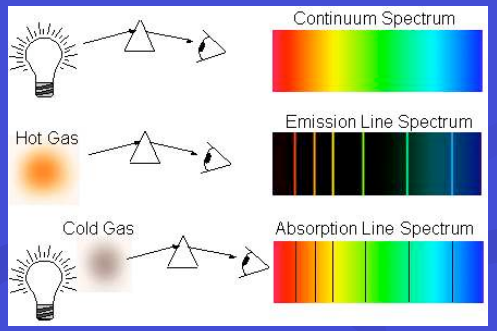
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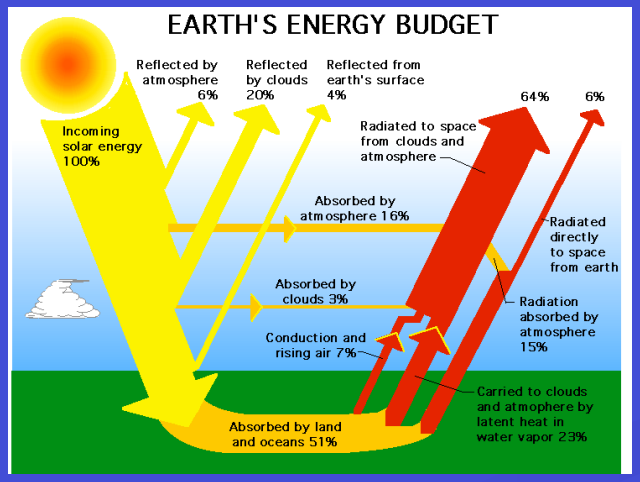
Introduction to the Fundamentals of Atmospheric Science

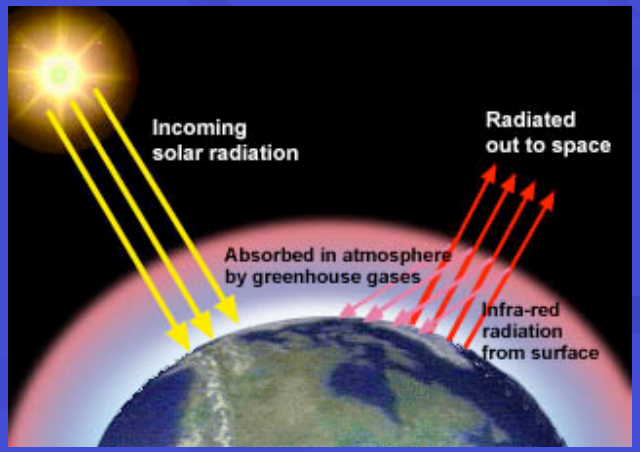
Lecture Notes #4 – Part 2: Radiative Transfer

1. Spectrum of Radiation
2. Quantitative Description of Radiation
3. Blackbody Radiation
4. Scattering, Absorption, Emission
5. Radiative Transfer in Planetary Atmospheres
6. Radiation Balance at the Top of the Atmosphere

