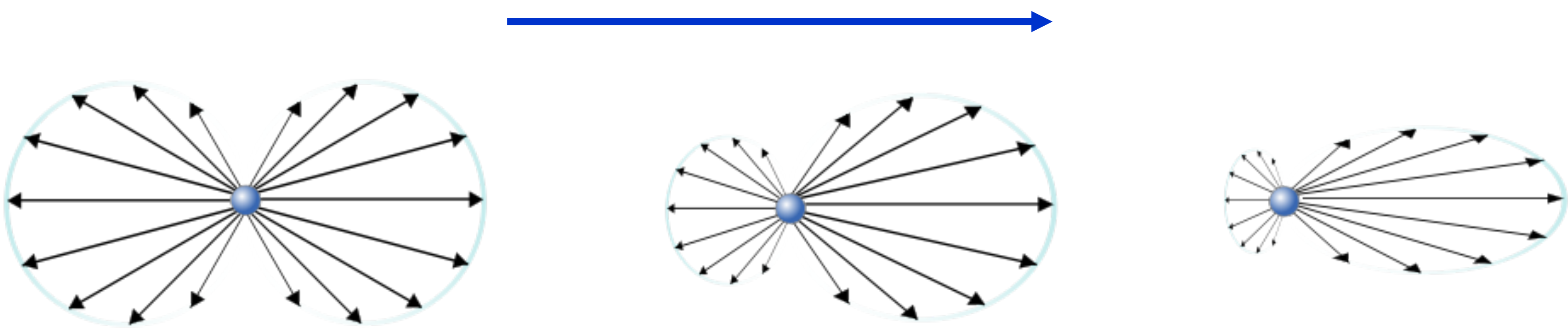
Planet	I_{solar} (Wm^{-2})	α (%)	T (K)	$T_{observed}$ (K)	$T_{1\ layer}$ (K)
Venus	2600	71	240	700	285
Earth	1350	33	251	295	303
Mars	600	17	216	240	259

