Introduction to Radiative Transfer

David Crisp
Jet Propulsion Laboratory, California Institute of Technology

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Summary of Topics to be Covered

- Introduction to the Electromagnetic Spectrum

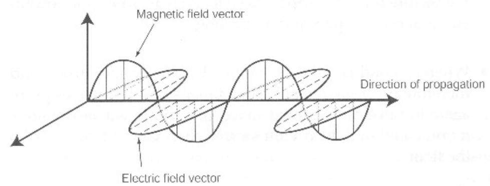
- Processes that absorb, emit and scatter solar and thermal radiation
  - Reflection/Scattering by planetary surfaces
  - Absorption, emission, and scattering by gases
  - Scattering and absorption by airborne particles

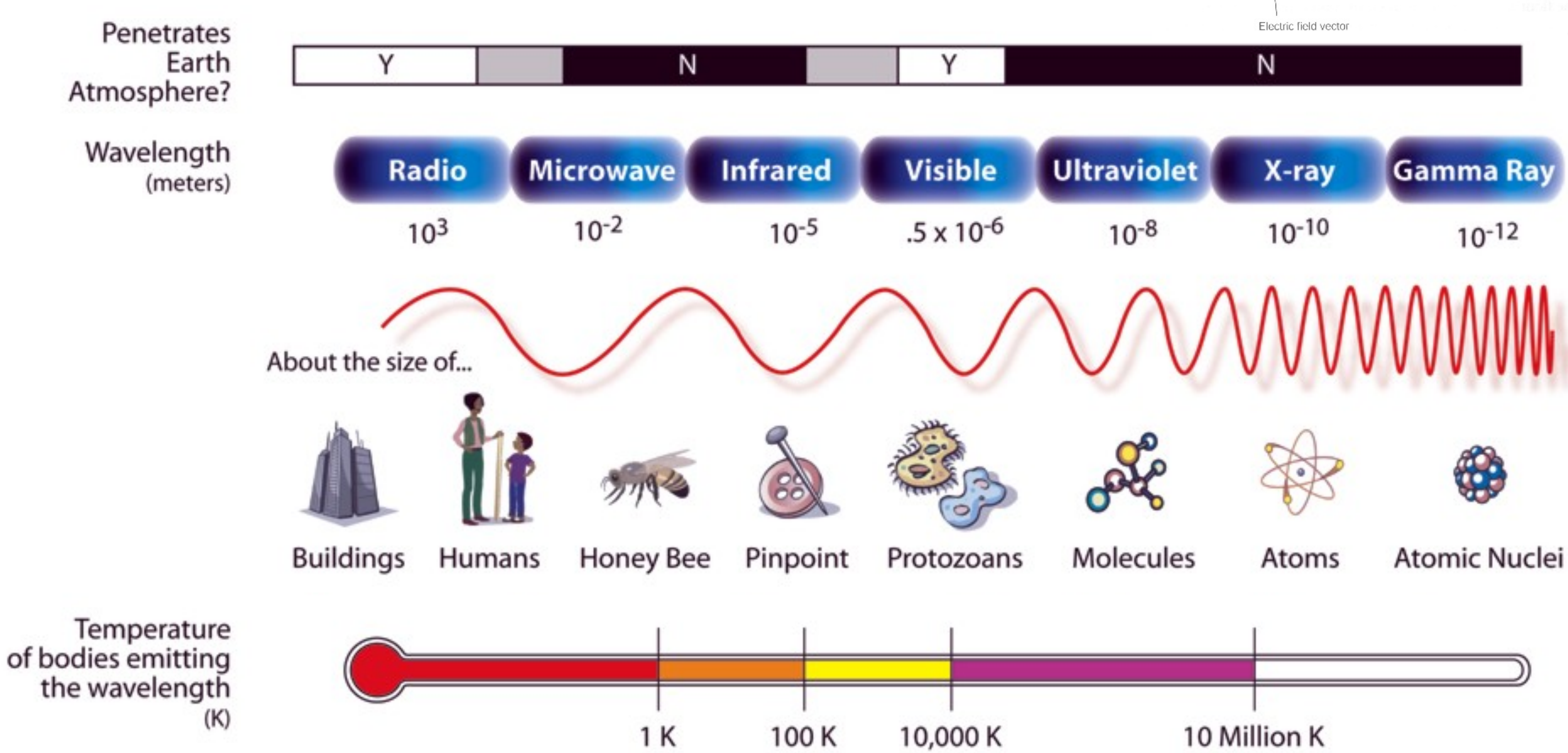
- A (very) brief introduction to multiple scattering methods

- A few applications of radiative transfer models
  - Simulating surface-atmosphere spectra
  - Remote sensing of surface and atmospheric properties
  - Modeling planetary climates

A Very Brief Review of the Electromagnetic Spectrum

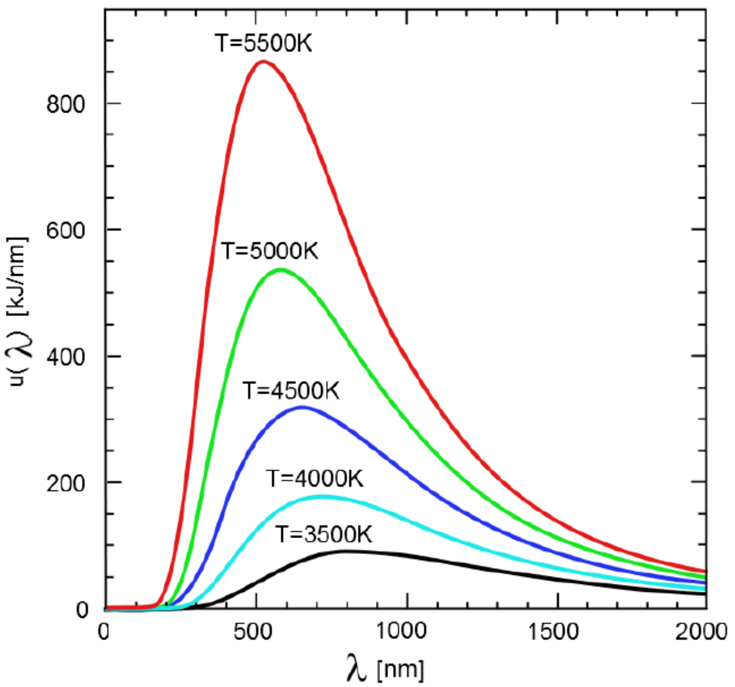
- In remote sensing, almost all of the information about a planetary environment is carried by Electromagnetic Radiation
  - a.k.a. "light"





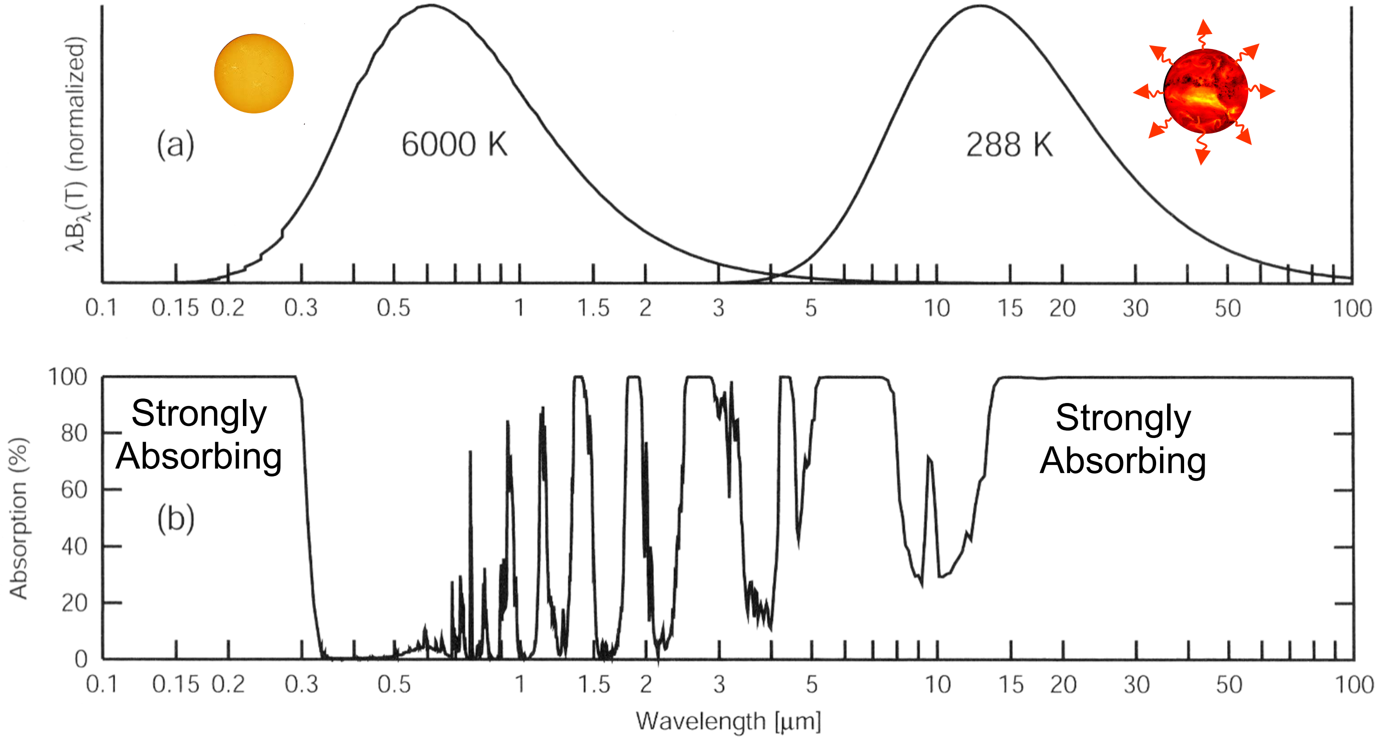
Interaction of Radiation with Planetary Environments

- Electromagnetic radiation can be *absorbed, emitted,* or *scattered* when it interacts with a planetary surface or atmosphere
- Kirchoff''s Law of Thermal Radiation: in thermal equilibrium, the emissivity of a body equals its absorptivity (e.g. a poor reflector is a good emitter)
- Wein's Law: The wavelength dependence of emission from a body depends on its temperature
- The wavelength dependence of thermal emission is defined by the Planck function



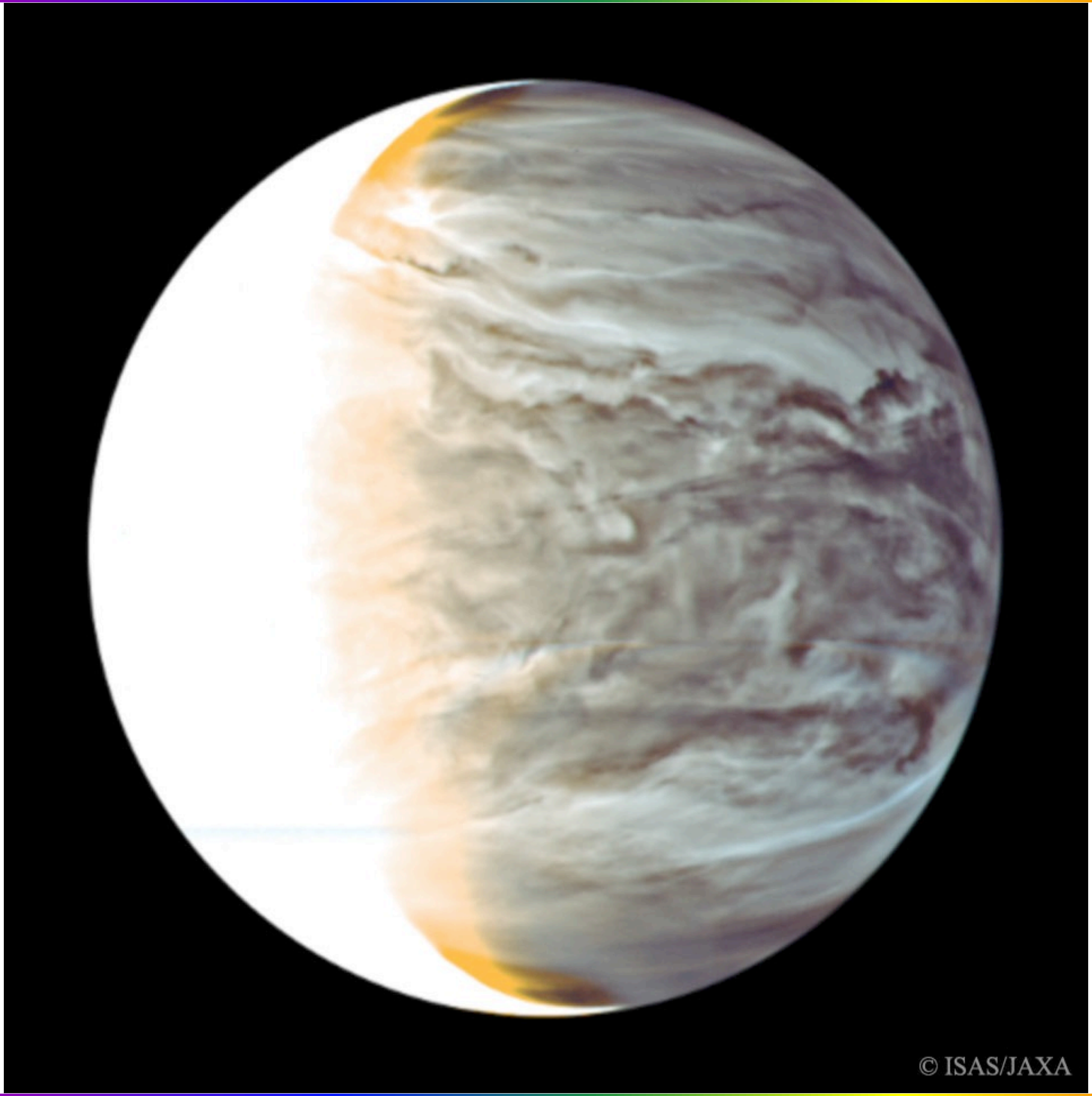
$$B(\lambda,T) = \frac{2hc^2 / \lambda^5}{e^{hc/\lambda kT}-1}$$

Solar and Thermal Radiation



- The sun is hot (5777 K), and therefore emits most of its radiation at short wavelengths (high energies)
- The Earth and (most) other planets substantially cooler, and emit most of their radiation at longer wavelengths (lower energies)
- The Earth's atmosphere absorbs strongly in the UV and thermal IR

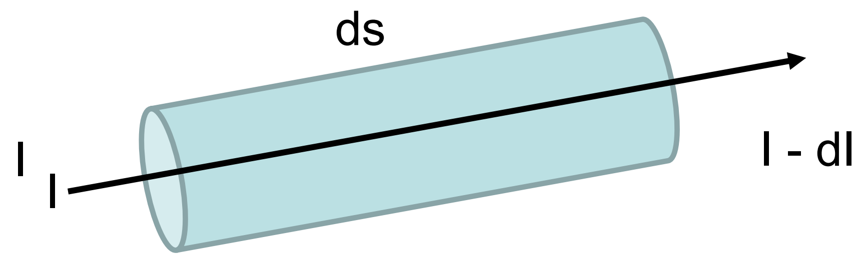
Venus: An Example of Reflection and Thermal Emission



In this near infrared image of Venus taken by the Japanese Akatsuki spacecraft, we see:

- Reflection of sunlight from the bright, sunlit crescent at the left,
- Thermal emission from the hot lower atmosphere that traversers the clouds and escapes to space on night side on the right.

Extinction, Optical Depth, and Transmission



- As light traverses a distance , ds, in a scattering or absorbing medium, it experiences "extinction"
- The amount of extinction is proportional to the "optical depth," τ, where

$$\tau = \int \sigma (\lambda, s) N(s) ds$$

- Here, $\sigma (\lambda, s)$ is the extinction cross section of the molecule or particle, which, in general changes with wavelength, λ , and distance along the path, and the number density of the molecules or particles, N(s).