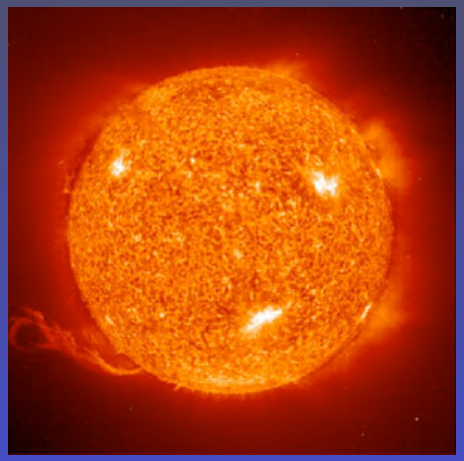




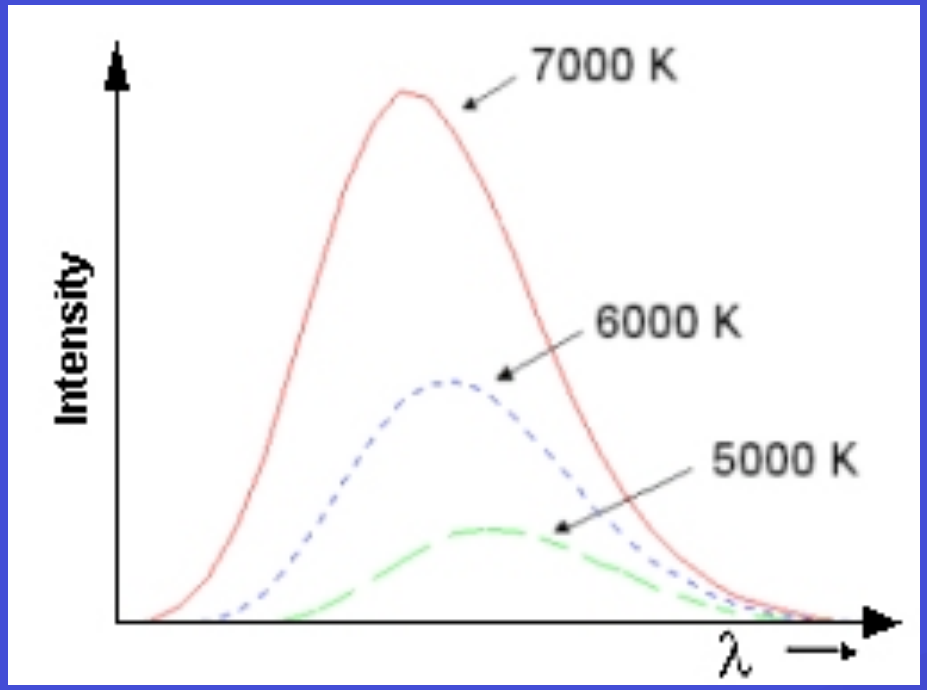


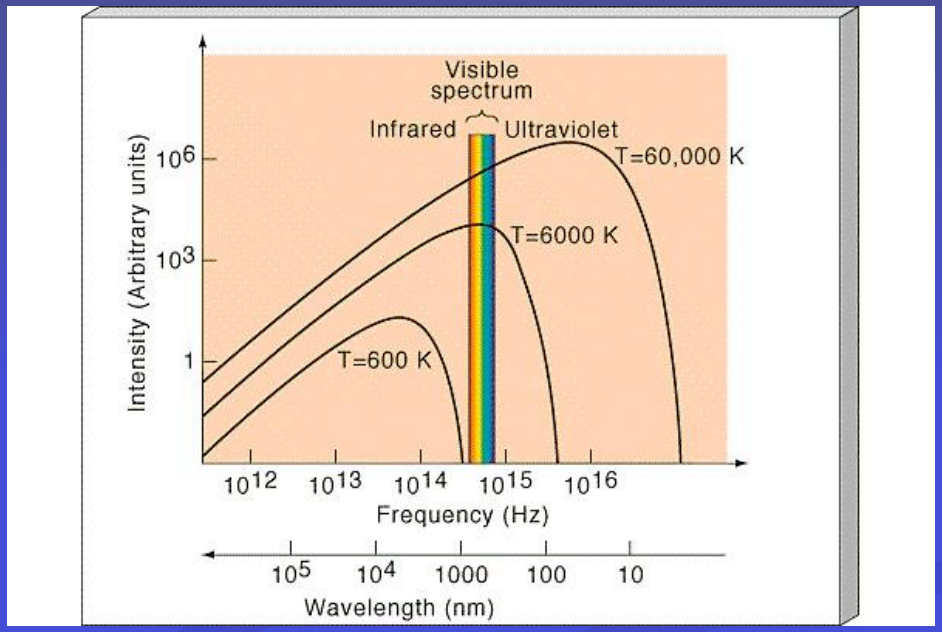


Radiation: Emission



Thermal Blackbody Emission



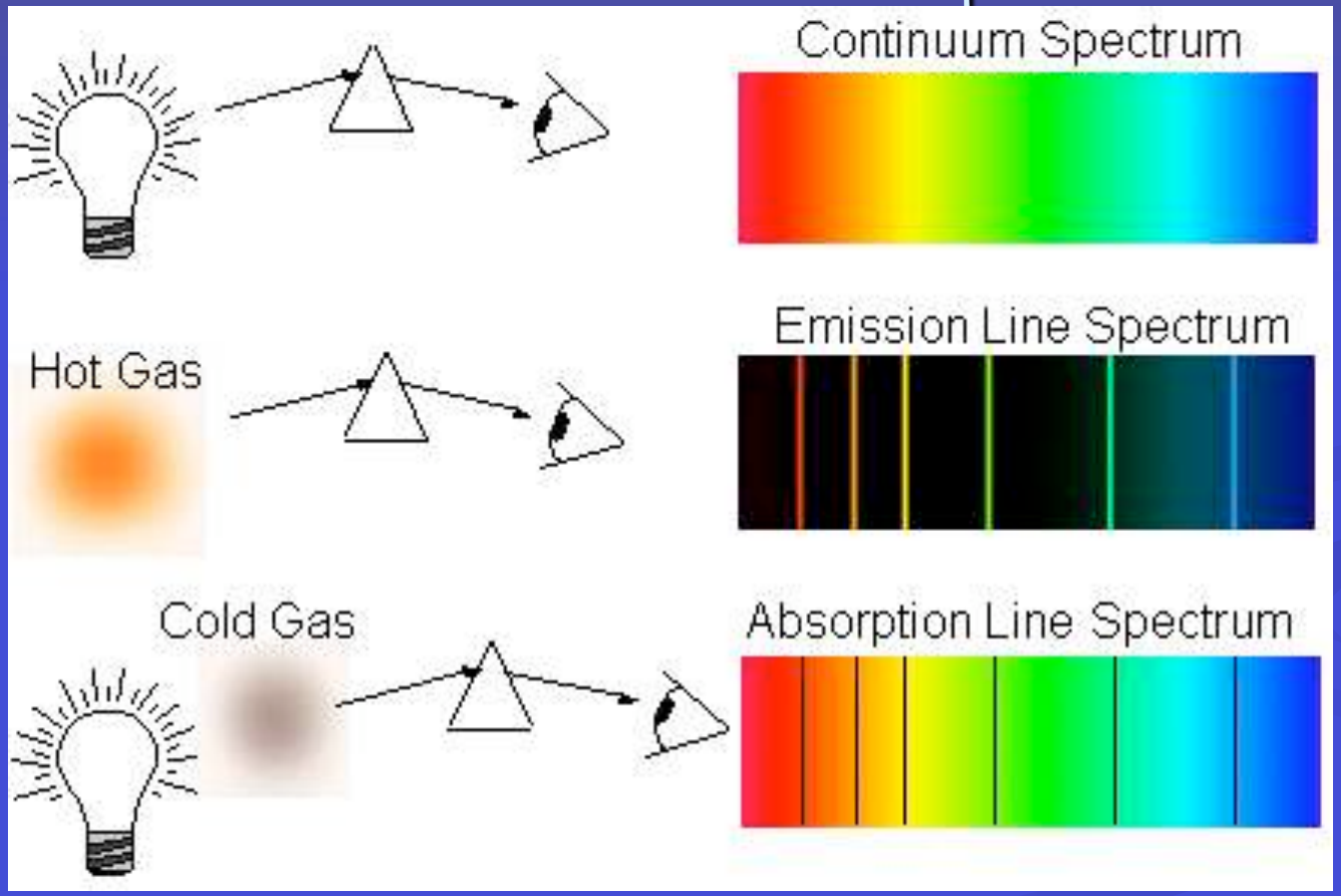


The Spectrum of Solar Radiation

The Sun is a near-blackbody at 5770 K

Radiation: Absorption and Emission Lines

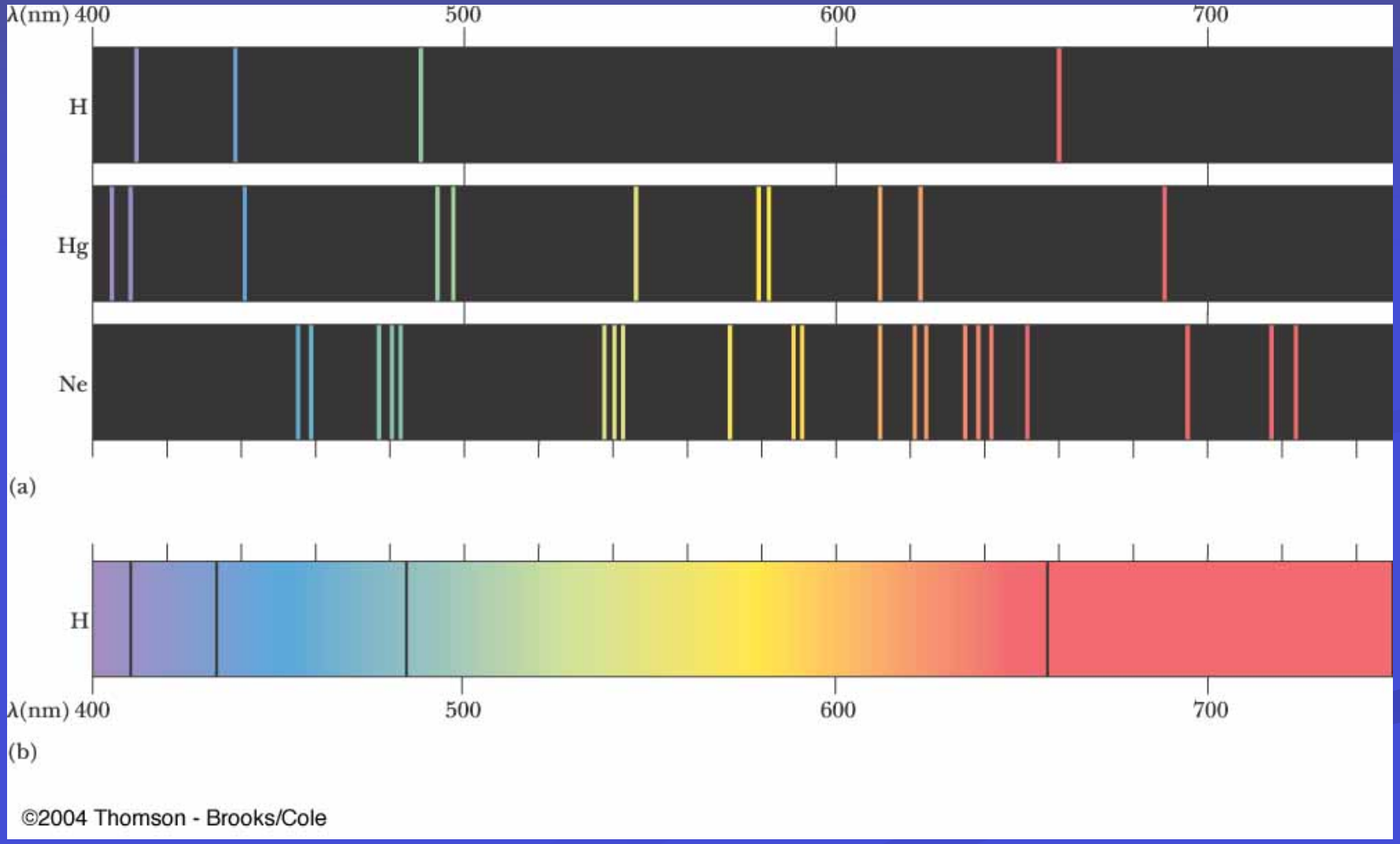
Line emission and absorption



Line wavelengths correspond to energy changes in absorbing atoms.

Spectroscopy

Each element (and molecule) has a unique spectroscopic signature. This is due to their unique structure and energy level distributions.



Atomic Structure: Photon Absorption & Emission

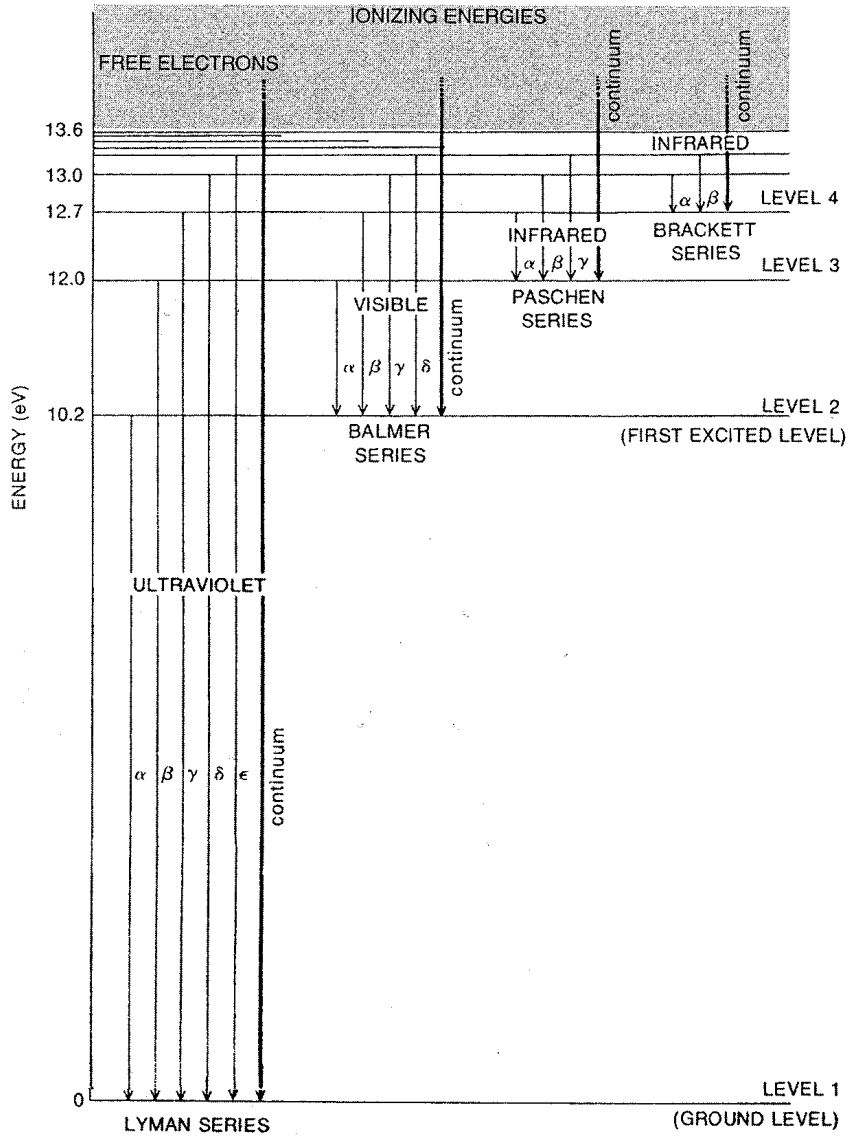


FIGURE 3.7 The energy levels of hydrogen and the series of transitions among the lowest of these energy levels. (Adapted from Pasachoff and Kutner 1978)

Absorption and Emission Lines

Photon Energy: $E = h\nu = hc/\lambda$

Not every photon in an absorption or emission line will have exactly the same energy (and thus wavelength) due to processes which shift the energy levels of the atom or molecule by small amounts.