Aerosols, Clouds and Radiation

- Scattering
- Absorption and Emission

Types of Scattering

Direction of Incident Radiation



Rayleigh Scattering

Mie Scattering, Small Particles

Mie Scattering, Large Particles

$$I : \frac{I_0}{\lambda^4}$$

Less wavelength dependence

Image credit: *Sharayanan*, Wikipedia

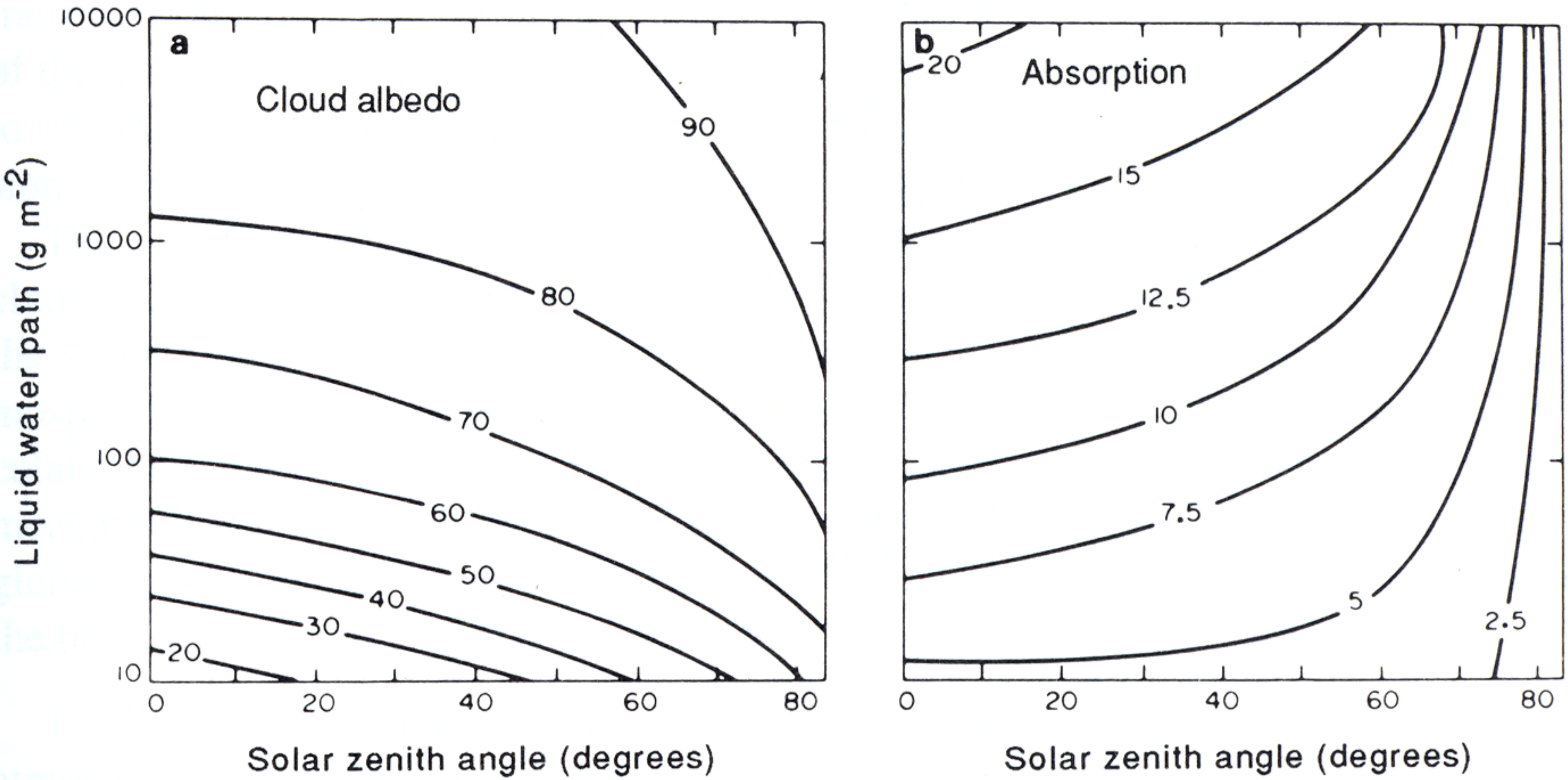
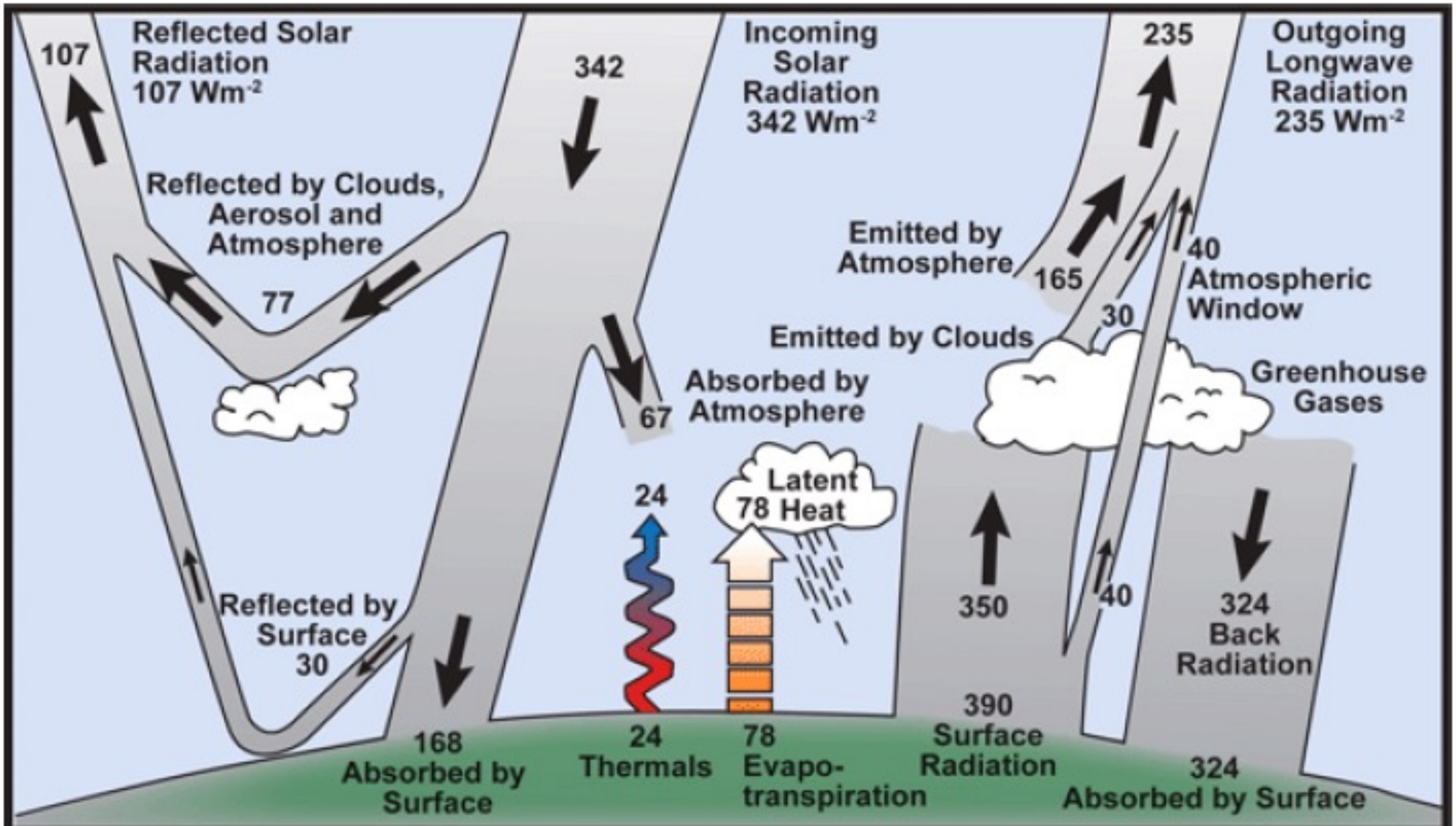