- The "transmission" is given by $T = \exp(-\tau)$
  – This relationship is often called "Beer's Law"

Extinction, Absorption, and Scattering

- The total extinction cross section of a gas, aerosol, or cloud particle, σ_{ext}, is given by the sum of the scattering cross section, σ_{scat}, and the absorption cross section, σ_{abs}

- Similarly, the extinction optical depth can be expressed as the sum of a scattering and absorption optical depth,

$$\tau_{ext} = \tau_{abs} + \tau_{sca}$$

- The single scattering albedo is defined as the ratio of the scattering cross section (or optical depth) and the extinction optical depth

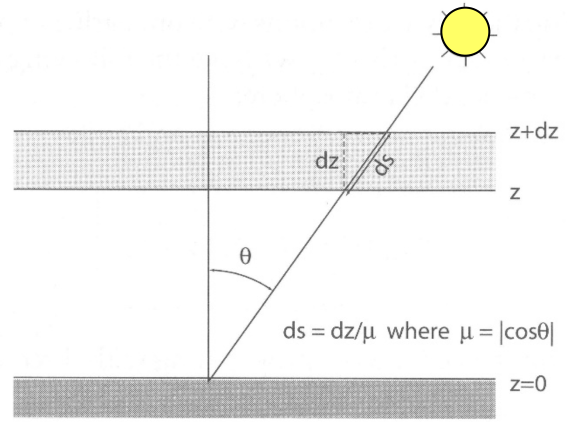
$$\omega = \tau_{scat} / \tau_{ext}$$

Radiance, Flux, and Pathlength

- It is easiest to relate slant paths to vertical paths by considering a horizontally-infinite system
  - Then, the vertical distance, dz, is related to the optical path length

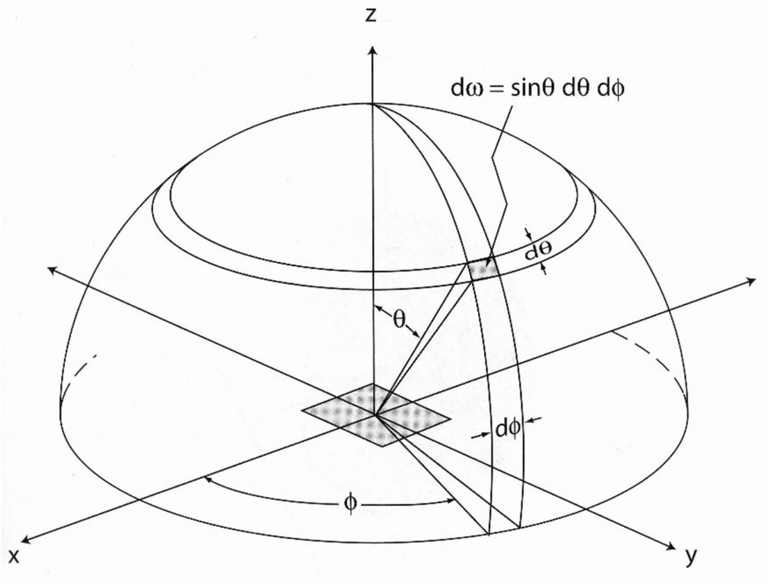
    $$ds = dz / \cos(\theta)$$

    where θ is the zenith angle

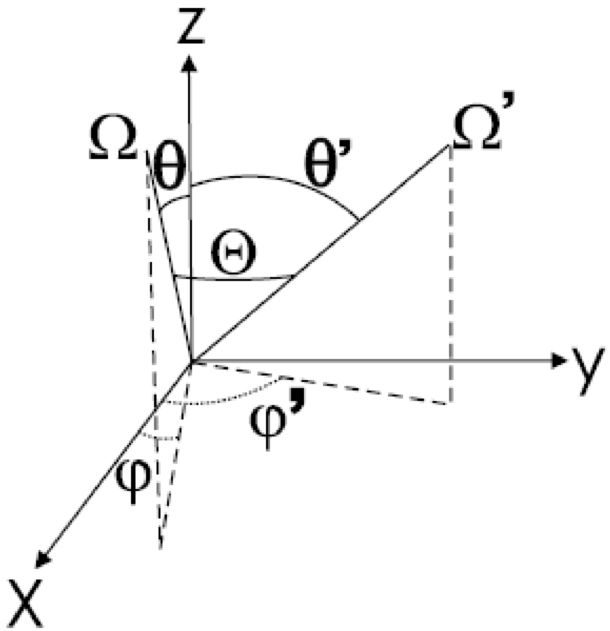


- A ***radiance*** or “intensity” specifies the amount of radiation per unit solid angle (e.g. $W/m^2/sr/\mu m$)

- An ***irradiance*** or “flux” is the total, angle-integrated radiation through a surface



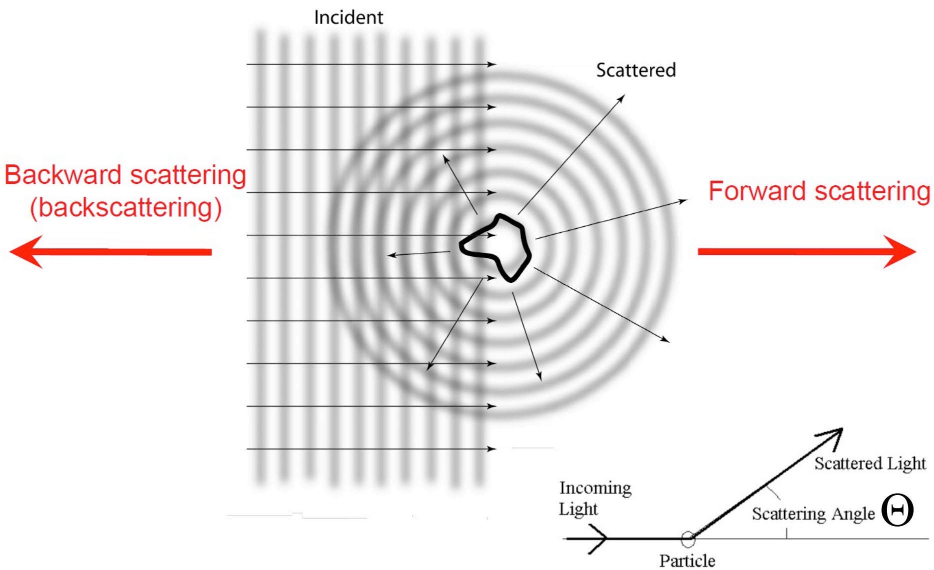
The Scattering Angle



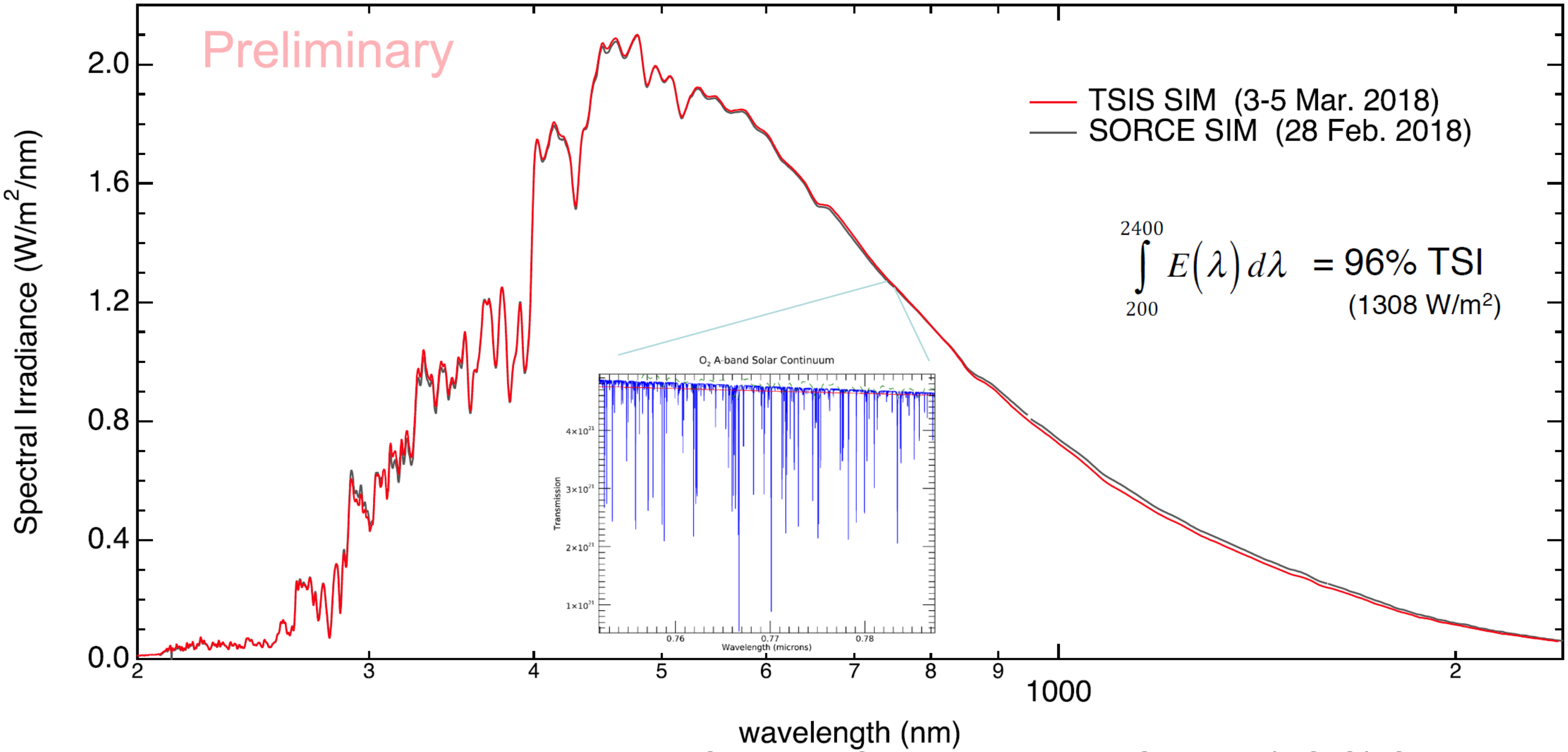
Θ denotes the scattering angle, the angle between the directions of incident and scattered radiation, Ω and Ω', respectively, in the plane of scattering (see Figure at left). In terms of zenith and azimuthal angles, the scattering angle is given by

$$\cos\Theta = \cos\theta\cos\theta' + \sin\theta\sin\theta'\cos(\phi' - \phi),$$

This terminology is useful for describing both the angle dependence of the incoming and scattered radiation field and to describe the angle-dependent scattering by a specific particle or ensemble of particles, also known as the Particle Phase Function, $P(\Theta)$



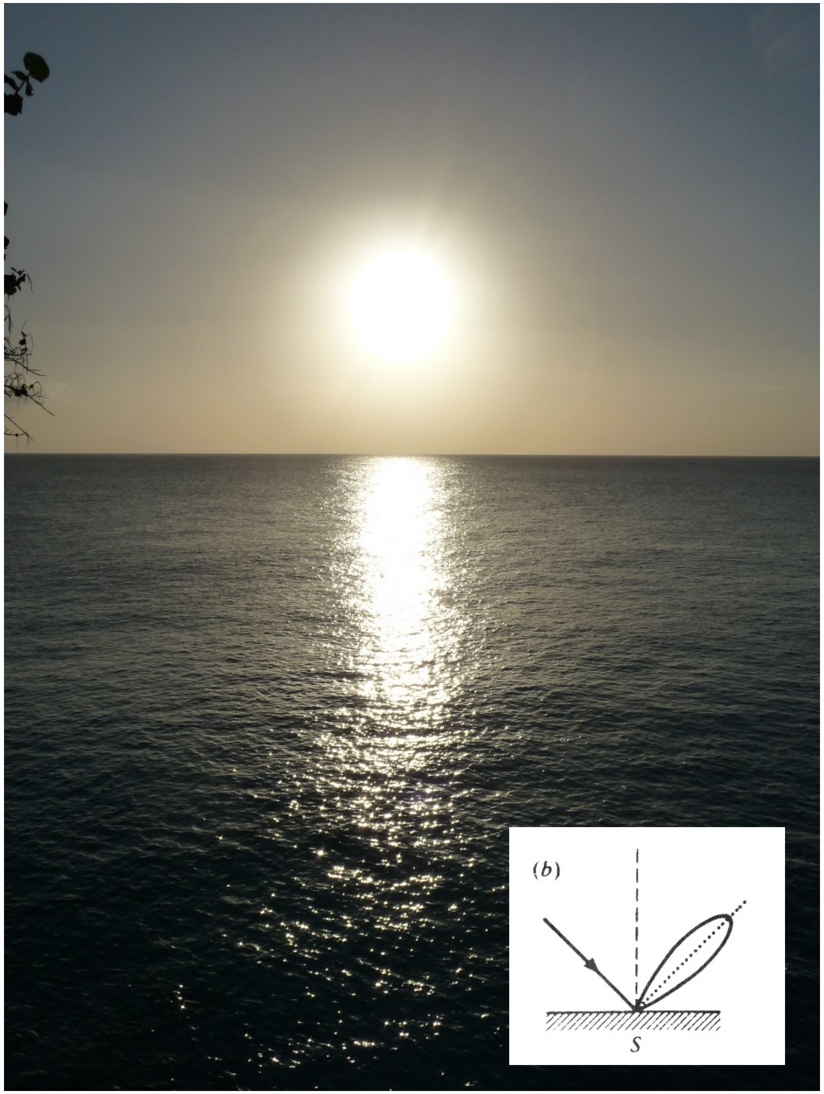
The Solar Flux at the Top of the Atmosphere (TOA)

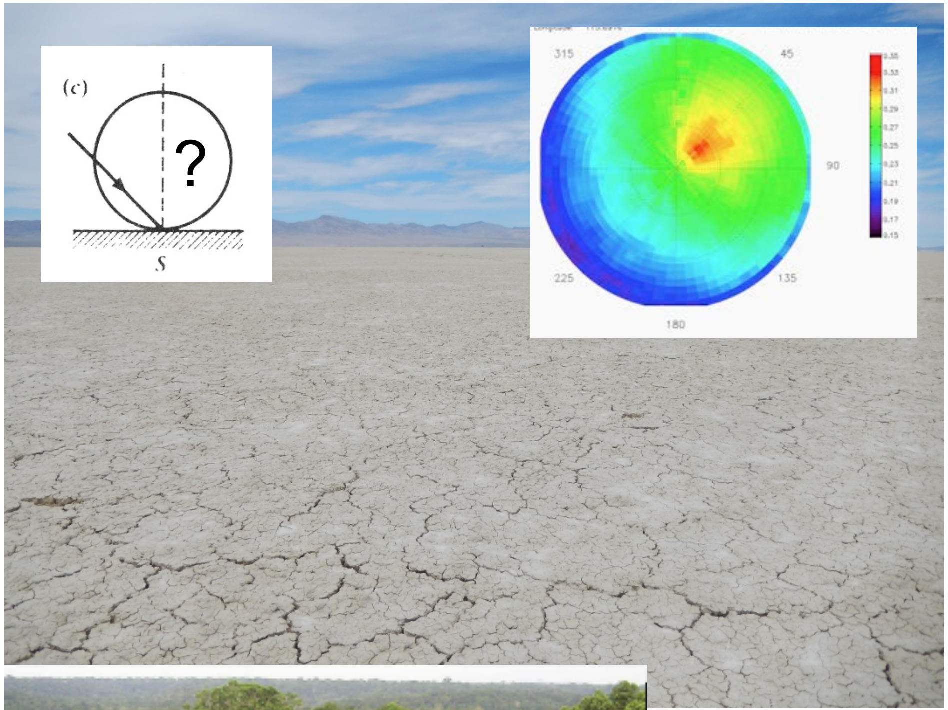


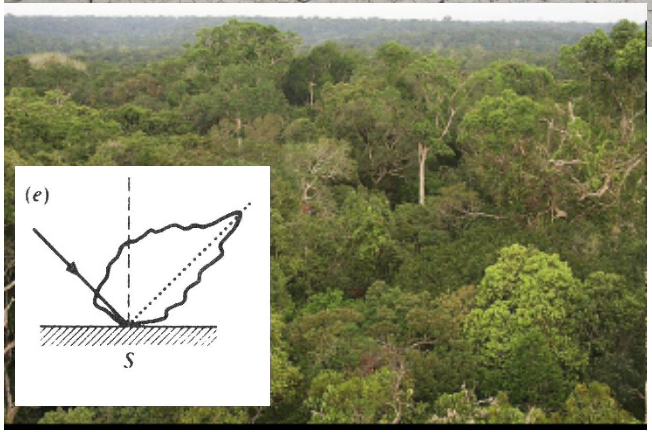
A new instrument, the Total and Spectral Solar Irradiance Sensor (TSIS) Spectral Irradiance Monitor (SIM) SIM was deployed on ISS in December 2017 (Principal Investigator, Peter Pilewskie, LASP). First light shows lower fluxes than Source SIM at wavelengths between 0.85 and 2 microns