These processes contribute to **line broadening:**

(1) **Natural Broadening:** Inherent uncertainty in the energy levels associated with the Heisenberg Uncertainty Principle.

(2) **Doppler Broadening:** Shifting in the wave-lengths of photons due to their relative motion toward or away from the source.

(3) **Pressure Broadening:** Shifting of the energy levels in an atom or molecule due to the interactions with nearby particles.

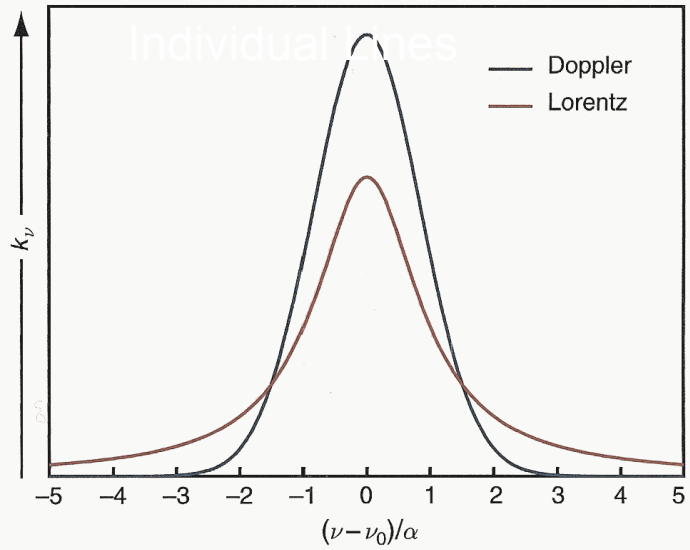


Fig. 4.21 Contrasting absorption line shapes associated with Doppler broadening and pressure broadening. Areas under the two profiles, indicative of the line intensity S, are the same. [Courtesy of Qiang Fu.]

In planetary atmospheres Natural Broadening is relatively very small.

Quantifying Line Broadening

The absorption coefficient in the neighborhood of pressure and Doppler broadened lines can be represented by:

$$k_\nu = Sf(\nu - \nu_0)$$

Where the line intensity

$$S = \int_0^\infty k_\nu d\nu$$

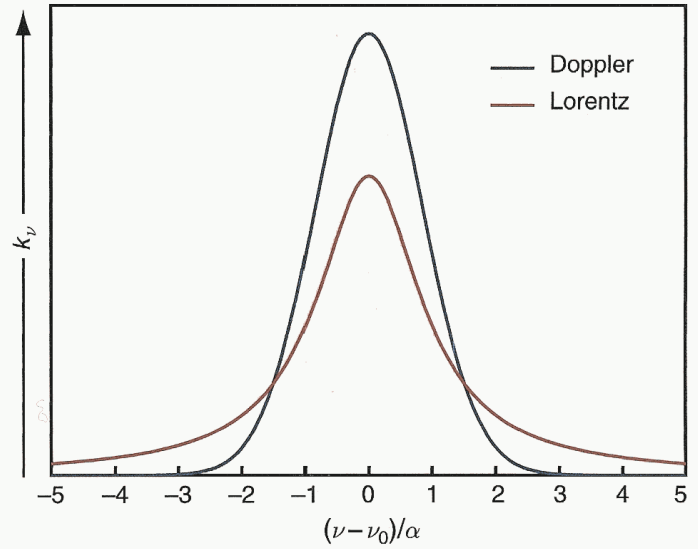


Fig. 4.21 Contrasting absorption line shapes associated with Doppler broadening and pressure broadening. Areas under the two profiles, indicative of the line intensity *S*, are the same. [Courtesy of Qiang Fu.]

For purely Doppler broadening the shape-factor is given by:

$$f = \frac{1}{\alpha_D \sqrt{\pi}} \exp\left[-\left(\frac{\nu - \nu_0}{\alpha_D}\right)^2\right]$$

Where the line half-width:

$$\alpha_D = \frac{\nu_0}{c^*}\left(\frac{2kT}{m}\right)^{\frac{1}{2}}$$

For both pressure broadening the Lorentz shape factor is:

$$f = \frac{\alpha}{\pi\left[(\nu - \nu_0)^2 + \alpha^2\right]}$$

$$\alpha = \frac{P}{T^N}$$

Molecular Spectra and Atmospheric Transmission

The visible, and especially the infrared, portion of the electromagnetic spectrum includes atmospheric absorption and emission by numerous atoms and molecules.

Molecular absorption spectra, e.g. from CO_2, H_2O, and N_2O, have thousands of lines, many of which overlap.

The transfer of radiation can be quantified by a statistical treatment of "bands" of molecular lines produced by energy changes between rotational and vibrational energy states in the molecules.

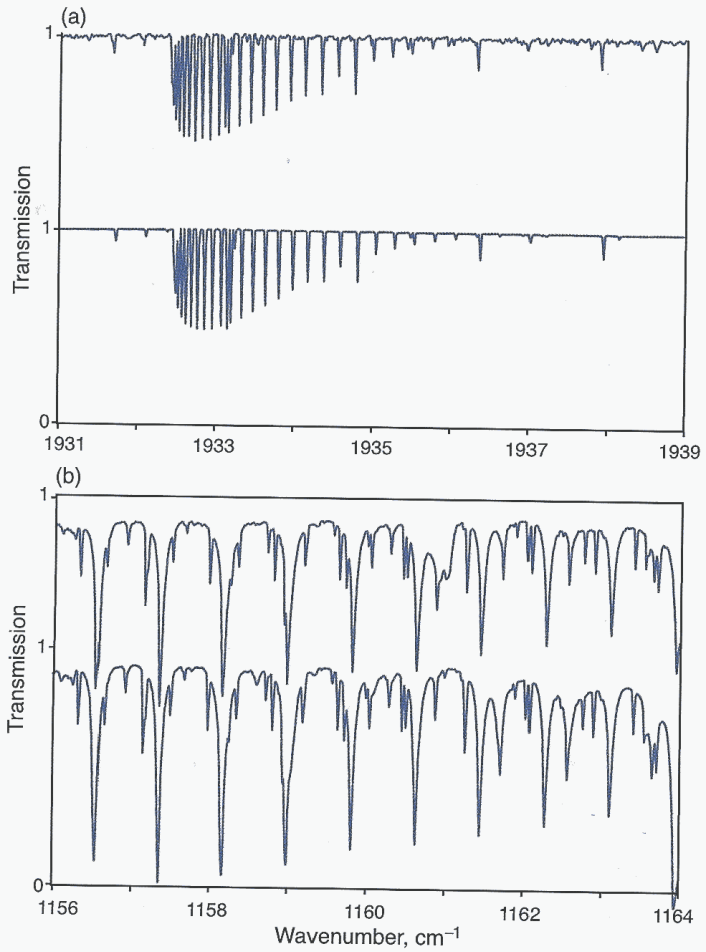


Fig. 4.22 Comparisons of observed and calculated transmissivity spectra. (a) Spectral range 1931 to 1939 cm^{-1} for carbon dioxide and (b) Spectral range 1156 to 1164 cm^{-1} for ozone and nitrous oxide. The upper plot in each panel is the observed spectrum and the lower plot is the calculated spectrum. [From R. M. Goody, R. M. and Y. L. Yung, *Atmospheric Radiation*, 2nd ed., Oxford University Press (1995), p.120. By permission of Oxford University press, Inc.]