Image credit: *Stephens, G.L., 1978: Radiation profiles in extended water clouds. J. Atmos. Sci., 35, 2123-2132*

Cloud and Aerosol Effects

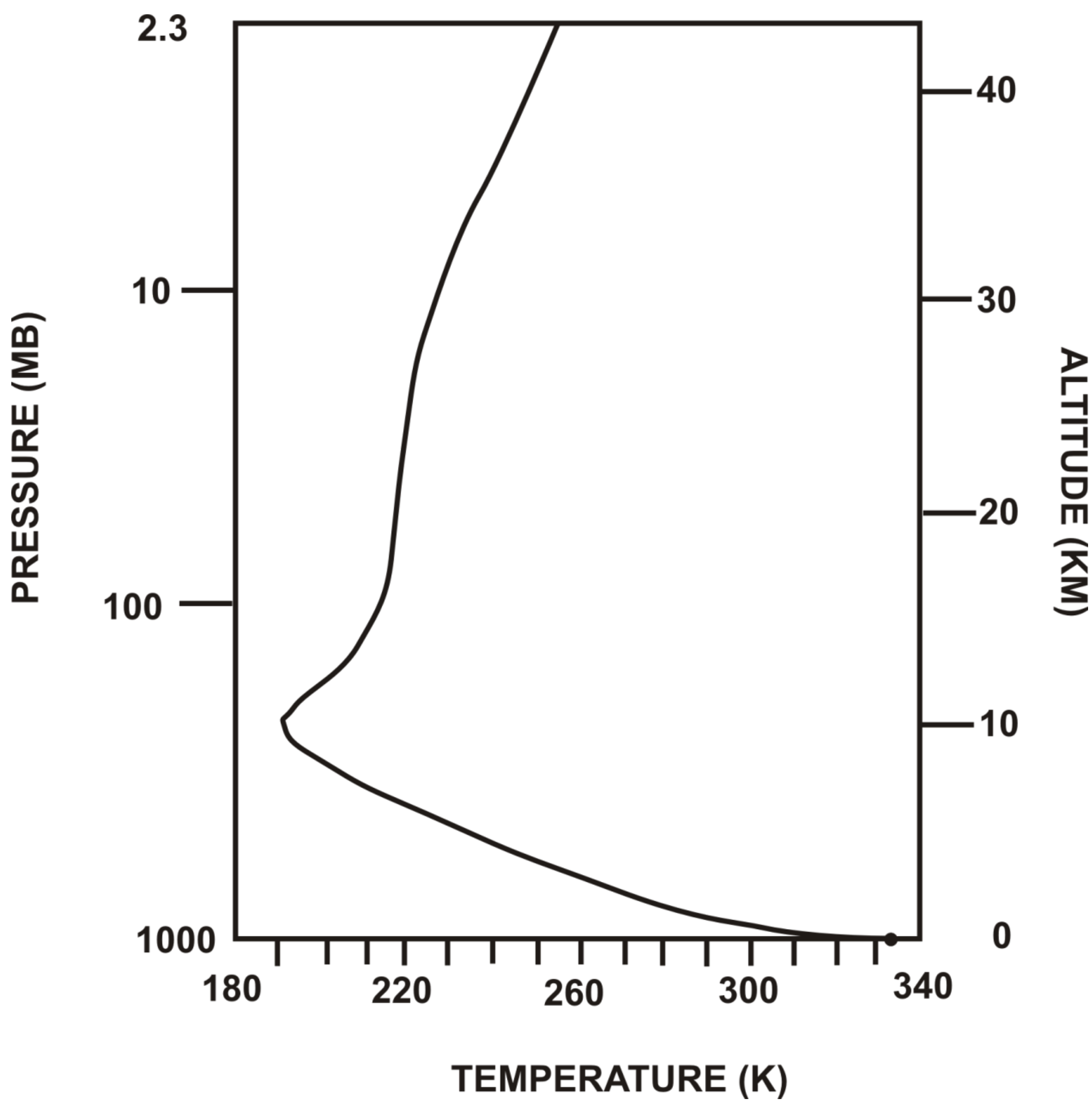
- Air: Rayleigh scattering principally of shorter wavelengths (blue and ultraviolet)
- Aerosols: Mostly Mie scattering; some absorption depending on composition
- Cloud droplets and ice crystals: Mie scattering and absorption
- Rain drops: Geometric optics in visible spectrum (rainbows)