Eric Richard (SSI Team)

Examples of Surface Scattering



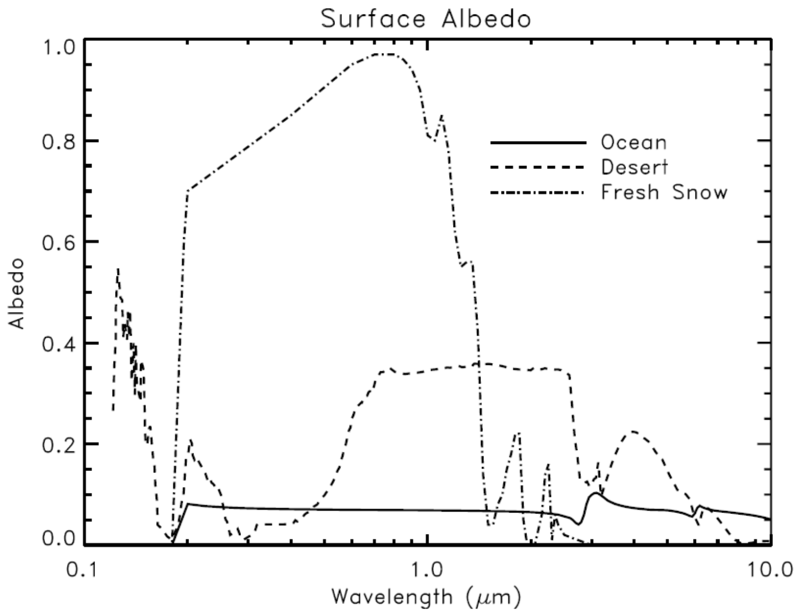


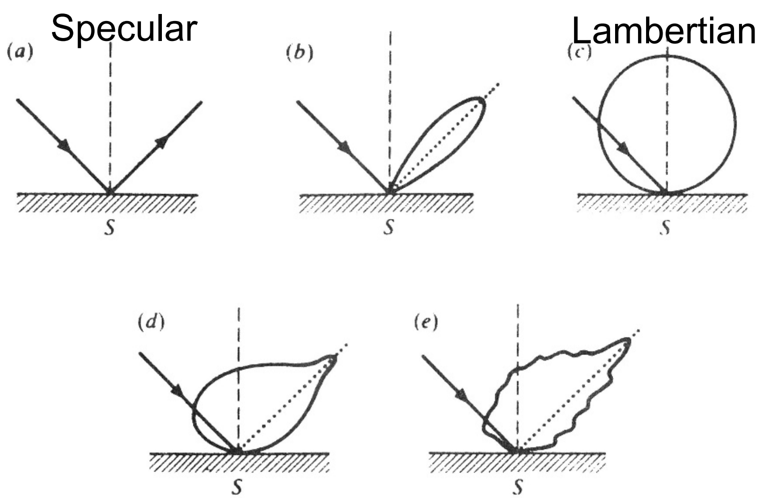


Interaction of Radiation with Planetary Surfaces

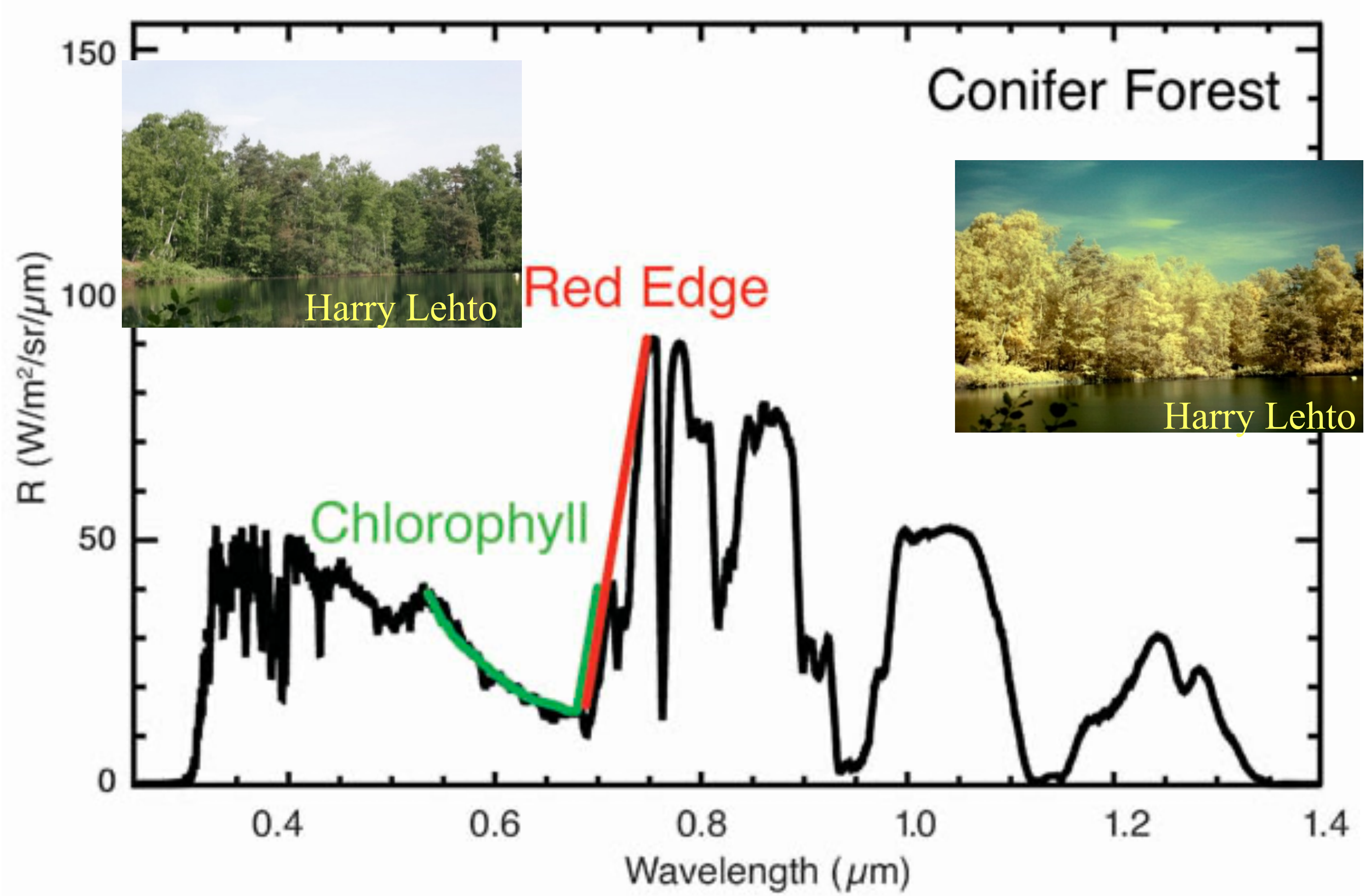
- The reflectance and transmittance of solid and liquid surfaces usually varies slowly with wavelength
  - Some are unusually bland (water)

- The angular dependence of the scattering by the surface (the *bidirectional reflection distribution function*) depends primarily on the physical properties of the surface
  - The scattering from flat "specular" surfaces follows the Law of Reflection: $\theta_r = \theta_I$
  - "Rough" or granular surfaces can scatter the incident radiation over a wider range of angles
  - "Lamberian" surfaces scatter the incident radiation equally in all directions





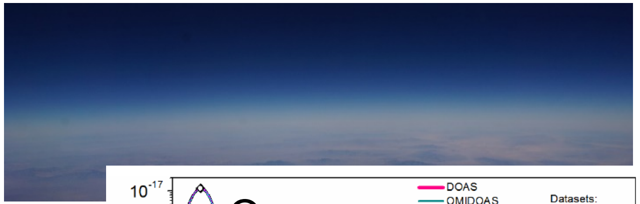
The Photosynthetic Red Edge

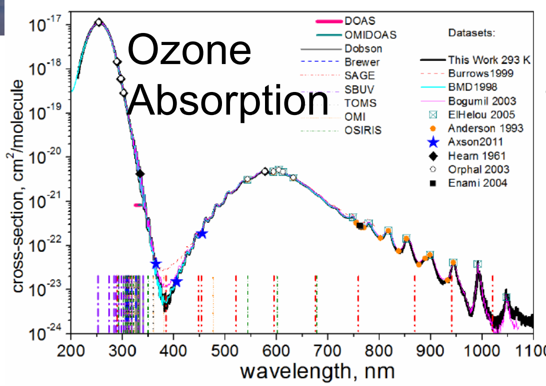


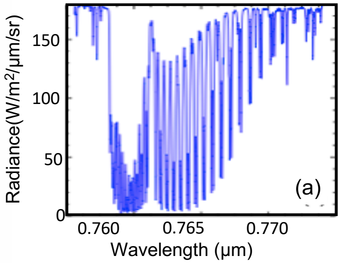
While surface reflectance generally varies more slowly with wavelength than gas absorption, there are notable exceptions to this rule, including the chlorophyll "red edge" and "Christiansen" features where the refractive index of the surface material passes through 1.0.

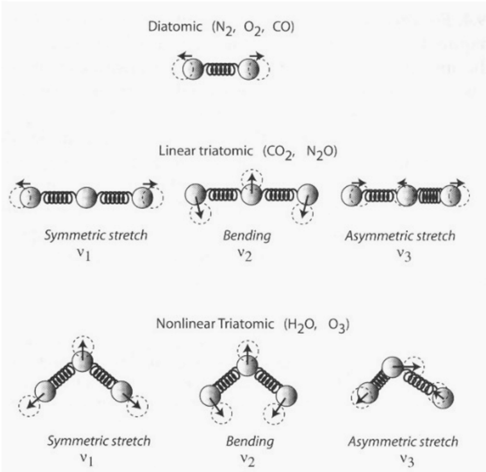
Interaction of Radiation with Planetary Atmospheres

- Atmospheres consist of gases and particles that can absorb, emit, or scatter radiation
- Gases produce
  - Rayleigh scattering at blue and UV wavelengths ($\sigma \propto 1/\lambda^4$)
  - Continuum absorption associated with electronic transitions at UV and visible wavelengths
  - Infrared absorption associated with vibration-rotation transitions at infrared wavelengths
    - Transitions are unique to the elemental composition and molecular structure
    - Provides a distinct spectral *fingerprint* for each gas
  - Some gases produce little IR absorption (N_2, noble gases)