5. Radiative Transfer (Beer's Law)

Consider solar radiation incident upon the top of the atmosphere. That radiation will be attenuated as it passes downward into the atmosphere due to extinction (absorption + scattering). The change in the intensity as the radiation pass through a thin layer ds = sec θ dz, where ds is the incremental distance along the beam of radiation, dz is the corresponding distance in the vertical, and Θ is the angle between the beam and the vertical, will be

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

where $ds = \sec\theta dz$

This implies: $\frac{dI_\lambda}{I_\lambda} = -k_\lambda \rho r ds$ and upon integrating $\int_z^\infty \frac{dI_\lambda}{I_\lambda} = \sec\theta \int_z^\infty k_\lambda \rho r dz$

gives $\ln\left(\frac{I_\lambda(\infty)}{I_\lambda(z)}\right) = \sec\theta \int_z^\infty k_\lambda \rho r dz$

Taking the antilog of both sides: $I_\lambda(z) = I_\lambda(\infty) e^{-\tau_\lambda \sec\theta} = I_\lambda(\infty) T_\lambda$

So we can write the transmission: $T_\lambda = e^{-\tau_\lambda \sec\theta}$

With optical depth defined as: $\tau_\lambda = \int_0^\infty k_\lambda \rho r dz$

Monochromatic Radiation Incident at Top of Atmosphere

$$I_\lambda(z) = I_\lambda(\infty)e^{-\tau_\lambda \sec\theta} = I_\lambda(\infty)T_\lambda$$

Optical Depth

$$\tau_\lambda = \int_0^\infty k_\lambda \rho r dz$$

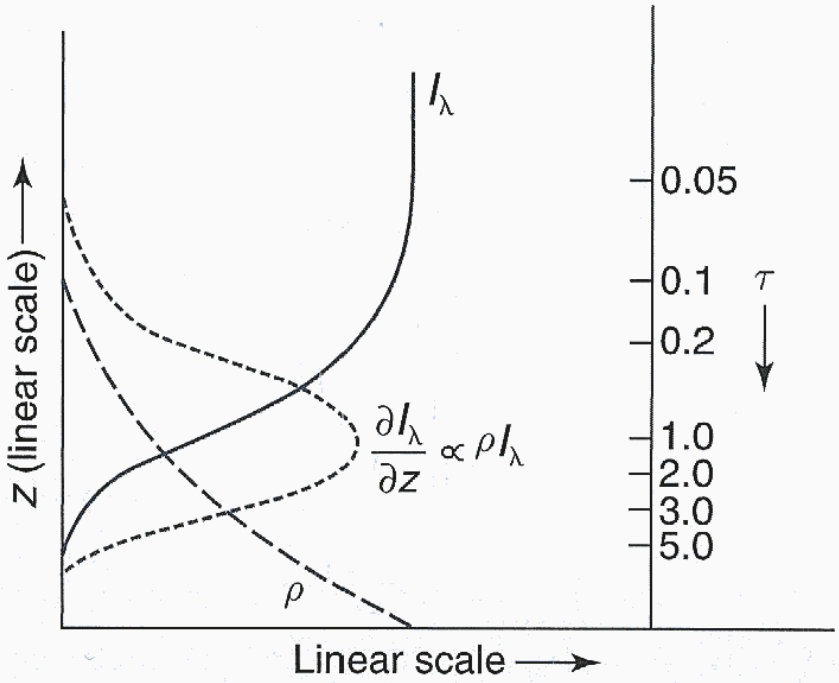


Fig. 4.23 Vertical profiles of the monochromatic intensity of incident radiation, the rate of absorption of incident radiation per unit height, air density and optical depth, for k_λ and r independent of height.

Absorption and Emission of IR Radiation

For **absorption** we have Beer's Law with an absorptivity of α_λ

$$dI_\lambda(absorption) = -I_\lambda \rho r k_\lambda ds = -I_\lambda \alpha_\lambda$$

For **emission** we use the Blackbody function with an emissivity ε_λ:

$$dI_\lambda(emission) = B_\lambda(T)\varepsilon_\lambda$$

From Kirchoff's Law, the absorptivity is equal to the emissivity, so:

$$dI_\lambda(Total) = -(I_\lambda - B_\lambda)k_\lambda \rho r ds$$

From the optical depth: $d\tau_\lambda = -k_\lambda \rho r ds$

Schwarzschild's Equation: $\dfrac{dI_\lambda}{d\tau_\lambda} = -(I_\lambda - B_\lambda)$

Schwarzschild's Equation for Radiation Transfer

$$\frac{dI_\lambda}{d\tau_\lambda} = -(I_\lambda - B_\lambda)$$

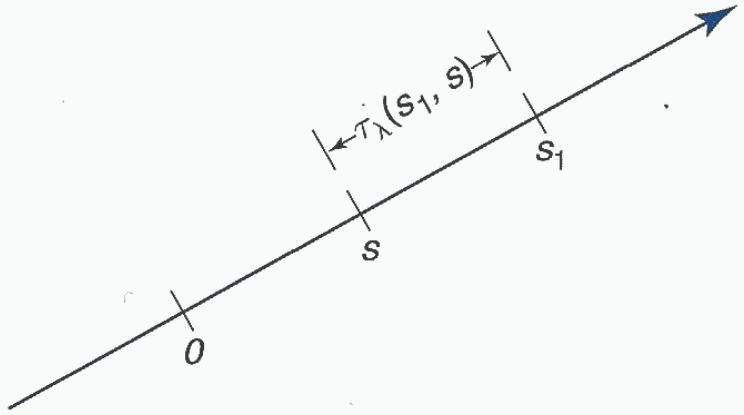


Fig. 4.26 Radiation passing through an absorbing medium along a ray path from 0 to S_1. The ray path may be directed either upward or downward. [From K. N. Liou, *An Introduction to Atmospheric Radiation*, Academic Press, p. 30, Copyright (2002), with permission from Elsevier.]

Radiative Heating Rate and Radiant Flux

From thermodynamics, we know that the internal energy per unit volume is a function of only temperature. In particular, the internal energy U is:

$$U = \rho C_p T$$

The rate of change of internal energy is dU/dt, which is equivalent to the energy flux divergence. In one dimension, z, we have

$$\frac{dU}{dt} = \rho C_p \frac{dT}{dt} = -\frac{dF}{dz}$$

So for the rate of change of temperature with respect to time:

$$\left(\frac{dT}{dt}\right)_p = -\frac{1}{\rho C_p}\frac{dF}{dz}$$

The Plane-Parallel Approximation for the Upward and Downward Flux

Radiation transfer calculations can be simplified enormously with the use of the plane-parallel approximation where the density of absorbing/emitting gases are assumed to be functions of altitude only. We then average the upward and downward intensities to get the hemispheric average upward and downward fluxes

$$F_\upsilon^{\downarrow\uparrow}(\tau_\upsilon) = \int_{2\pi} I_\upsilon^{\downarrow\uparrow}(\tau_\upsilon, \cos\theta)\cos\theta d\omega$$

OR:

$$F_\upsilon^{\downarrow\uparrow}(\tau_\upsilon) = 2\pi\int_0^1 I_\upsilon^{\downarrow\uparrow}(\tau_\upsilon, \mu)\mu d\mu$$

where $\mu = \cos\theta$; ranges from -1 to 1

So, back to rate of change of temperature:

$$\left(\frac{dT}{dt}\right)_p = -\frac{1}{\rho C_p}\frac{dF}{dz}$$

The energy flux is given by the radiation flux averaged over all directions ($d\omega$):

$$Flux = \int_{4\pi} I_\lambda dw = 2\pi \int_{-\pi/2}^{\pi/2} I_\lambda \cos\theta d\theta$$

$$\left(\frac{dT}{dt}\right)_p = -\frac{2\pi}{\rho C_p}\frac{d}{dz}\int_{-\pi/2}^{\pi/2} I_\lambda \cos\theta d\theta = -\frac{2\pi}{\rho C_p}\int_{-1}^{1}\frac{dI_\lambda}{ds}d\mu$$

Schwarzschild's Equation:

$$\frac{dI_\lambda}{ds} = -(I_\lambda - B_\lambda)k_\lambda \rho r$$

Net Radiative Heating Rate:

$$\left(\frac{dT}{dt}\right)_p = -\frac{2\pi}{C_p}\int_{-1}^{1} k_\lambda r (I_\lambda - B_\lambda) d\mu$$

Top of the Atmosphere Radiative Cooling to Space

Even though the atmosphere is absorbing at IR wavelengths, at high altitudes the overlying atmosphere is too thin to cause significant absorption.

So at the top of the atmosphere photons that are emitted in the vertical direction will "escape to space."

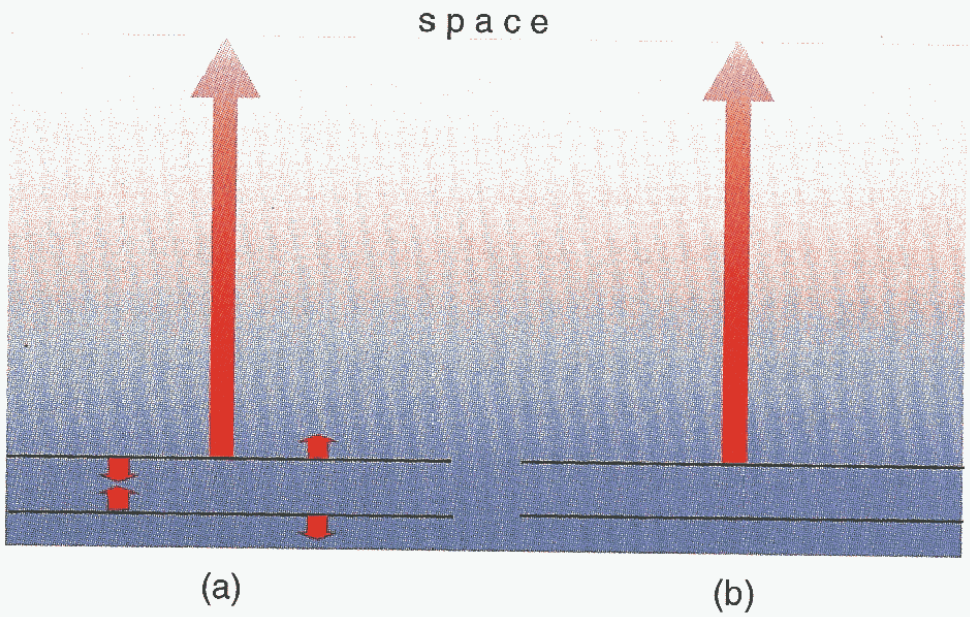


Fig. 4.28 Radiation geometry in cooling to space. (a) The complete longwave radiative balance for the layer in question (not drawn to scale) and (b) the simplified balance based on the assumption of cooling to space.