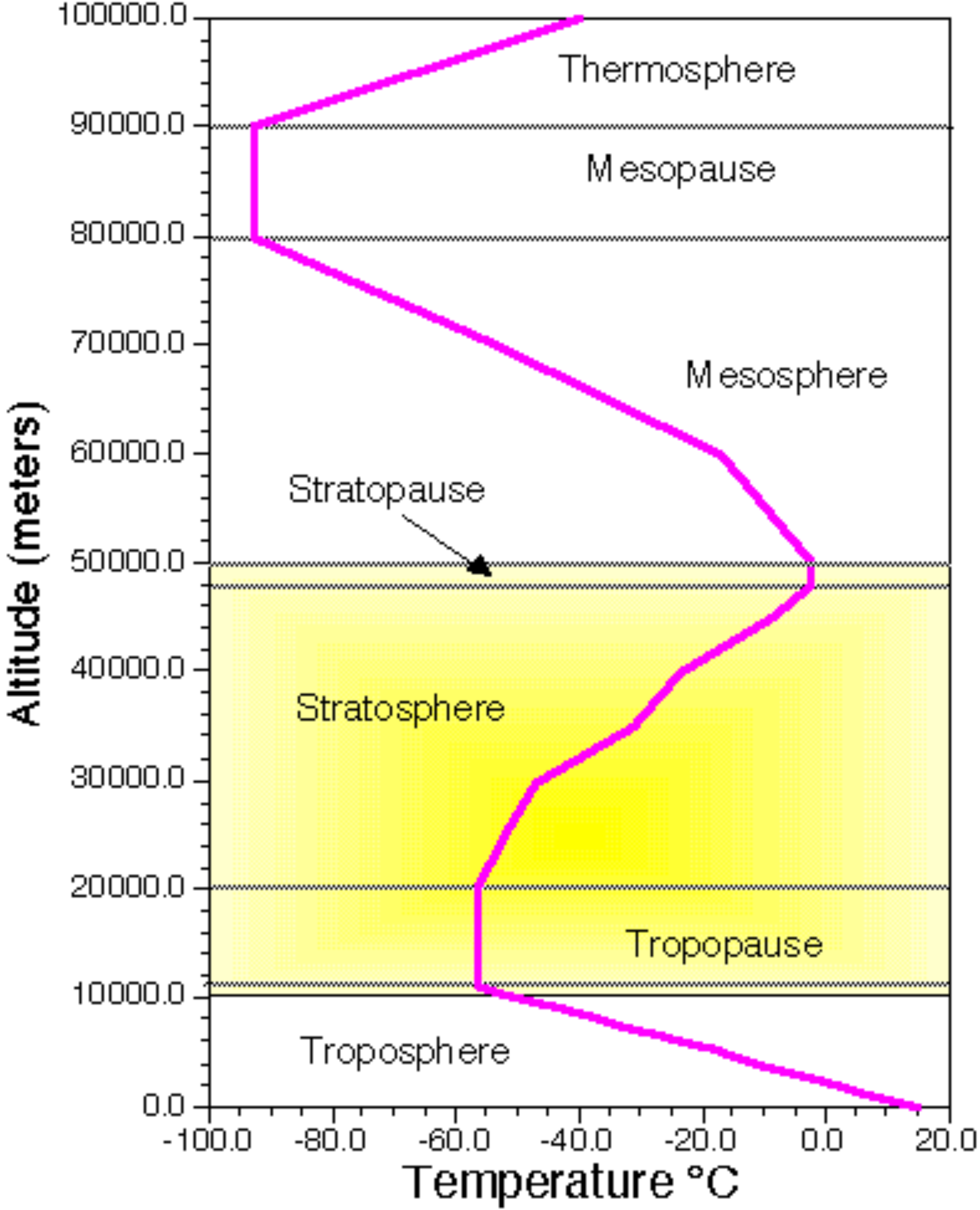
Elements of the Greenhouse Effect



from *IPCC AR4*