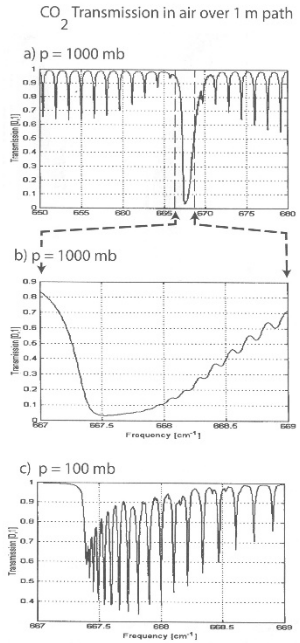






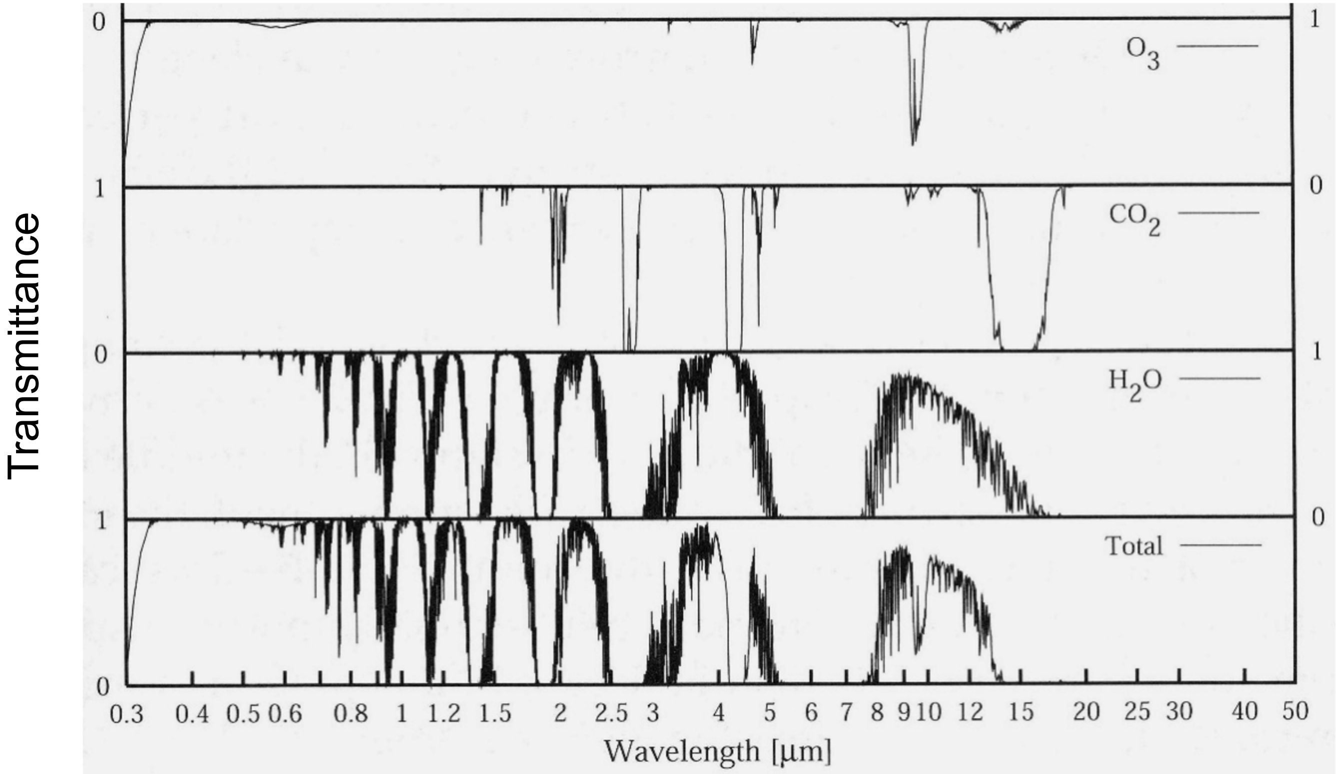


Vibration-rotation transitions for diatomic and triatomic molecules



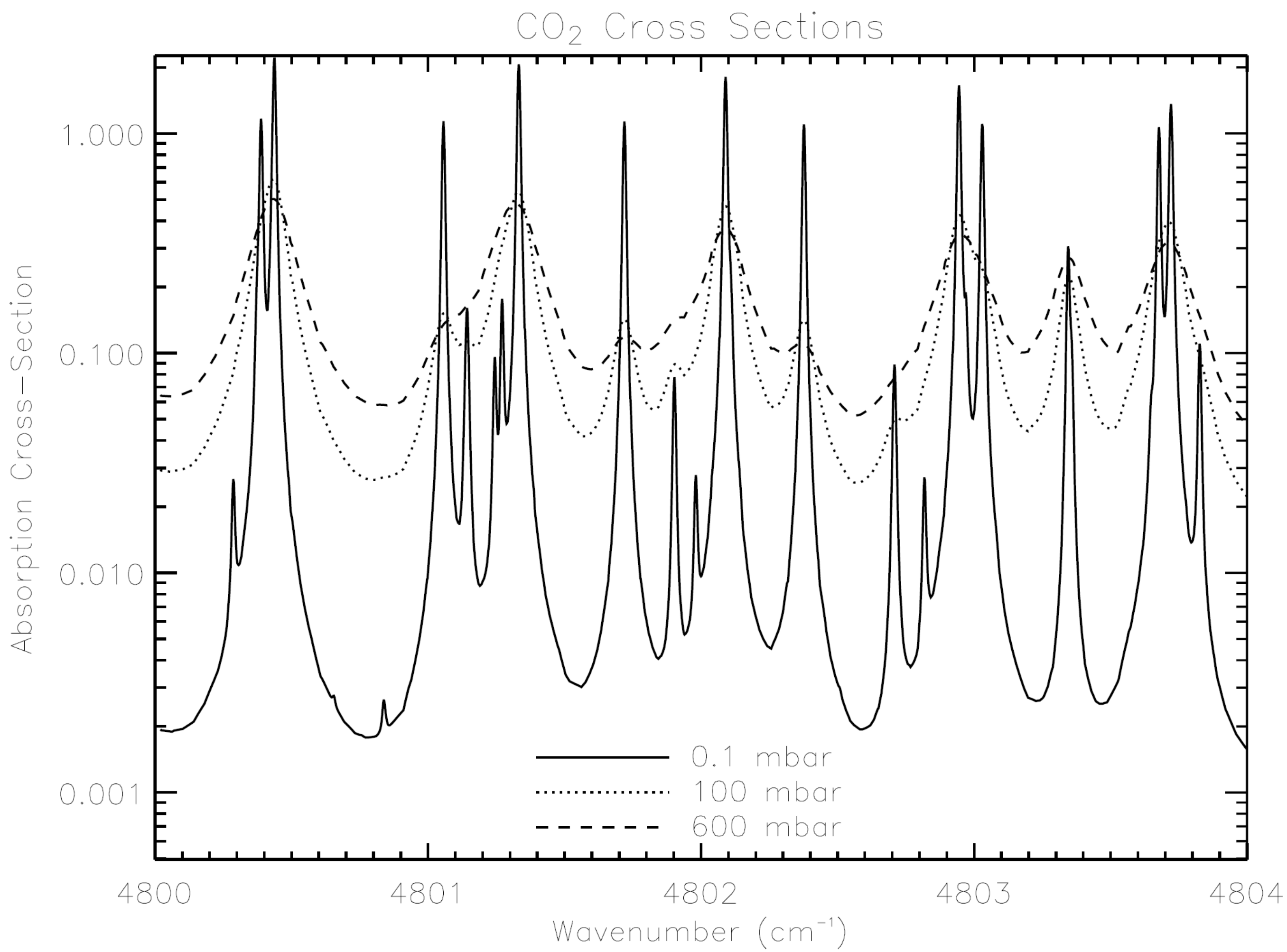
Infrared Gas Transmission in the Earth's Atmosphere

- The primary absorbing gases in the Earth's atmosphere are H_2O, CO_2, O_3, N_2O, CH_4, and CO
  - Water vapor is the strongest absorber (and most effective greenhouse gas)
  - Other gases fill many "spectral windows" between the water vapor bands
  - There is relatively little gas absorption at visible wavelengths (0.4 – 0.7 μm)



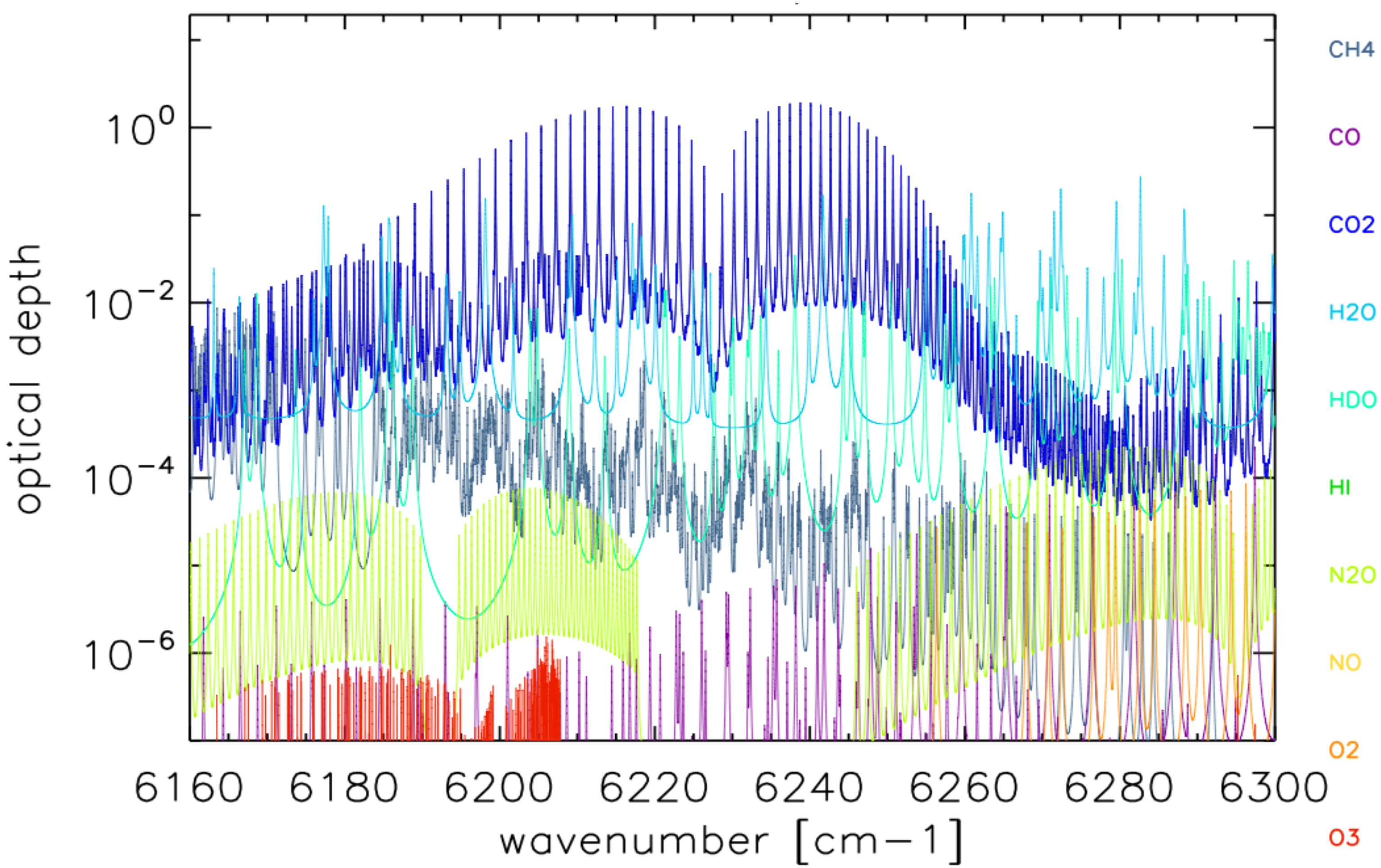
Molecules produce stronger absorption at wavelengths in the thermal infrared part of the spectrum because the energies of their fundamental vibrational transitions occur at these wavelengths.

CO_2 Absorption Cross Sections



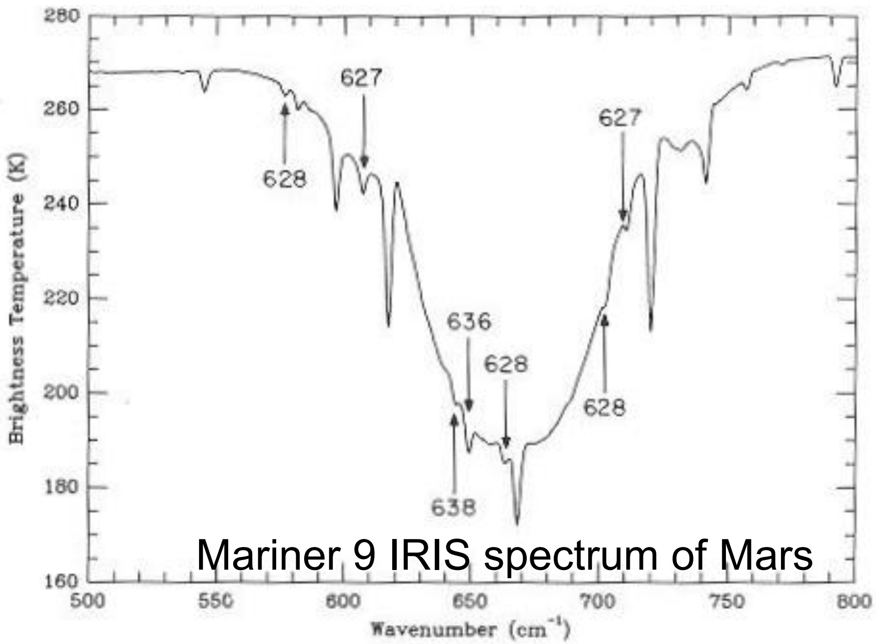
Gas absorption cross sections at near infrared wavelengths depend on both the atmospheric pressure and temperature.

Gas Absorption Cross Sections



While atmospheric gases have distinct absorption spectra, there is a substantial amount of overlap between their absorption features in most spectral regions.

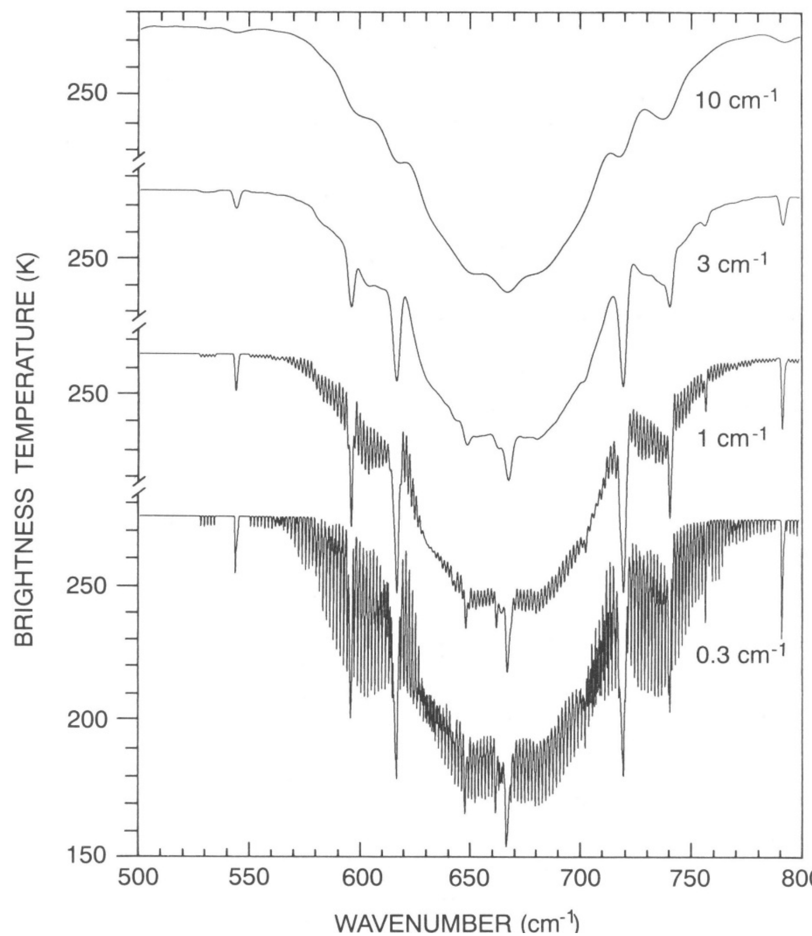
The CO2 ν_2 Fundamental at 15 μm



Mariner 9 IRIS spectrum of Mars

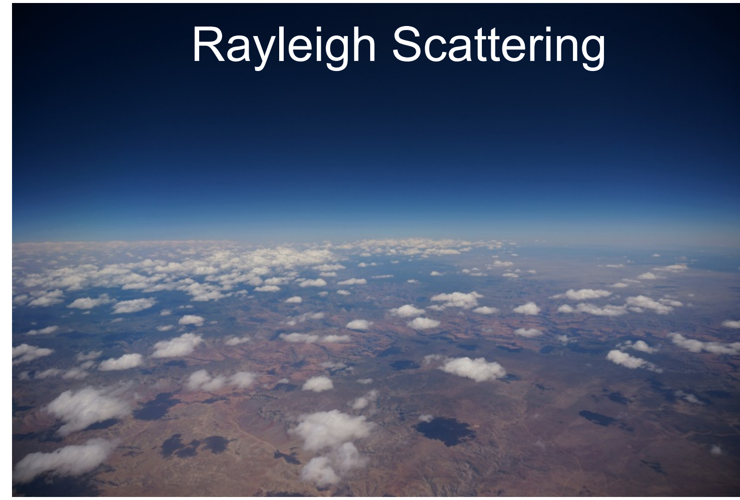
- The CO_2 15 μm (667 cm^{-1}) band is the primary feature used to retrieve the temperature structure of terrestrial planet atmospheres
- With high enough resolution and signal to noise ratios, this band can also yield isotopic information

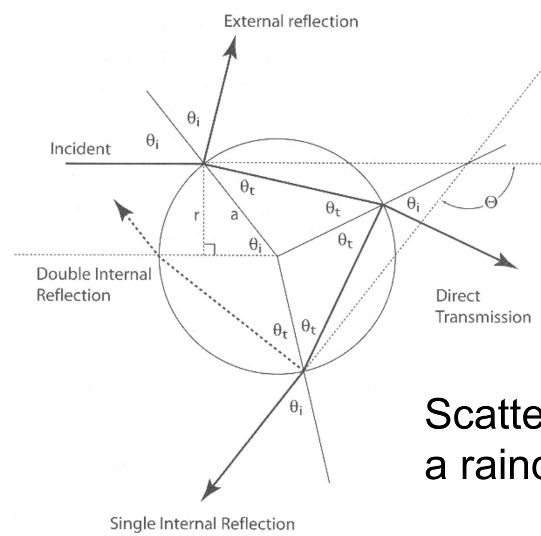
- Radiances are often shown as "Brightness Temperatures". (effective black-body temperature)



Scattering in Planetary Atmospheres

- Atmospheric scattering can be broadly defined as the redirection of radiation out of the original direction of propagation, due to interactions with molecules and airborne particles
  - In “conservative” scattering, no energy is exhanged, only a change in the spatial distribution of the radiation
  - Reflection, refraction, diffraction etc. are actually all just forms of scattering
- Airborne particles (cloud droplets, aerosols) also absorb and emit radiation
- The total scattering + absorption cross section of a particle is referred to as the “extinction” cross section