Radiative Heating vs. Cooling

The radiative component of the heating rate is equivalent to the net absorption of IR, ultraviolet (UV), and visible photons.

In the troposphere, IR heating is dominated by H_2O and CO_2.

In the stratosphere and above, heating is due to absorption of ultraviolet, and to a much lesser degree visible, sunlight and cooling is due to CO_2 radiative emission.

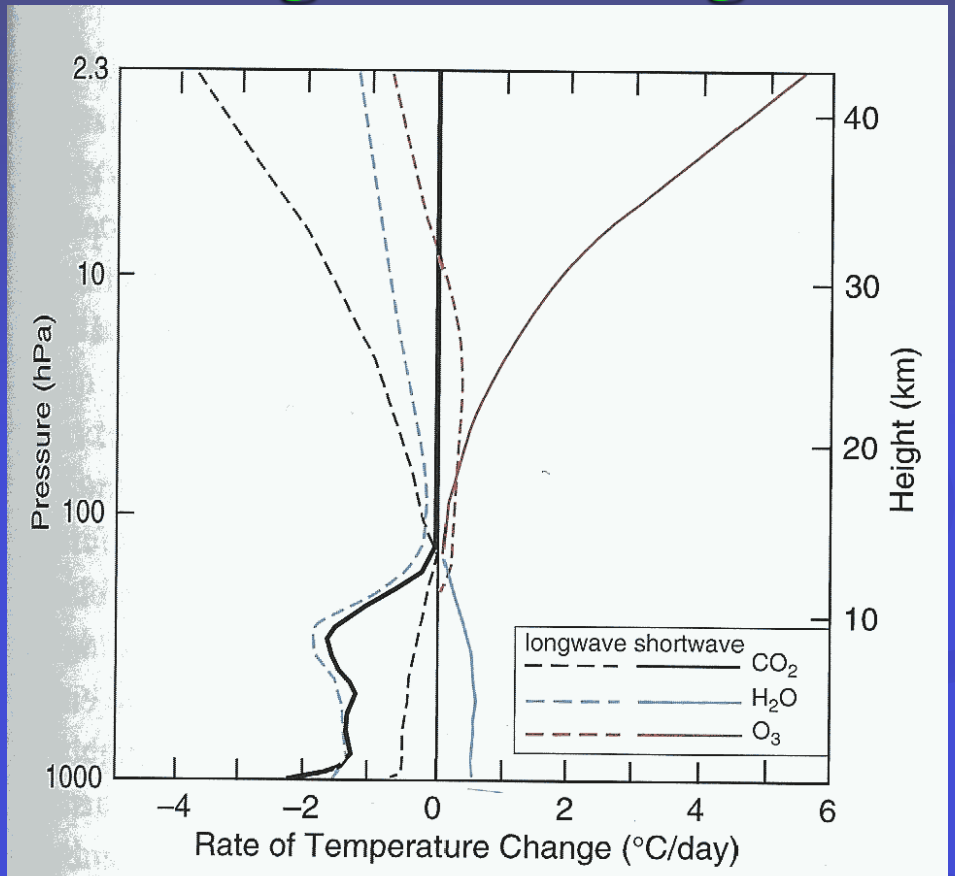


Fig. 4.29 Vertical profiles of the time rate of change of temperature due to the absorption of solar radiation (solid curves) and the transfer of infrared radiation (dashed curves) by water vapor (blue), carbon dioxide (black), and ozone (red). The heavy black solid curve represents the combined effects of the three gases. [Adapted from S. Manabe and R. F. Strickler, *J. Atmos. Sci.*, **21**, p. 373 (1964).]

Vertical Profile of Heating in Clouds

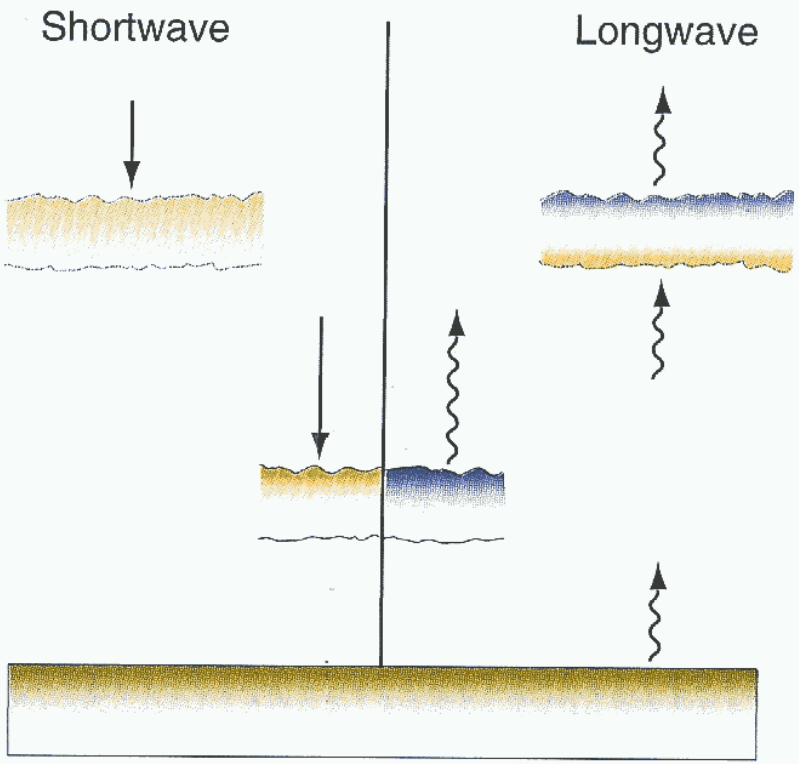


Fig. 4.30 Schematic of vertical profiles of heating in cloud layers at various heights in the atmosphere as indicated. Orange shading indicates warming and blue shading indicates cooling. Effects of shortwave radiation are represented on the left, and effects of longwave radiation on the right.

Terrestrial Thermal Radiation – not exactly Black-body

The effective BB temperature of the monochromatic radiation is sometimes referred to as the **Brightness Temperature.**

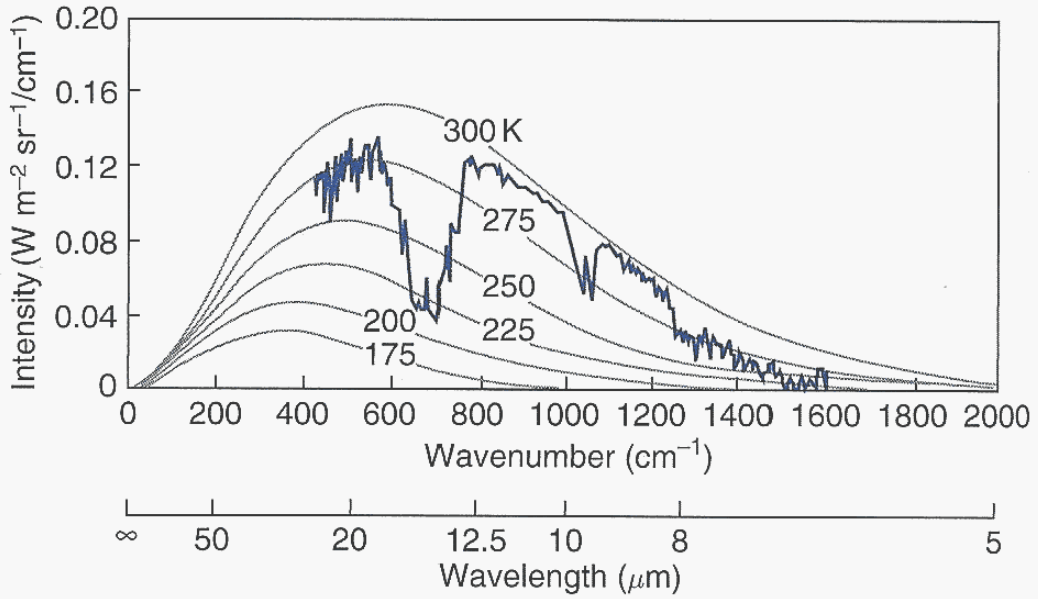


Fig. 4.31 Monochromatic intensity of radiation emitted from a point on the Earth measured by an infrared interferometer spectrometer carried aboard a spacecraft. The gray curves are blackbody spectra computed from Eq. (4.10). The monochromatic intensity of the radiation at any given wavelength is indicative of the temperature of the layer of the atmosphere from which that radiation is emitted (i.e., the level of unit optical depth for that wavelength), which can be inferred from the blackbody spectra. [Adapted from K. N. Liou, *An Introduction to Atmospheric Radiation*, Academic Press, p. 117, Copyright (2002), with permission from Elsevier.]