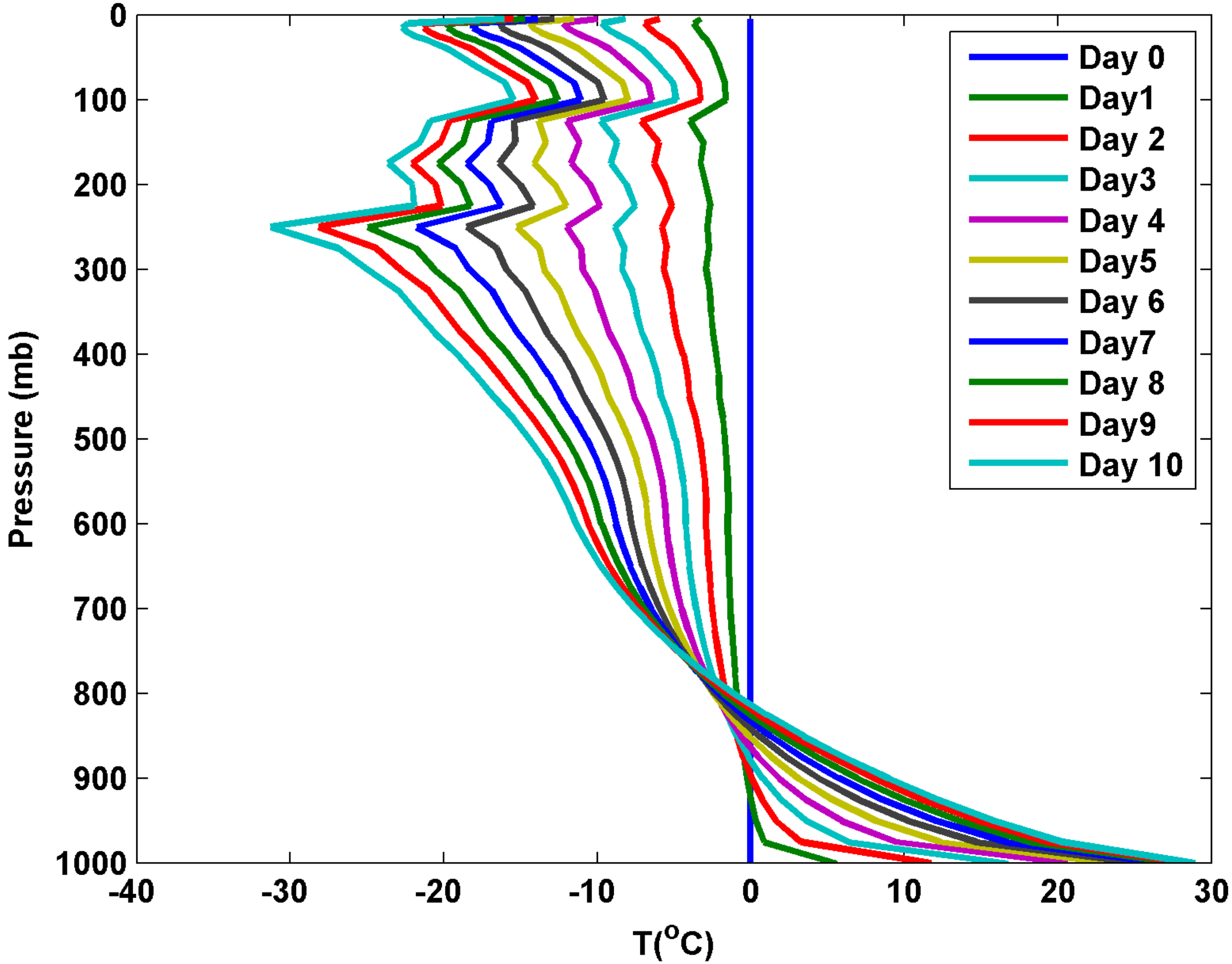
Full calculation of radiative equilibrium