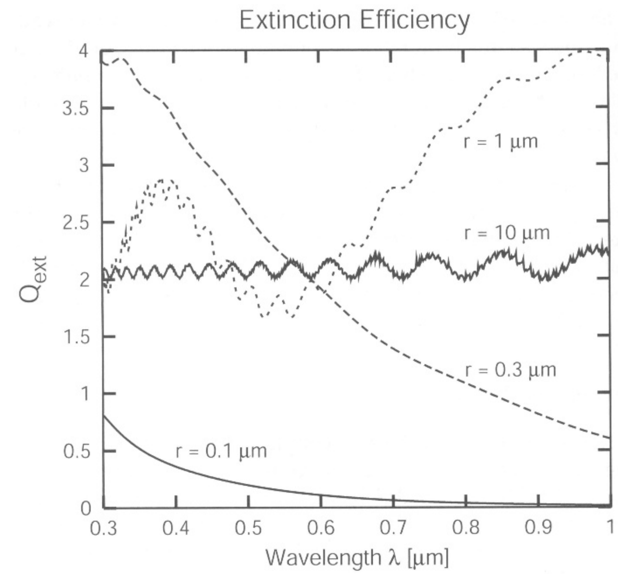


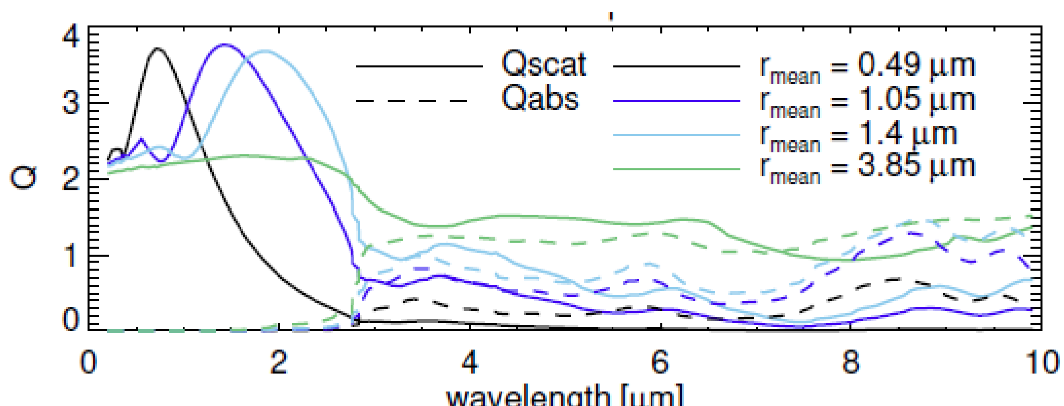


Scattering by a raindrop

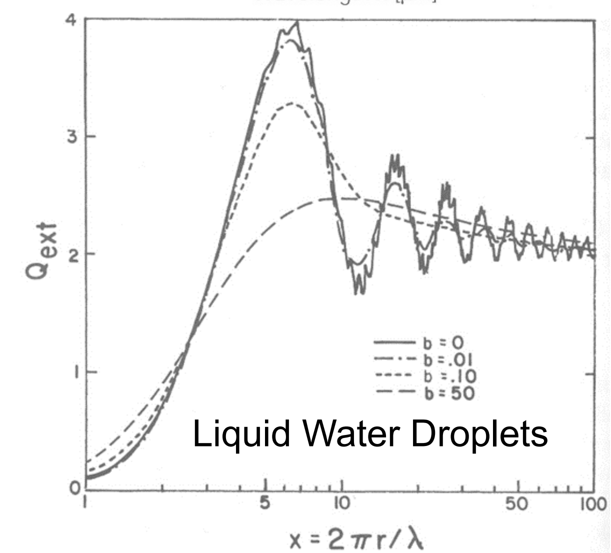
Single Scattering by Airborne Particles

- The extinction cross section depends on the composition (complex refractive index) and the particle's size (relative to the wavelength, $x=2\pi r/\lambda$)
  - Particles are most efficient at scattering radiation with a wavelength comparable to their circumference (x = 1)
  - The extinction efficiency is the ratio of the extinction cross section to the physical cross section. For spheres: $Q_{ext} = \sigma_{ext}/\pi r^2$

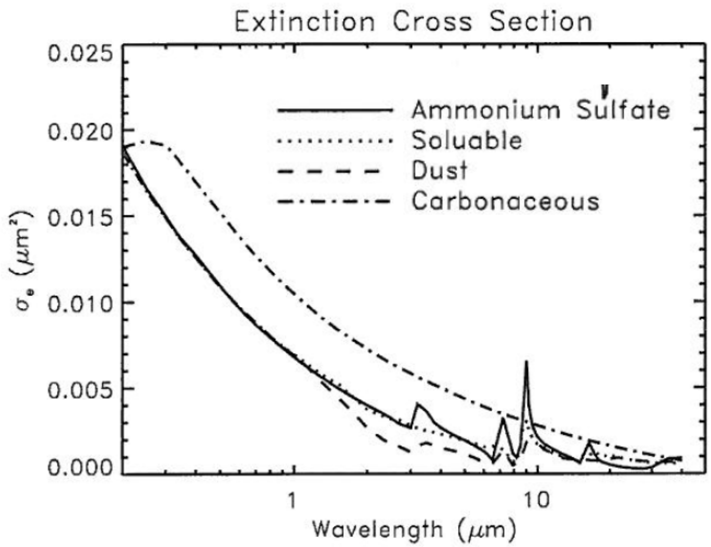


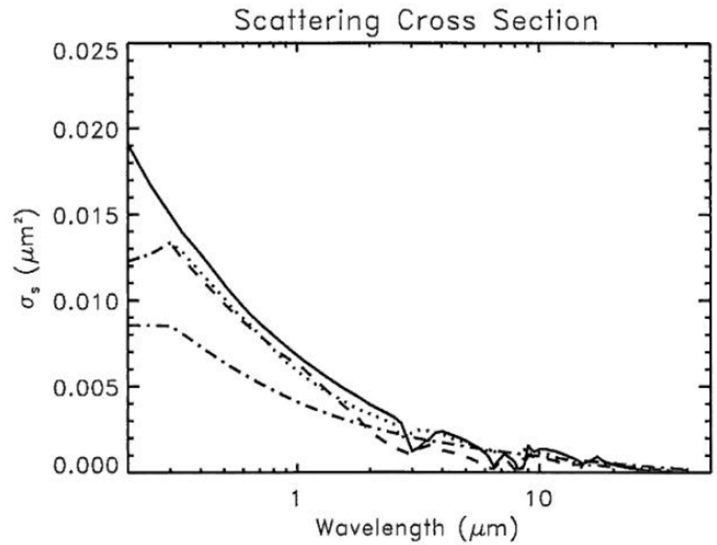


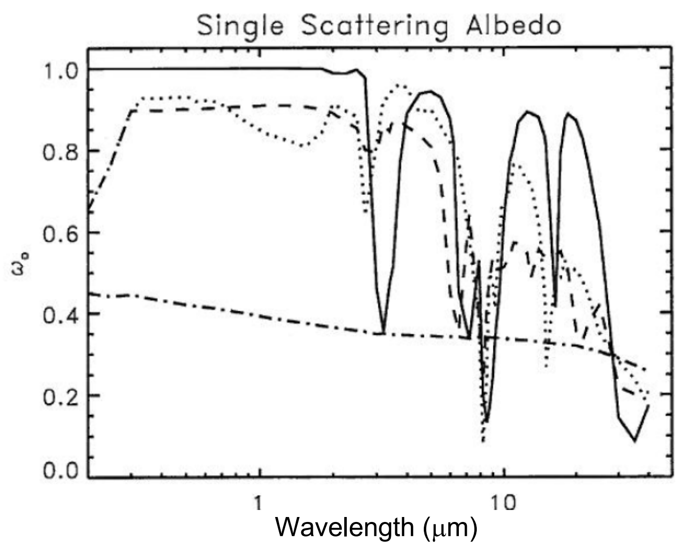
Absorption and Scattering by H_2SO_4 Aerosols



Aerosol Extinction and Scattering Cross Sections and Single Scattering Albedos



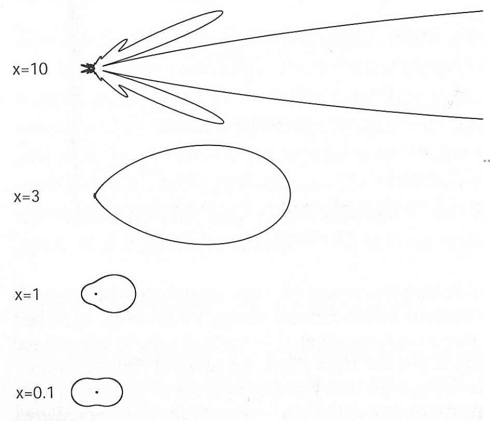


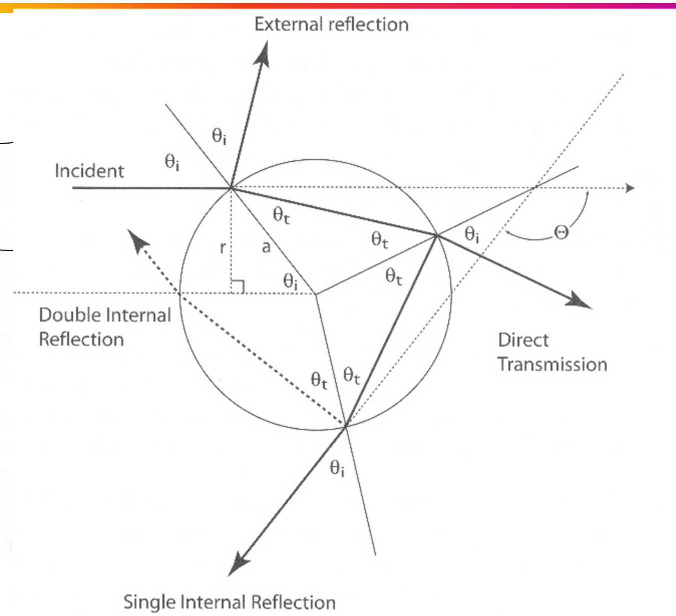


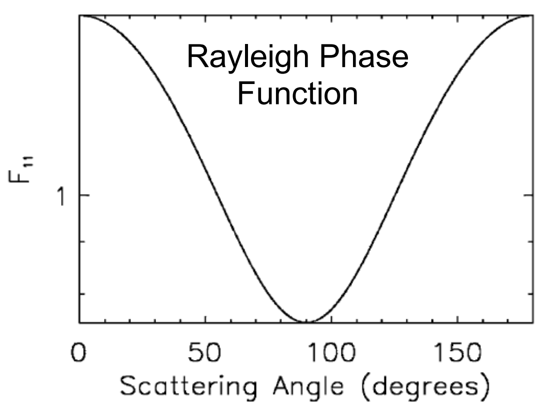
The wavelength-dependent extinction and scattering cross sections and single scattering albedos are shown for a range of typical terrestrial aerosol types to illustrate the effects of particle composition and sized distribution on the aerosol optical properties

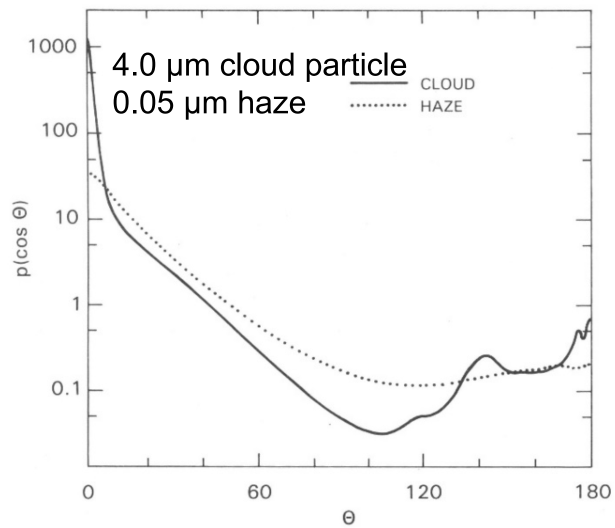
The Scattering Phase Function

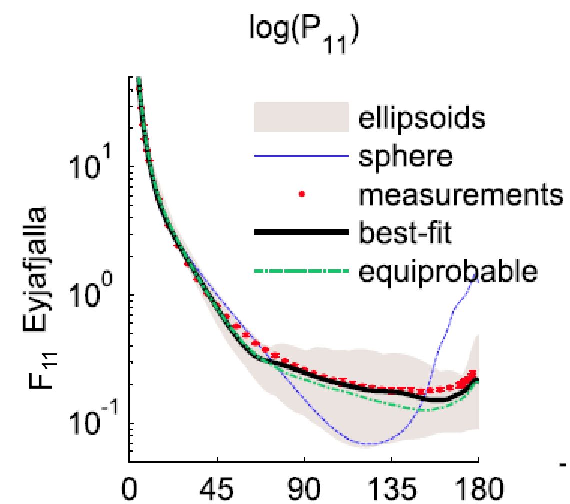
- The angle dependence of the scattering depends on particle size and shape
  - Gases and small particles scatter in both the backward and forward directions
  - Large particles are predominately forward scattering.







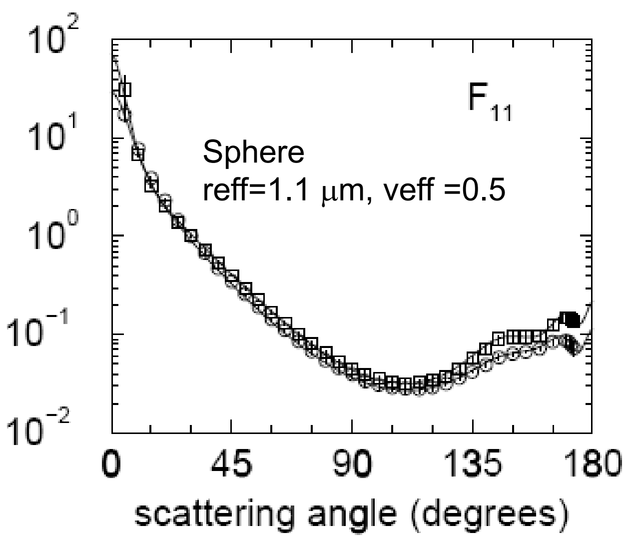


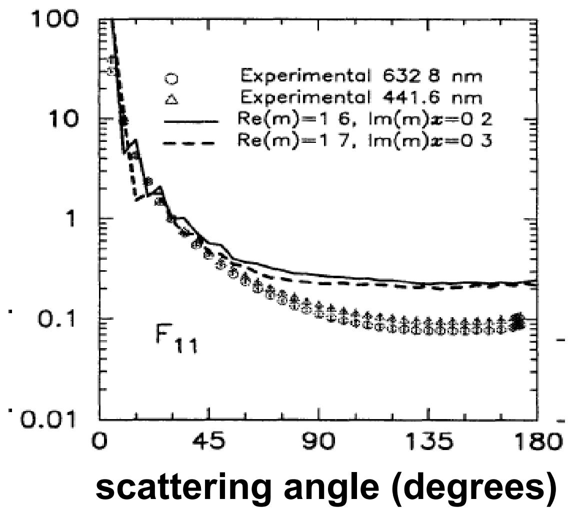


Dust and Ice Particles are not Spherical

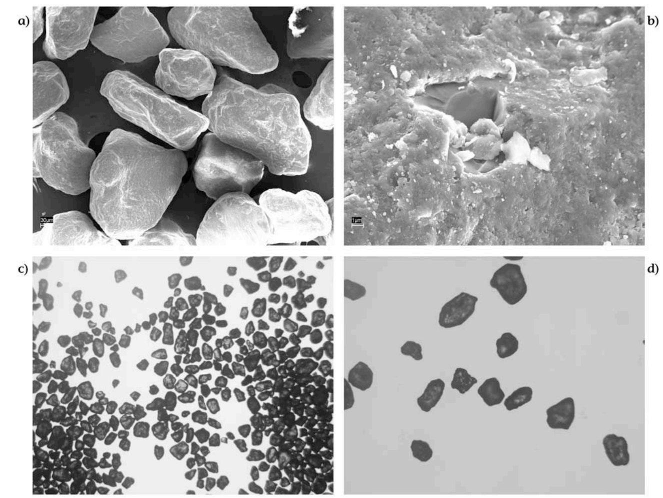
- Non-spherical particles generally produce more scattering at forward and intermediate phase angles than equivalent spheres
- The use of spherical particles in remote sensing and climate modeling simulations will introduce systematic errors in the retrieved aerosol optical depths and atmospheric optical path lengths.

Water Ice





Comparison of Phase Functions for spheres (left) and non-spherical red clay particles (right) (Volten et al. 2001).