Atmospheric Remote Sensing by Satellites

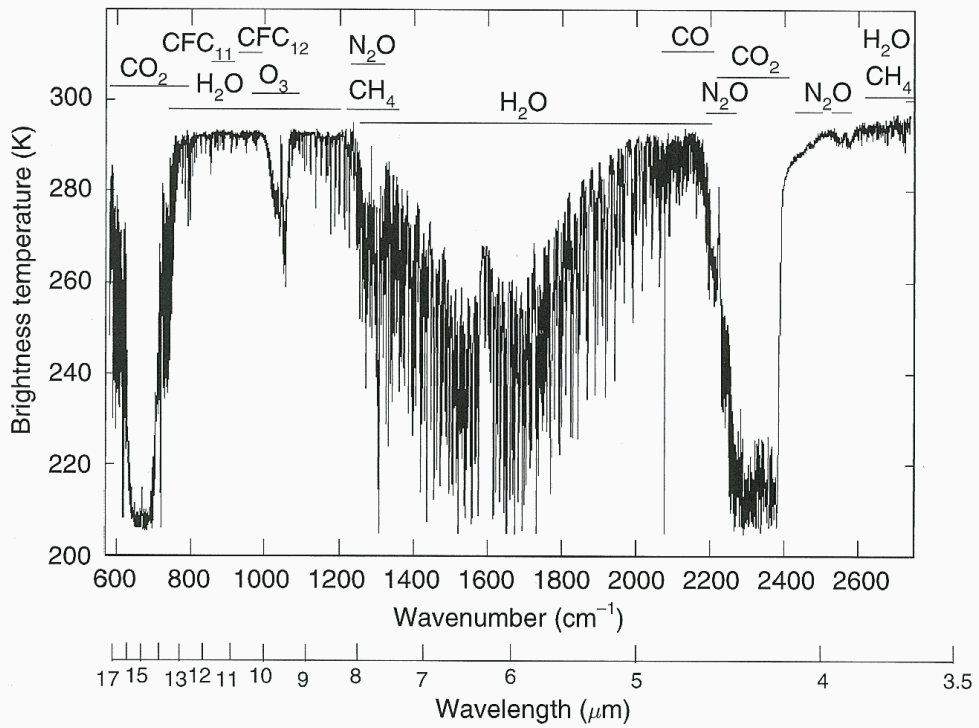




Fig. 4.32 As in Fig. 4.31, but a more finely resolved top of atmosphere spectrum sensed by an instrument aboard the NASA ER-2 aircraft flying over the Gulf of Mexico at the 20-km level. Note that in this plot the ordinate is brightness temperature rather than monochromatic intensity. [From K. N. Liou, *An Introduction to Atmospheric Radiation*, Academic Press, p. 122 (2002). Courtesy of H. -L. Allen Huang and David Tobin.]

Radiances and Weighting Functions

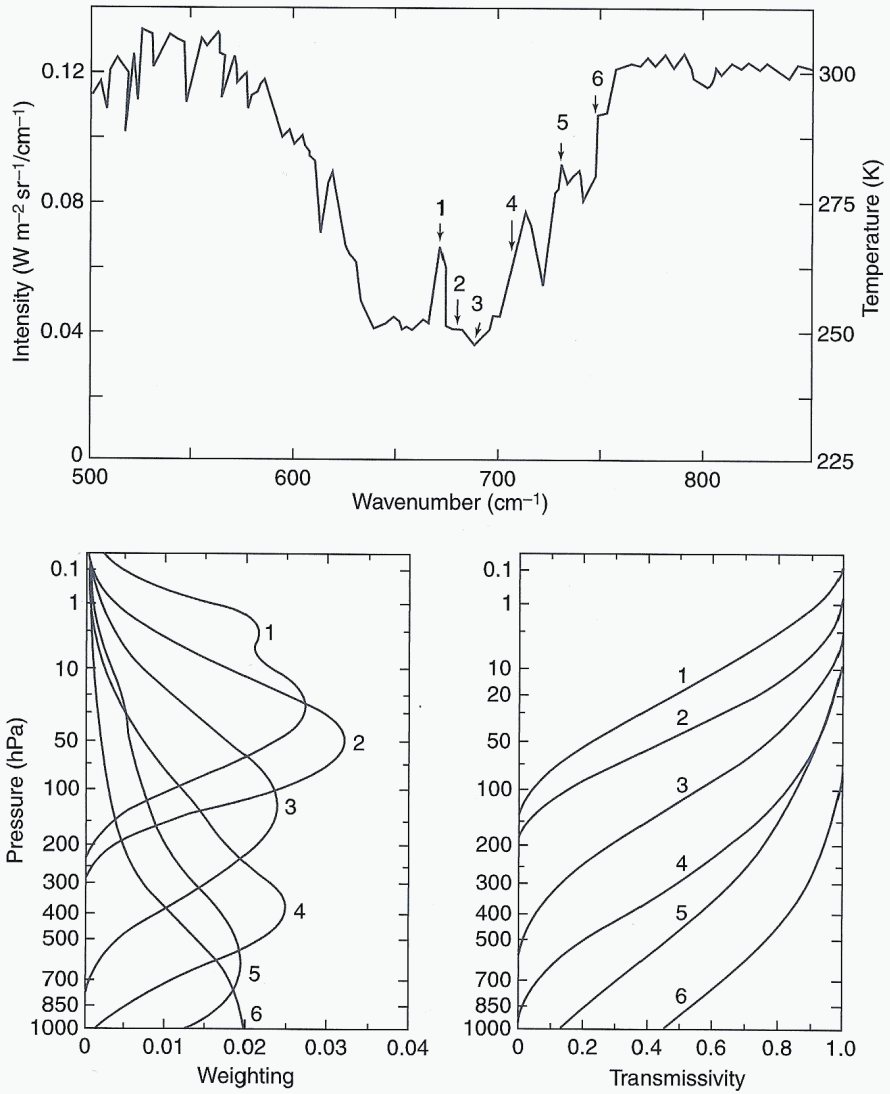


Fig. 4.33 (Top) Intensities or radiances (scale at left) and equivalent blackbody temperatures (scale at right) in the vicinity of the 15-μm CO_2 absorption band, as observed from the satellite. Arrows denote the spectral bands or "channels" sampled by the satellite-borne vertical temperature profiling radiometer (VTPR). The weighting functions and transmittances for each of the channels are shown below. [Adapted from K. N. Liou, *An Introduction to atmospheric radiation*, Academic Press, pp. 389–390, Copyright (2002), with permission from Elsevier.]

Radiation Balance at Top of Atmosphere

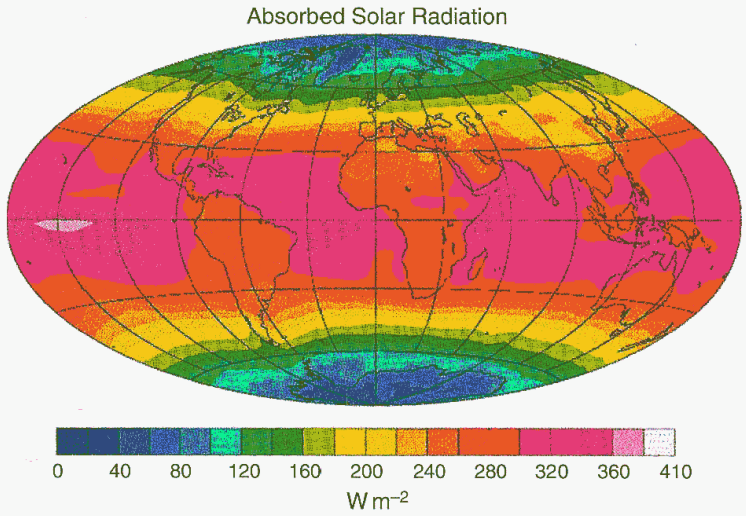


Fig. 4.34 Global distributions of the annual-mean radiation at the top of the atmosphere. [Based on data from the NASA Earth Radiation Budget Experiment. Courtesy of Dennis L. Hartmann.]