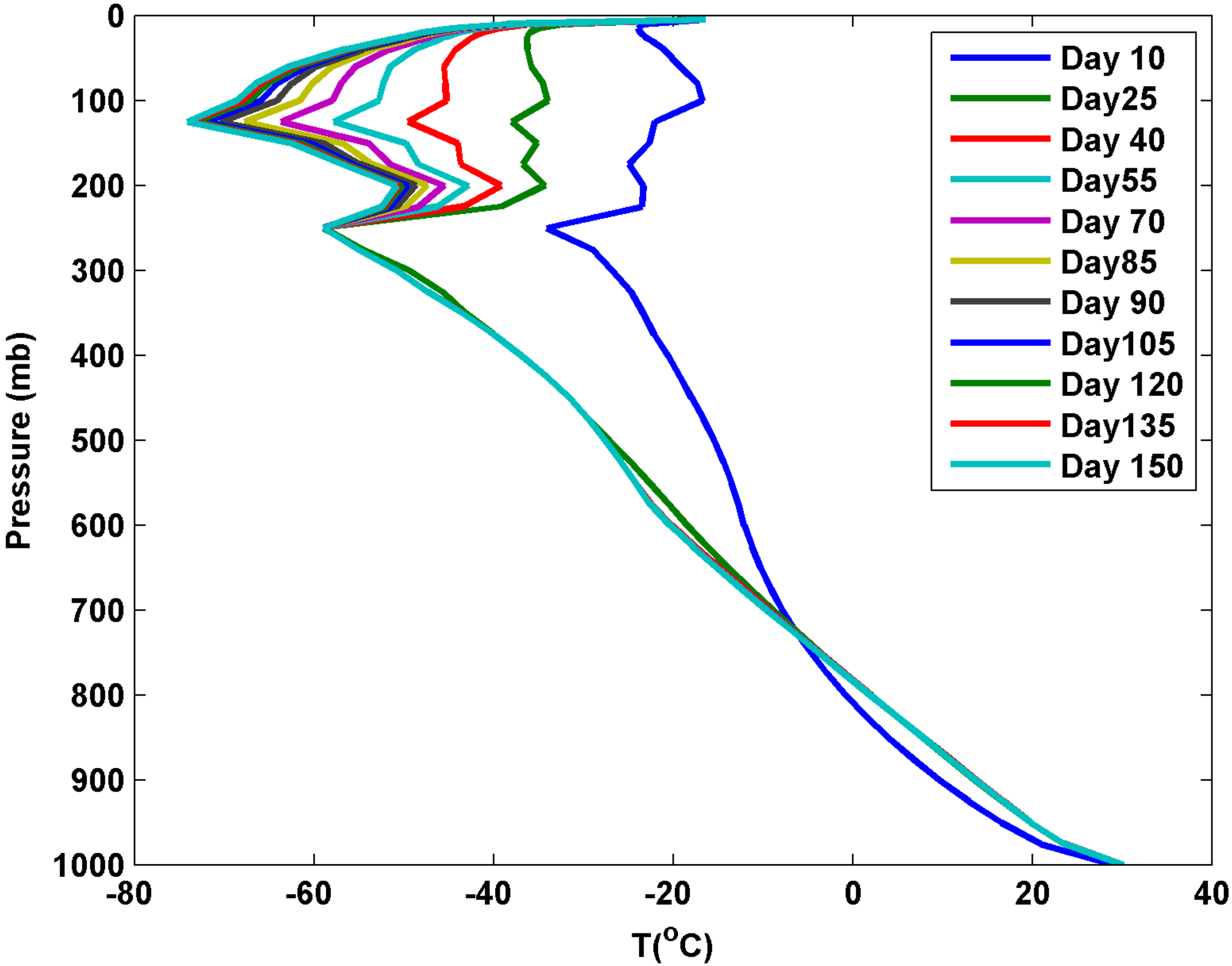




Thermosphere
Mesopause
Mesosphere
Stratopause
Stratosphere
Tropopause
Troposphere
Altitude (meters)
Temperature °C
100000.0
90000.0
80000.0
70000.0
60000.0
50000.0
40000.0
30000.0
20000.0
10000.0
0.0
-100.0
-80.0
-60.0
-40.0
-20.0
0.0
20.0