Sahara dust

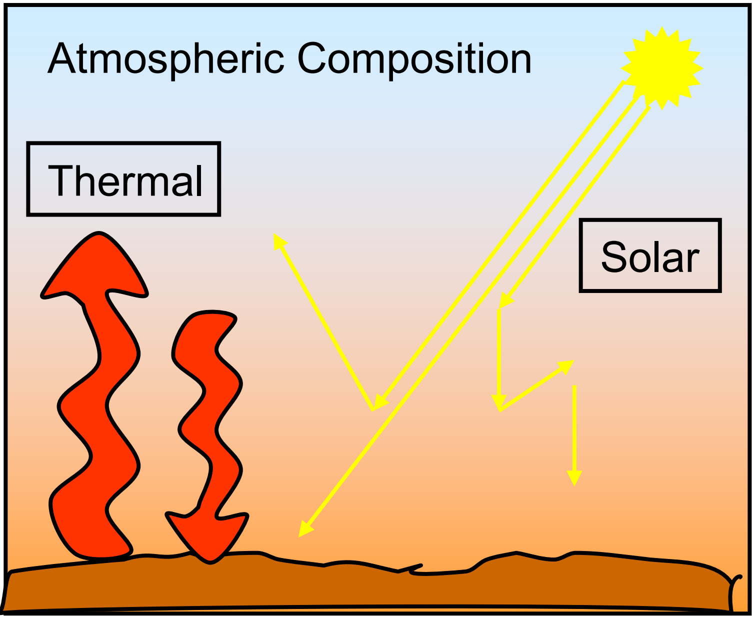
Putting it All Together: Radiative Transfer in Scattering/Absorbing/Emitting Atmospheres

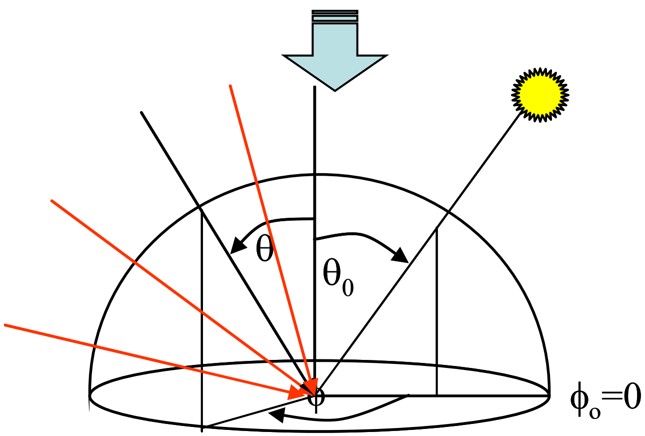
- Efficient, accurate methods for simulating the absorption, emission, and scattering of solar and thermal radiation are essential for generating:
  - Synthetic radiances use in the retrieval of atmospheric and surface properties from remote sensing observations
  - Radiative heating and cooling rate calculations for climate models

- These problems are intrinsically challenging when radiances or fluxes are needed over broad spectral regions because
  - Gas absorption cross sections change rapidly with wavelength
  - Methods for estimating radiances and fluxes in the presence of multiple scattering must be applied to spectral regions that are sufficiently narrow that the optical properties are essentially constant (monochromatic)

- The following sections will review:
  - Remote sensing retrieval algorithms
  - Climate models

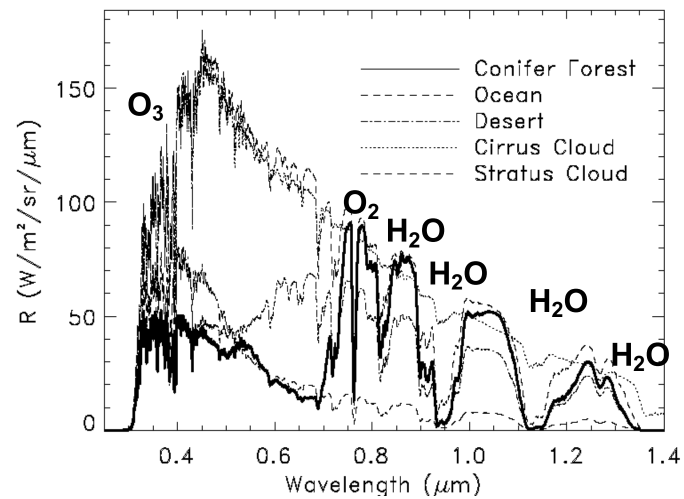
Simulating Planetary Spectra: Radiative Transfer Models



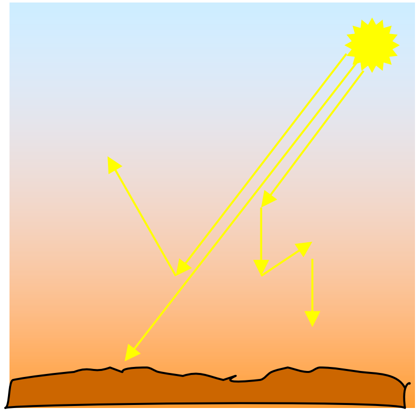


Simulating the radiation field Resolve the spectral dependence of gases, cloud, aerosols, surface albedos and radiation sources.

- Multiple Scattering Model
- Gas Absorption
  - Line-By-Line model for IR vibration-rotation bands
    - Includes absorption by H_2O, CO_2, O_3, N_2O, CH_4, and O_2
  - UV Absorption
- Optical Properties of Clouds and Aerosols
- Wavelength dependent albedos of the surface



The Equation of Transfer in Scattering, Absorbing, Emitting Atmospheres



- As solar or thermal radiation traverses an atmosphere, it can be scattered multiple time as it interacts with gases as airborne particles.
- If the optical properties of the atmosphere (optical depth, τ_ν, single scattering albedo, ω_ν, scattering phase function, $P(\Theta)$ are known at wavenumber, ν, the intensity of the radiation at any point in the atmosphere can be determined from the ***Equation of Transfer***

$$\mu \frac{dI_\nu}{d\tau_\nu} = I_\nu\left(\tau_\nu, \mu, \phi, \boldsymbol{x}\right) - S_\nu\left(\tau_\nu, \mu, \phi, \boldsymbol{x}\right)$$

where I_ν is the spectral radiance, μ is the cosine of the zenith angle, and ϕ is the azimuth angle. The source function, S_ν, is given by:

$$\begin{aligned} S_\nu\left(\tau_\nu, \mu, \phi, \boldsymbol{x}\right) = \; & \omega_\nu F_\nu^\odot e^{-\tau_\nu/\mu_\odot} \cdot P_\nu\left(\tau_\nu, \mu, \phi, -\mu_\odot, \phi_\odot, \boldsymbol{x}\right)/4\pi \\ & + \left(1-\omega_\nu\right) B_\nu\left(T\left(\tau_\nu\right)\right) \\ & + \omega_\nu \int_0^{2\pi} d\phi' \int_{-1}^{1} d\mu' \cdot I_\nu\left(\tau_\nu, \mu', \phi', \boldsymbol{x}\right) P_\nu\left(\tau_\nu, \mu, \phi, \mu', \phi', \boldsymbol{x}\right)/4\pi \end{aligned}$$

Single Scattering

Thermal Source

Scattering Source

The New Frontier: Fluxes and Heating Rates in Realistic Scattering/Absorbing Atmospheres

- If scattering can be ignored, the absorption and emission of solar and thermal radiation can be approximated by Beer's Law. For example, the solar flux at wavelength, λ, level, z and solar zenith angle, θ_o, in a plane parallel atmosphere, F_s (z) can be approximated by:

$$F(\lambda,z) = F_o(\lambda) \exp [-(\int \sigma(\lambda,z') N(z') dz') / \cos\theta_o] = F_o \exp [- \tau(\lambda,z-z_o) / \cos\theta_o]$$

- If the optical cross-sections of all absorbing constituents, $\sigma(\lambda,z')$, at all wavelengths of interest, this equation can be solved exactly on a grid that completely resolves the spectral structure of the optical properties
  - For wavelengths where vibration-rotation transitions of gases dominates the absorption, this is called a "line-by-line" solution
- In realistic atmospheres, where extinction is contributed by the absorption, emission and multiple absorption by gases, clouds, and aerosol, this simple formulation does not work because the optical path lengths are modified by multiple scattering

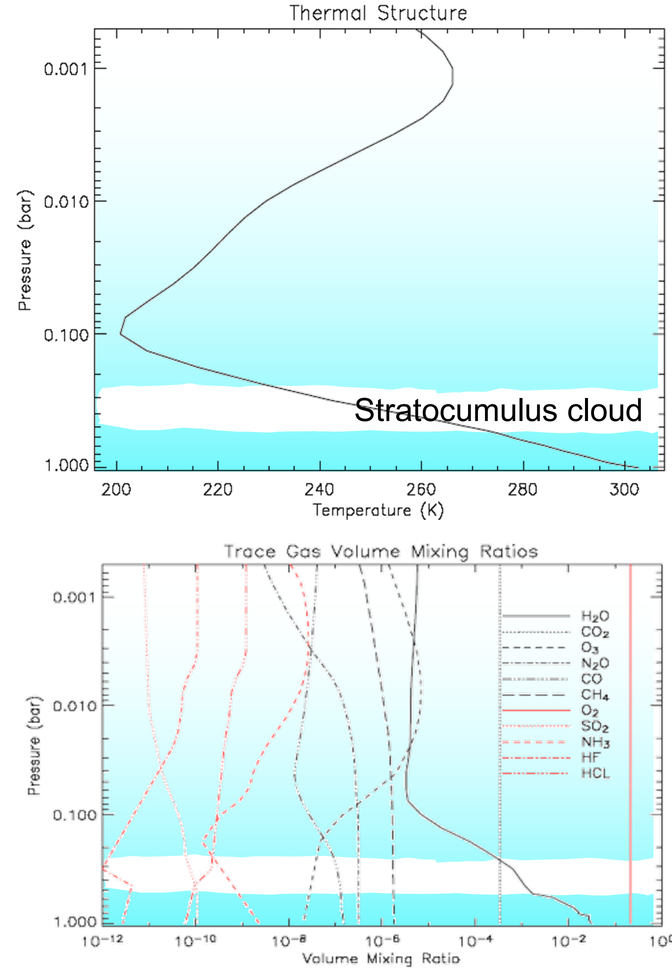
Solving the Equation of Transfer in Scattering, Absorbing Planetary Atmospheres

- Discrete Ordinates: (Stamnes, K., et al.: Numerically stable algorithm for discreteordinate-method radiative transfer in multiple scattering and emitting layered media, Appl. Opt., 27, 2502-2509.)
  - Treat the radiative transfer equation (RTE) as a boundary value problem
  - The integral in the RTE is approximated with Gaussian Quadrature, and radiances are evaluated along the specific Gaussian angles or “streams”
  - In multi-layer atmospheres, the radiances at all levels and angles are solved simultaneously by inverting a large matirx
- Doubling-Adding (Hansen, J., and Travis, J.: Light scattering in planetary atmospheres. Space Sci. Rev. 16, 527-610, 1974.)
  - Compute reflection and transmission properties for very thin sub-layer assuming single scattering
  - Add two such identical sub-layers by computing successive reflections back and forth between the layers (doubling) and repeat process until layer properties computed
  - Repeat for all layers and add contiguous (non-identical) layers, accounting for multiple reflections between layers (adding)
- Monte Carlo Methods (Plass, G., and Kattawar, G.: Monte Carlo Calculations of Radiative Transfer in the Earth's Atmosphere-Ocean System: I. Flux in the Atmosphere and Ocean, J. Phys. Oceanograph, 2, 139-145, 1972.)
  - Follow photons as they traverse a medium and are scattered and absorbed

Resolving Atmospheric Properties

- In general, the radiation field within a planetary atmosphere depends on the thermal structure and optical properties, which vary with altitude.
  - Thermal Structure:
    - Vertical variations in the thermal structure and optical properties are accounted for by dividing the atmosphere into a series of discrete levels
  - Optically Active Gases
    - Gas number densities, $N_g(z)$, are interpolated to the level structure defined by the thermal structure and the optical depth in each layer is defined as $\delta\tau_g = \int \sum (\sigma_g(\lambda,z') N_g(z') dz')$
  - Clouds and Aerosols
    - The vertical distribution of discrete cloud and aerosol layers are interpolated to the vertical grid
    - The differential absorption (abs) and scattering (sca) optical depth in each layer is given by:

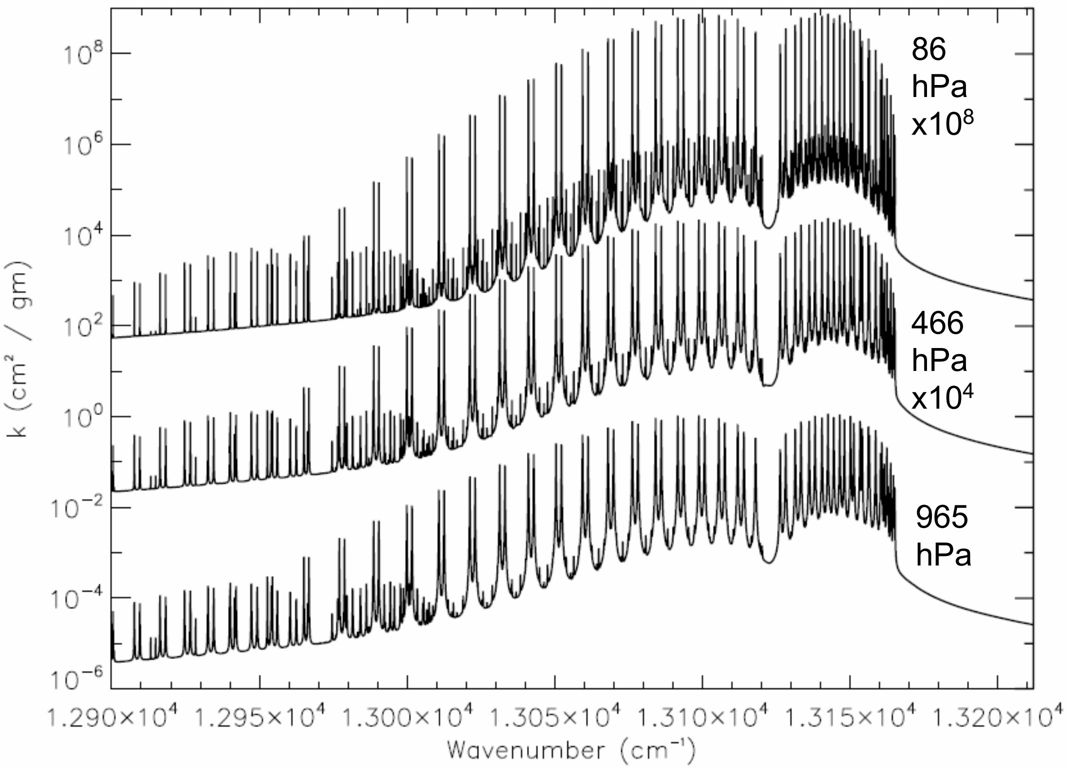
$$\delta\tau_{abs} = \int \sum (\sigma_{abs}(\lambda,z') N_a(z') dz')$$
$$\delta\tau_{sca} = \int \sum (\sigma_{sca}(\lambda,z') N_a(z') dz')$$



The vertical structure of temperature and trace gases and clouds for a typical terrestrial atmosphere with a saturated altostratus cloud.