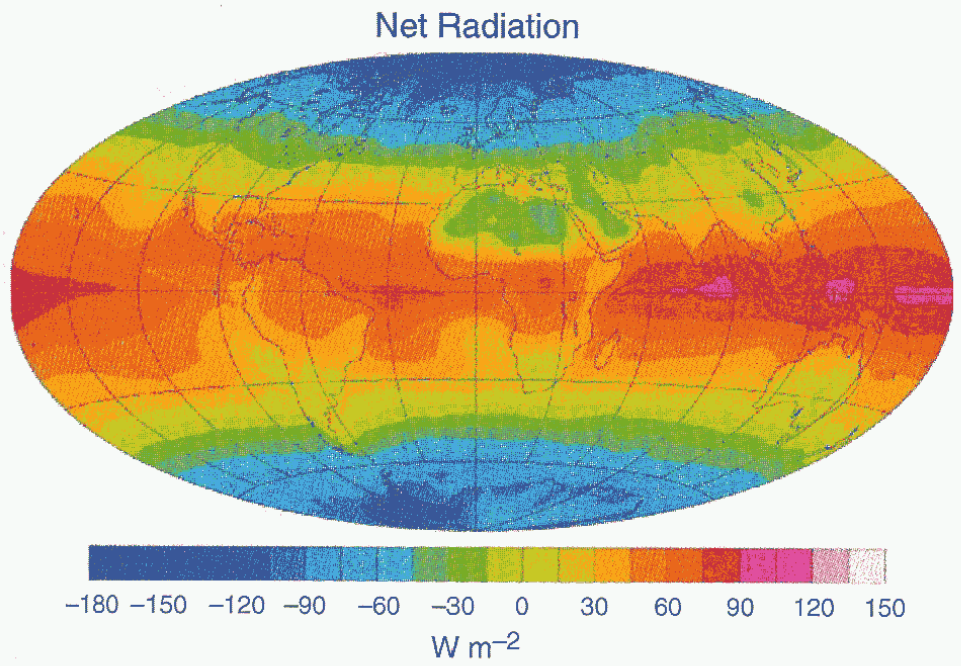
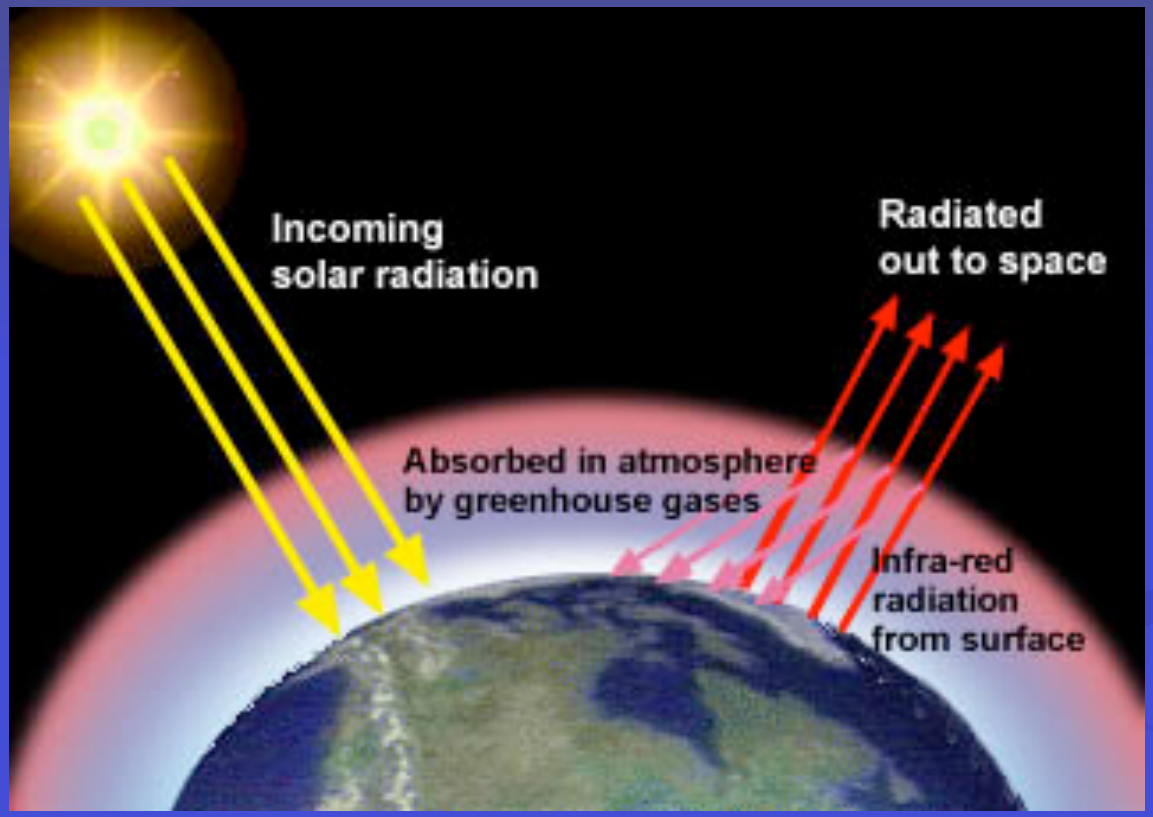
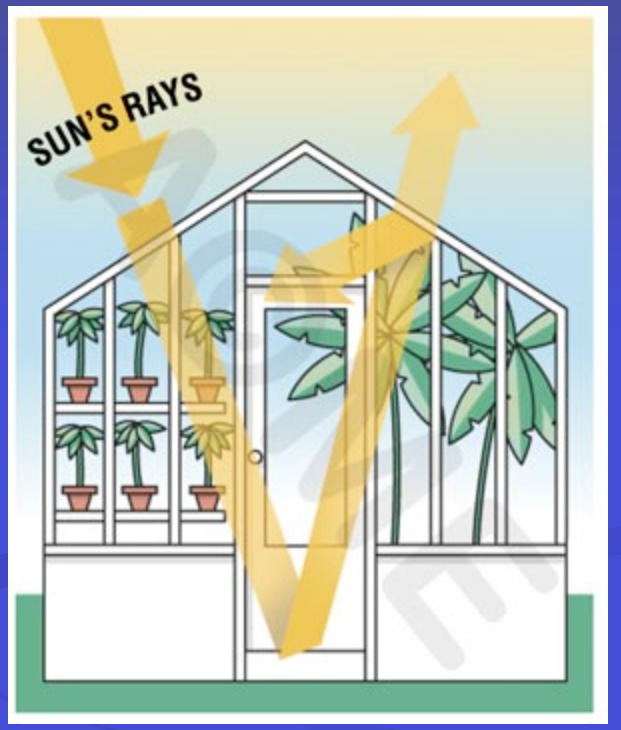


Fig. 4.35 Global distribution of the net imbalance between the annual-mean net incoming solar radiation and the outgoing longwave radiation. Positive values indicate a downward flux. [Based on data from the NASA Earth Radiation Budget Experiment. Courtesy of Dennis L. Hartmann.]

The Greenhouse Effect





The Greenhouse Effect

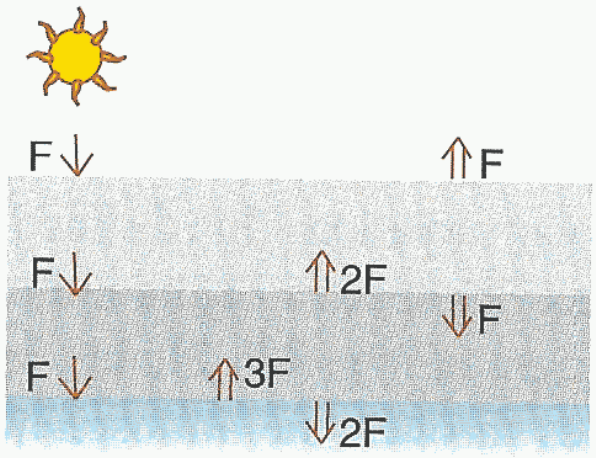


Fig. 4.9 Radiation balance for a planetary atmosphere that is transparent to solar radiation and consists of two isothermal layers that are opaque to planetary radiation. Thin downward arrows represent the flux of *F* units of shortwave solar radiation transmitted downward through the atmosphere. Thicker arrows represent the emission of longwave radiation from the surface of the planet and from each of the layers. For radiative equilibrium the net radiation passing through the Earth's surface and the top of each of the layers must be equal to zero.

The Greenhouse Effect

Two-Stream Approximation:

(1) Assume that the atmosphere is transparent to solar radiation
(2) Extinction is independent of wavelength (Grey Approximation)
(3) Steady State
(4) Let the energy flux of (Infrared) radiation be denoted by:

$$F = F^{\uparrow}, F^{\downarrow}$$

Then the transfer equation for each component becomes:

$$-\frac{dF^{\uparrow}}{d\chi} = -F^{\uparrow} + \pi B(T) \qquad (1)$$

$$\frac{dF^{\downarrow}}{d\chi} = -F^{\downarrow} + \pi B(T) \qquad (2)$$

Note that $\pi B(T) = \sigma T^4$ by the Stefan-Boltzmann Law

Greenhouse: continued

The energy continuity equation states that the divergence of the energy flux is equal to the time rate of change of the energy per unit volume:

$$\frac{dF}{d\chi} = \frac{d(\rho C_P T)}{dt} = \rho C_P \frac{dT}{dt}$$

So the steady state assumption is equivalent to the statement that the net flux F is constant:

$$F = F^{\uparrow} - F^{\downarrow} = const$$

The constant is determined by the boundary conditions:

$F^{\downarrow}(\chi=0) = 0$ or the downward flux at the top of the atmosphere is zero

$F^{\uparrow}(\chi=0) = F_0 = 240$ Watts/m^2 (absorbed solar flux) by equilibrium

$$F = F^{\uparrow} - F^{\downarrow} = F_0$$

Greenhouse - continued

If we add the two equations (1) and (2) for the individual fluxes we get:

$$-\frac{d}{d\chi}\left(F^{\uparrow}-F^{\downarrow}\right)+\left(F^{\uparrow}+F^{\downarrow}\right)=2\pi B(T)$$

But the first term is zero since the derivative of a constant is zero.