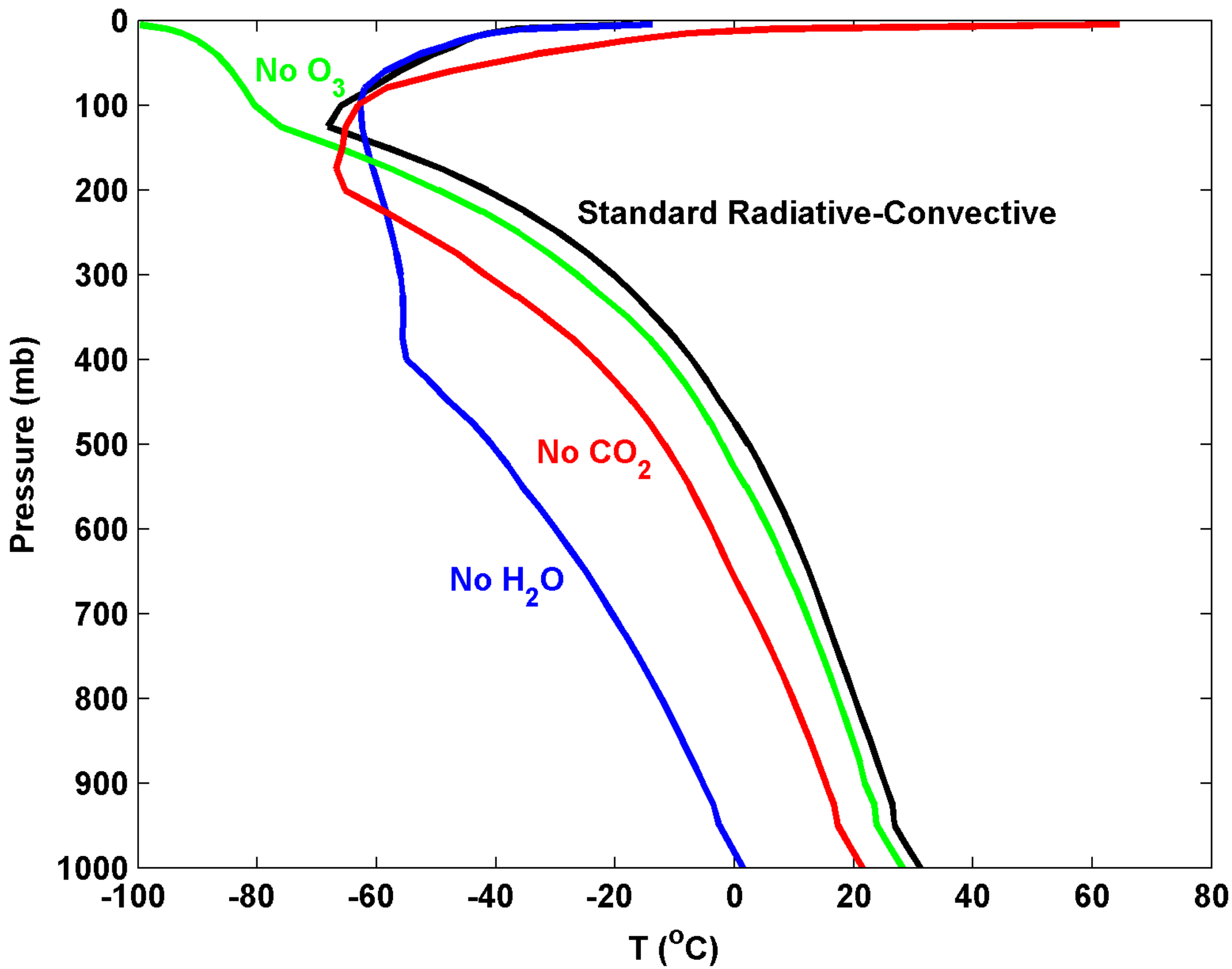
Time scale of approach to equilibrium





Day 10
Day25
Day 40
Day55
Day 70
Day85
Day 90
Day105
Day 120
Day135
Day 150
Pressure (mb)
T(°C)
0
100
200
300
400
500
600
700
800
900
1000
-80
-60
-40
-20
0
20
40

Contributions of various absorbers



Note: All simulations have variable clouds interacting with radiation

Problems with radiative equilibrium solution

- Too hot at and near surface
- Too cold at and near tropopause
- Lapse rate of temperature too large in the troposphere
- (But stratosphere temperature close to observed)