Exact Methods for Solving Broad-band Radiative Transfer Problems

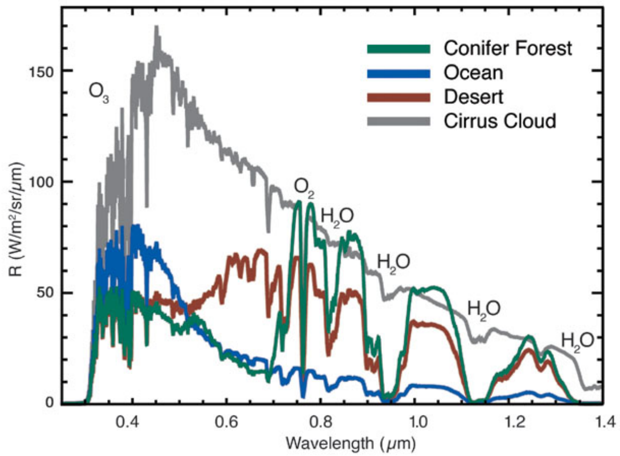
- The most accurate solutions to the equation of transfer in scattering, absorbing, emitting atmospheres can be obtained from "full-physics" methods that
  - Employ a spectral grid that is fine enough to resolve the spectral structure of all (gas, aerosol, surface) optical properties, and their variations along the optical path
  - Perform a (vector or scalar) multi-stream, multiple scattering calculation at each spectral grind point

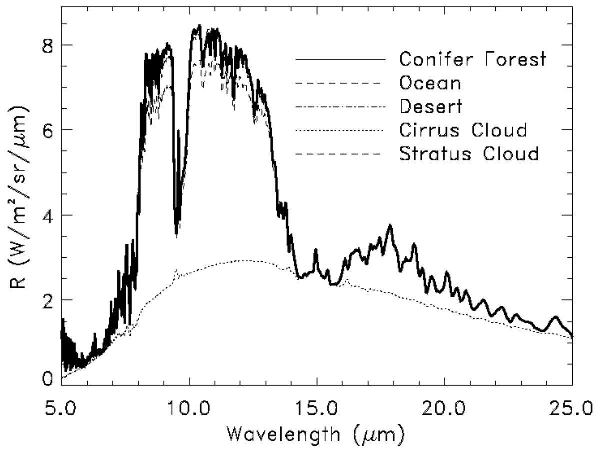


Wavelength-dependent absorption cross sections at 3 pressure levels are shown for molecular oxygen are shown for the A-Band near 760 nm (13000 cm^{-1})

Exact Methods for Solving Broad-band Radiative Transfer Problems

- The primary problem with exact methods is their computational expense, especially for broad-band (bolometric) calculations
  - 10^6 to 10^7 spectral grid points are needed to fully resolve the spectral structure throughout the solar and thermal spectral range
  - 4 to 8 vertical grid points per scale height are needed to accurately resolve the pressure and temperature dependent changes in the gas absorption cross-sections and the vertical structure of clouds and aerosols. This requires hundreds of layers.
  - 8 to 256 "streams" are needed to resolve the angle dependence of the radiation field

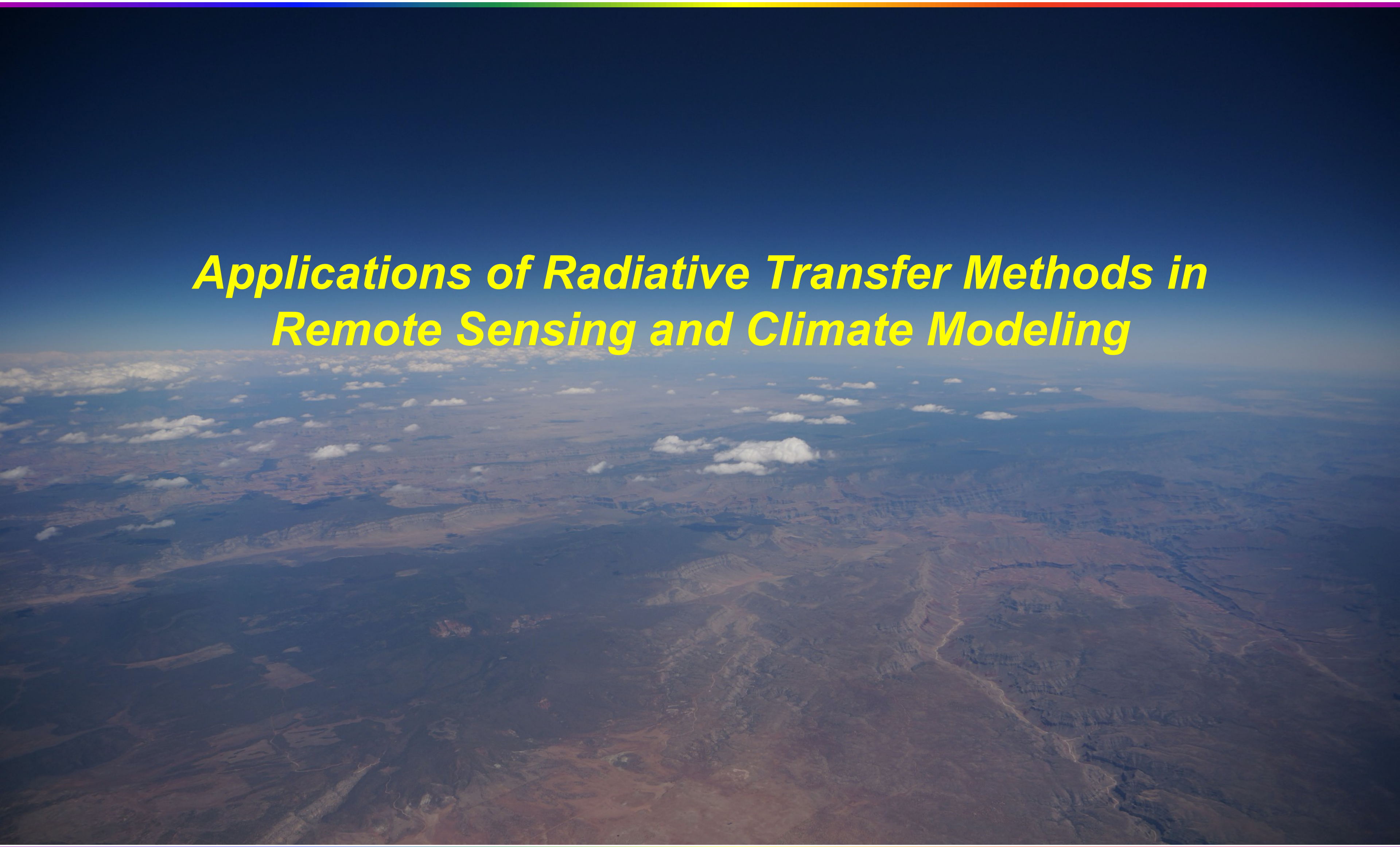




More Efficient Methods

- A variety of fast approximate methods have been developed to increase the efficiency of radiance and flux calculations for
  - Climate models, where level-dependent bolometric fluxes are needed at large numbers of spatial grid points, and fluxes must be recomputed often as the atmospheric and surface properties evolve
  - Remote sensing applications where high resolution radiances and radiance Jacobians ($\partial r_i / \partial x_j$, where r is the radiance at wavelength, i, and x is a an optical property at level, j) are needed for a large number of soundings
- These methods typically increase their efficiency by
  - Reducing the number spectral grid points (band models, etc.)
  - Reducing the angular resolution (2-stream methods)
  - Reducing the vertical resolution (single layer atmospheres)
  - Neglecting all but the dominant radiative process (neglecting multiple scatting within gas absorption bands, considering only the first or 2^{nd} orders of scattering, etc.
- All of these methods can reduce the accuracy of simulated radiances and fluxes

Applications of Radiative Transfer Methods in Remote Sensing and Climate Modeling



Retrieving Surface and Atmospheric Properties from Remote Sensing Retrieval Algorithms

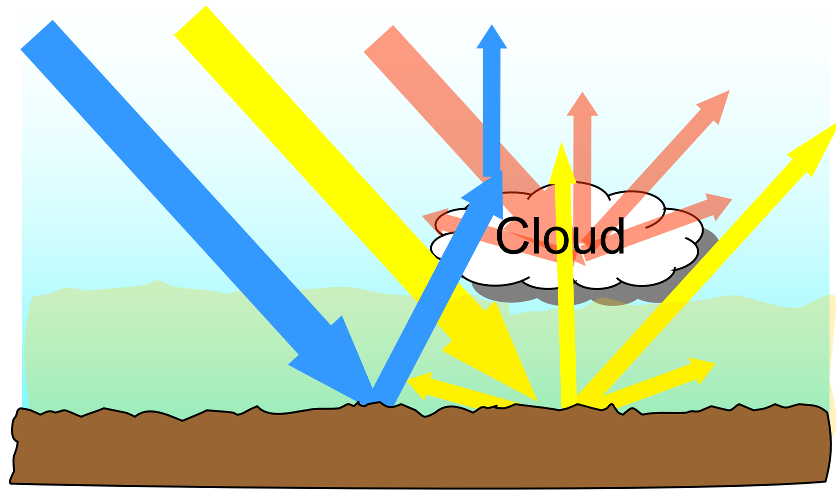
What is a Retrieval Algorithm?

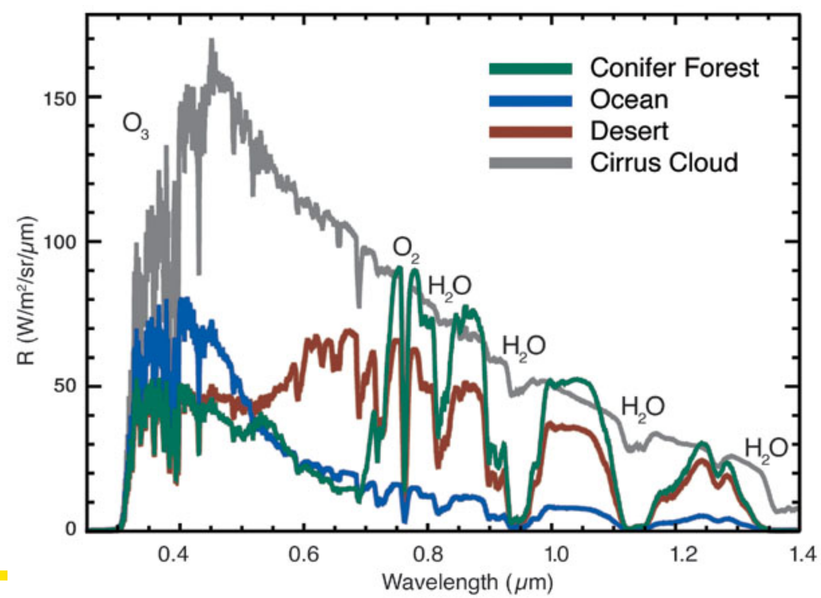
- In the context of remote sensing, a retrieval algorithm is a tool for inferring information about a planetary environment from the spectrum of the radiation that it reflects or emits
- Given a reflected solar or emitted thermal spectrum, the first task is to identify the principal features of the spectrum
  - Constraints on surface temperature or atmospheric temperature profile
  - Distinct spectral features that can be attributed to known gases
  - Evidence of clouds our hazes
  - Evidence of a liquid or solid surface? What is its reflectance/emittance?
- Given an initial guess of these environmental properties, we
  - create an environmental model and generate a synthetic spectrum
  - process that synthetic spectrum with an “instrument simulator” that simulates the observing system
  - compare the simulated spectrum to the observed spectrum.
  - optimize the environmental parameters to improve the fits.
- Continue this process until the fits is adequate.

Applications: Remote Sensing with Reflected Solar Radiation

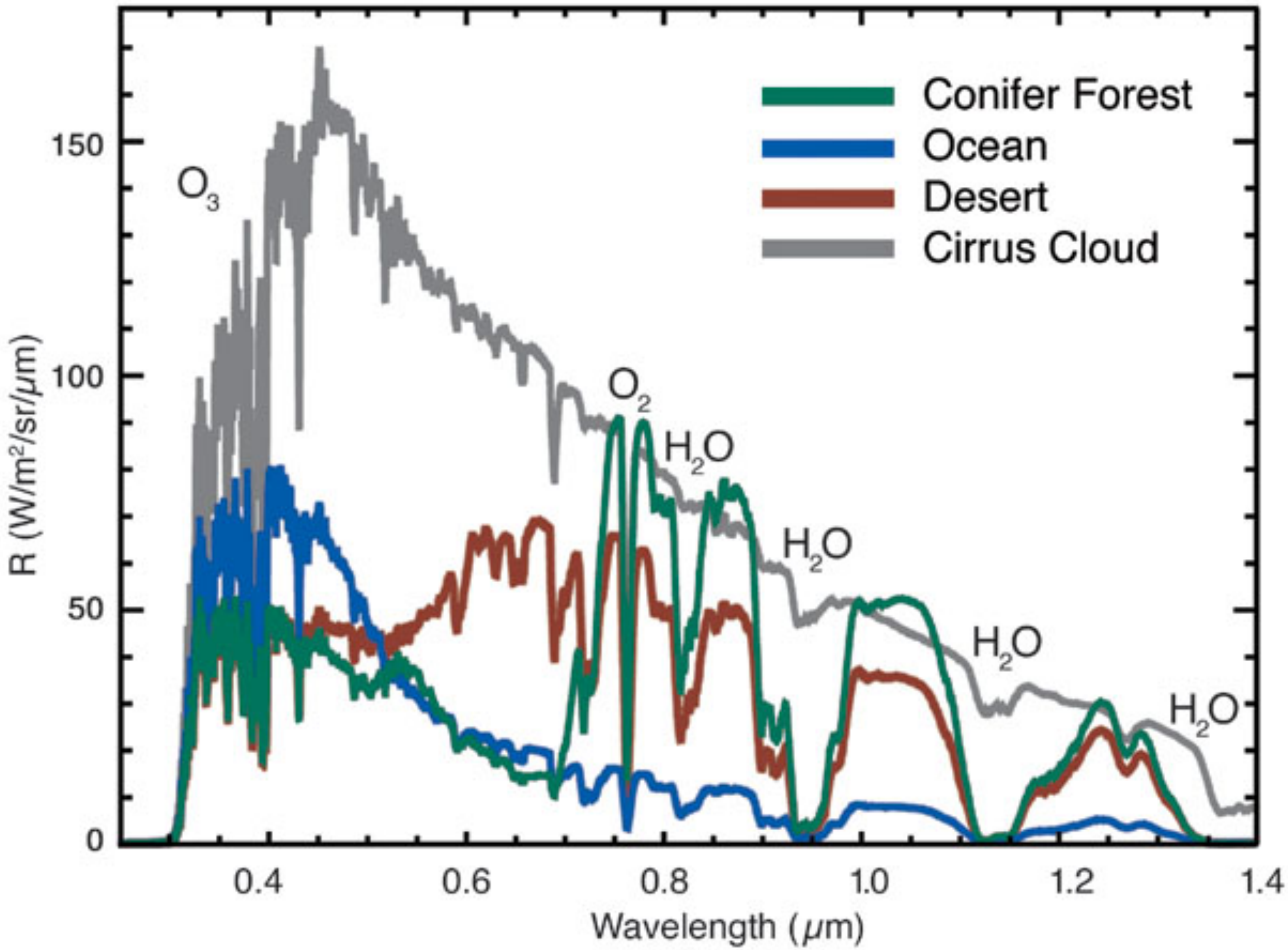
Solar spectra yield information about:

- Optical properties of the reflecting surface (cloud deck/ground)
  - Albedo, “surface” cover
- Atmospheric pressure of “surface”
  - Need a well-mixed gas with a known spectrum is needed (e.g. O_2 or CO_2)
- Detection and quantification of column abundance of key trace gases - UV/VIS/near-IR
  - H_2O, O_2, O_3, N_2O, CH_4, NH_3 …
- Limitations
  - Little information about temperatures of surface or atmosphere
  - Clouds preclude full-column or surface measurements





Effect of Surface Type on Reflected Solar Radiation



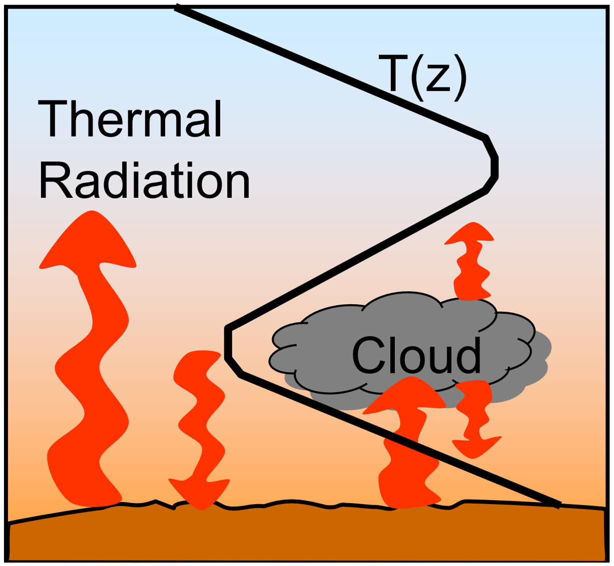
Applications: Remote Sensing Using Thermal IR Spectra

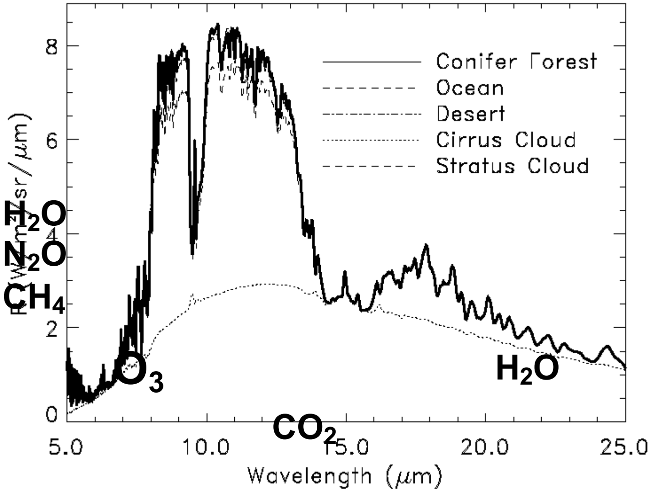
Thermal IR spectra can yield information about