This gives:

$$\pi B(T)=\frac{1}{2}\left(F^{\uparrow}+F^{\downarrow}\right)$$

Subtract (2) from (1):

$$\frac{d}{d\chi}\left(F^{\uparrow}+F^{\downarrow}\right)=F^{\uparrow}-F^{\downarrow}=F_0 \qquad (3)$$

Integrating to get:

$$F^{\uparrow}+F^{\downarrow}=F_0\chi+const$$

From the upper boundary condition we find that the constant is F_o,

$$F^{\uparrow}+F^{\downarrow}=F_0(\chi+1) \qquad (4)$$

Greenhouse - continued

We have two equations, (3) and (4), with two unknowns, $F^{\uparrow}$ and $F^{\downarrow}$.

$$F^{\uparrow} = \frac{1}{2} F_0 (\chi + 2)$$

$$F^{\downarrow} = \frac{1}{2} F_0 \chi \qquad (5)$$

So for temperature as a function of optical depth χ we have:

$$\pi B(T) = \sigma T^4 = \frac{1}{2} F_0 (\chi + 1)$$

can obtain the atmospheric temperature (T) as a function of the atmospheric burden of greenhouse gases (χ). This is known as the **Greenhouse Equation.**

Two-Layer Model of the Atmosphere

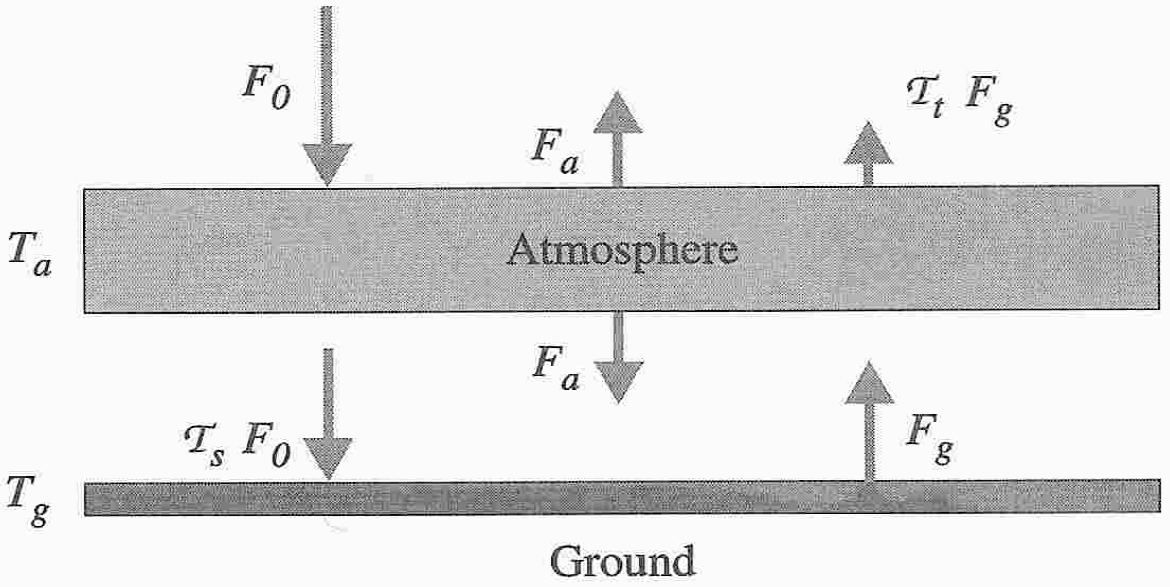
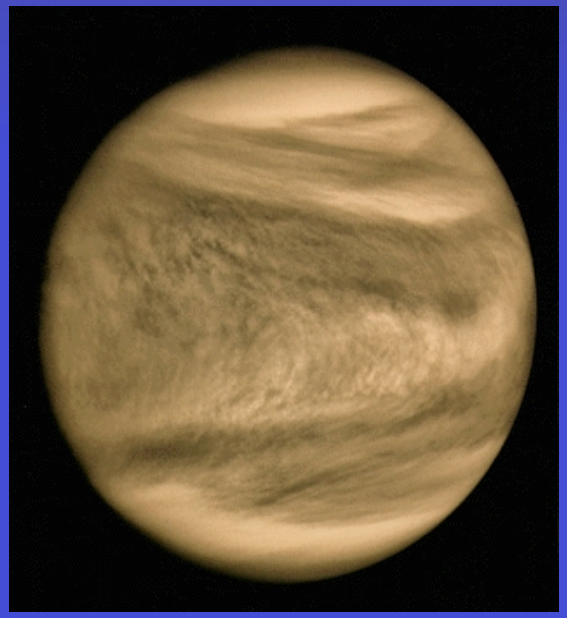


Figure 1.2 A simple model of the greenhouse effect. The atmosphere is taken to be a shallow layer at temperature T_a and the ground a black body at temperature T_g. Various solar and thermal fluxes are shown.

The lower atmosphere and surface temperatures are larger with an atmosphere, because of the additional radiation emitted downward from the atmosphere.

The Goldilocks Problem

Venus



Too hot

Earth



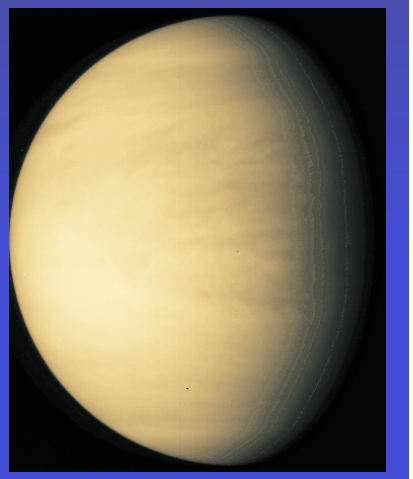
Just right!

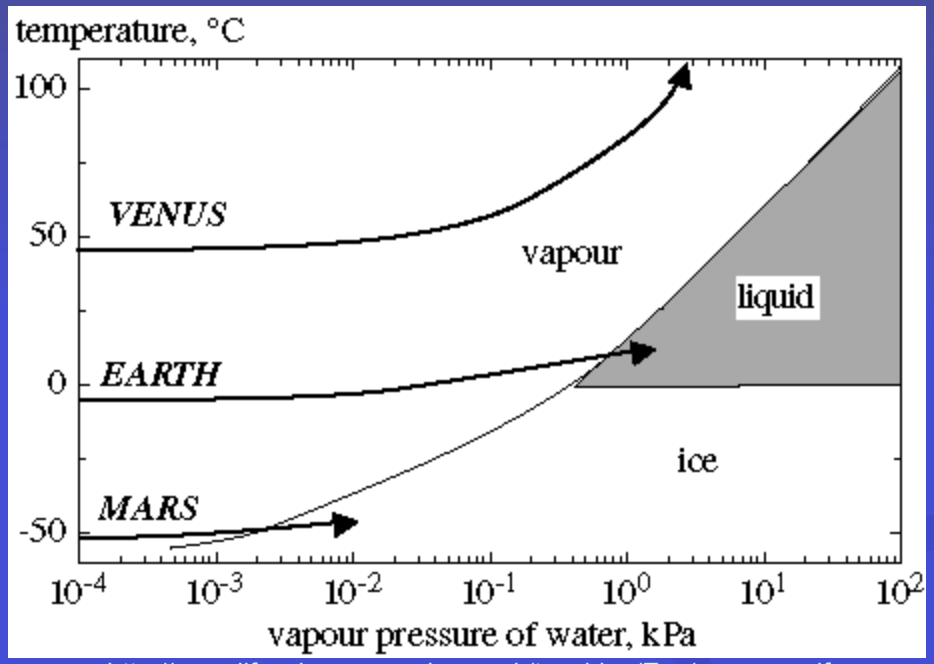
Mars



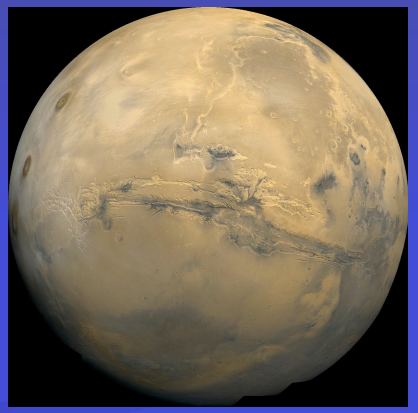
Too cold

Runaway Greenhouse: Mars, Venus, and Earth





http://www.lifesciences.napier.ac.uk/teaching/Env/runaway.gif





Questions for Discussion

(1) Is the Earth a perfect Blackbody?

(2) How large would day/night temperature difference be on Earth is the day was 48 hours instead of 24 hours?

(3) What would rainbows look like on Venus?

(4) Why doesn't a solid object radiate emission lines?

Questions for Discussion

(5) In global warming the surface temperature of the Earth increases due to increasing atmospheric CO_2. But the temperature of the upper atmosphere is expected to decrease. Why?

Questions for Discussion

(6) What can the radiation balance at the top of the atmosphere tell us about the surface of the planet?

(7) Is it likely that the last ice age is the last that the Earth will experience?

(8) Will the Earth ever experience a "runaway" greenhouse?