- Temperature of emitting surface
  - Window regions
- Atmospheric thermal structure
  - **Well-mixed gas: CO_2 15 μm band**
- Vertical distribution of temperatures and trace gases above emitting surface
  - **H_2O, O_3, CH_4, N_2O**

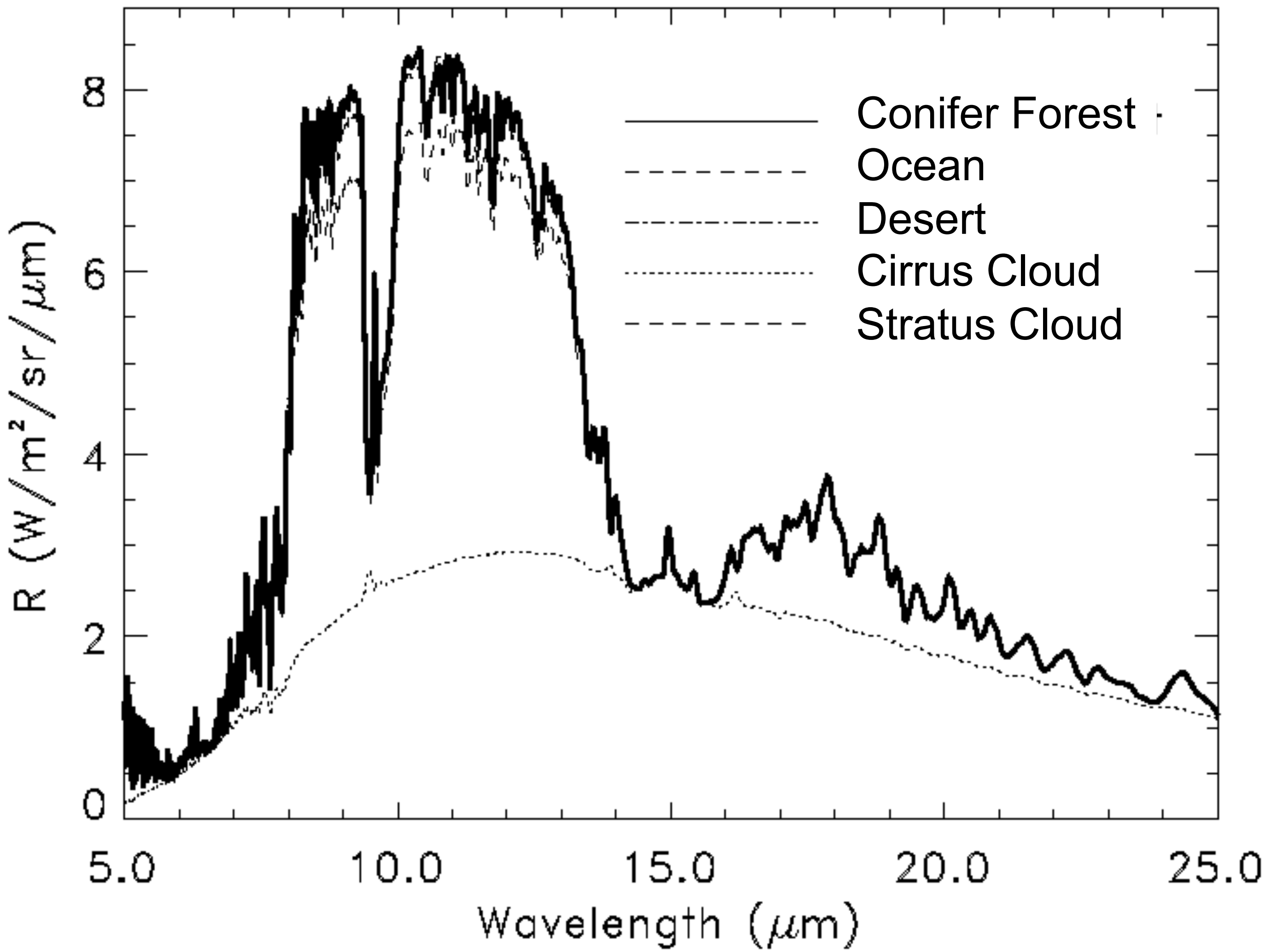
Limitations

- Atmospheric temperature information is essential for retrieving trace gas amounts
  - requires a well-mixed gas with a known spectrum
  - Limited information on constituents near the surface – surface/atmosphere temperature gradient needed
- Thermal IR provides limited constraints on planetary surface composition

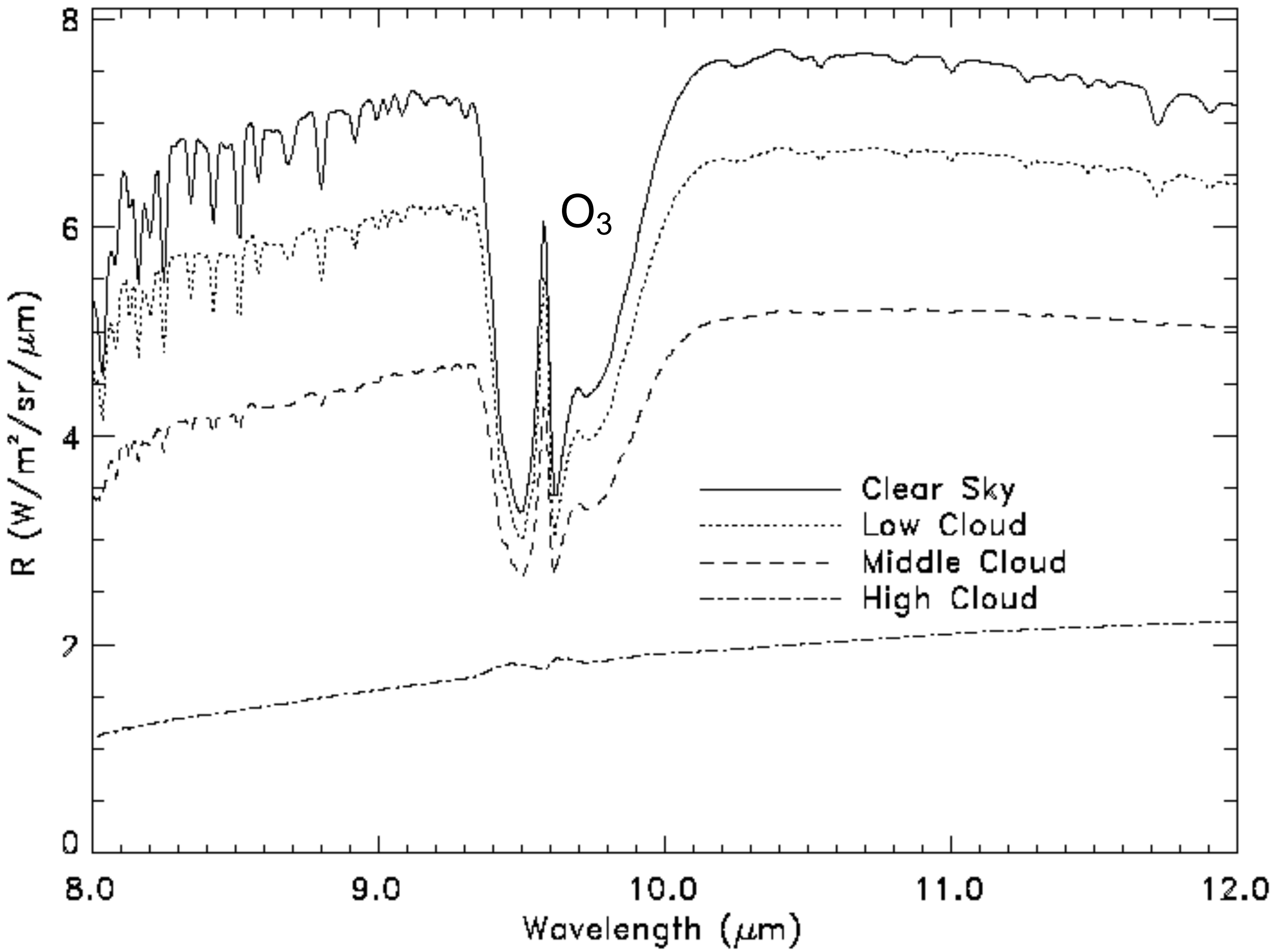


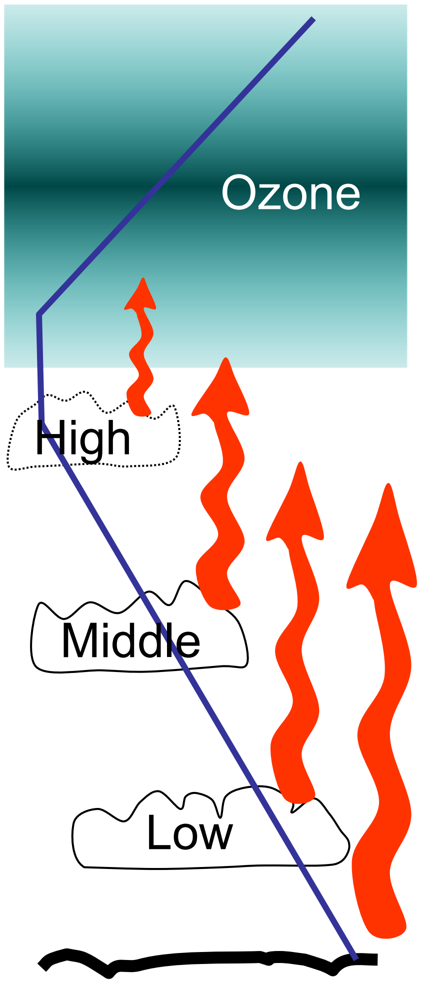


Effect of Surface Type on Thermal Emission



A Closer Look at the Effects of Clouds on Thermal Emission





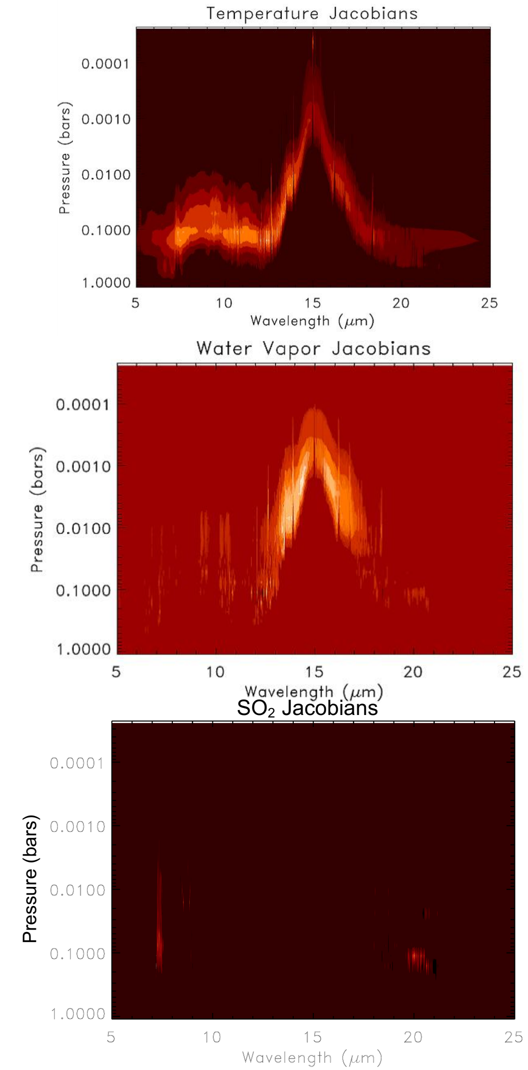
Cold, optically-thick high clouds block upward thermal radiation from the surface and lower atmosphere, reducing spectral contrast.

Automating the Process with Radiance Jacobians

- Radiance Jacobians specify the rate of change of the radiances, ***r***, at any wavelength, i, due to changes in optical property, $\boldsymbol{x} = \delta\tau(z), \omega(z), g(z), a$, at level, ***j***.

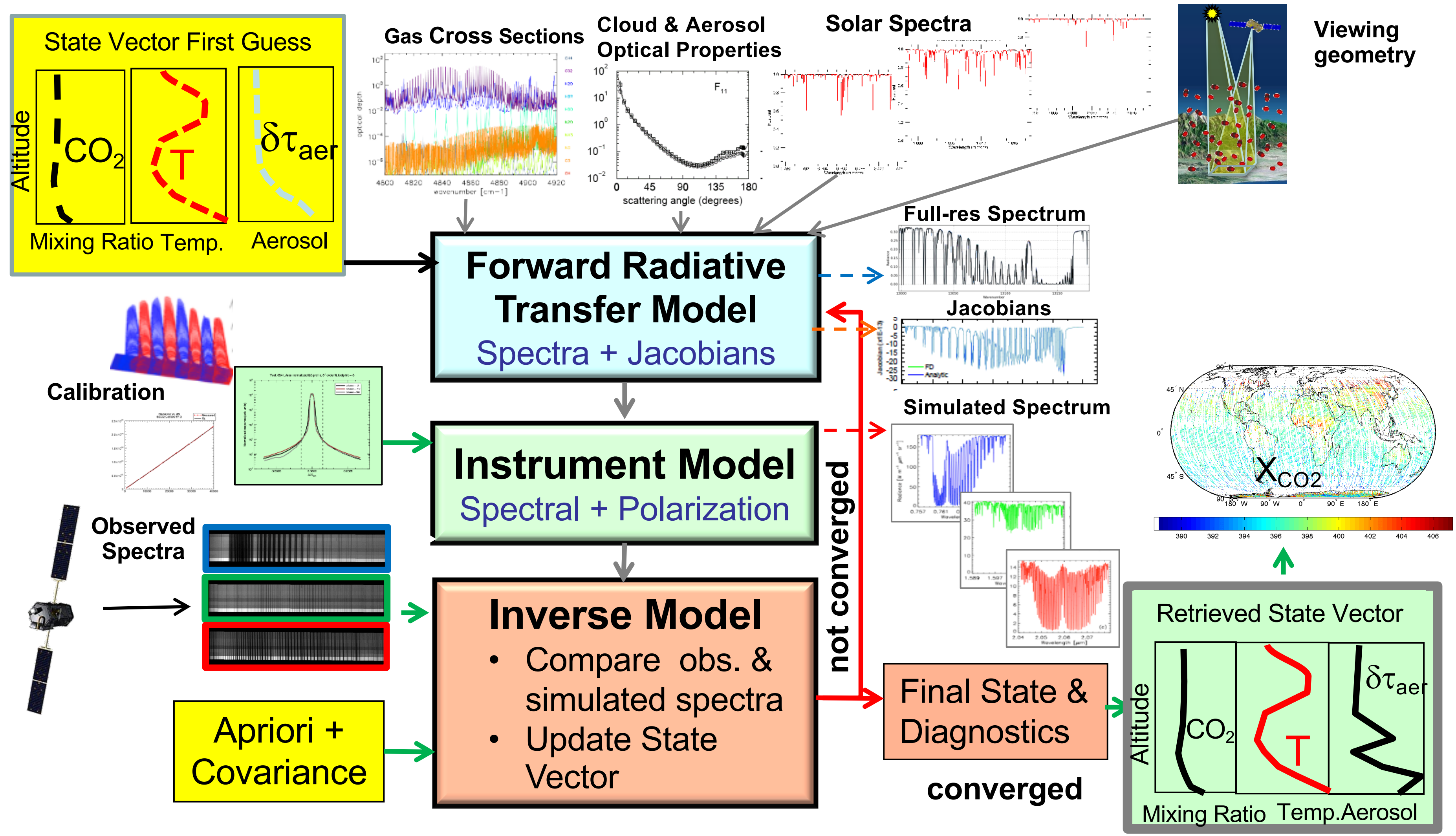
$$\boldsymbol{J} = \partial \boldsymbol{r}_i / \partial \boldsymbol{x}_j$$

- Many modern remote sensing retrieval algorithms are based on constrained, non-linear least-squares fitting algorithm that fit a non-linear function (a synthetic spectrum generated by a radiative transfer model) to an measured spectrum.
- In these fits, the atmospheric state variables (pressure, temperature, gas mixing ratios, aerosol distributions) are treated as coefficients of the function to be optimized.
- Jacobians (the first derivative of the function with respect to its fitting coefficients) are essential to optimize the fit.



Temperature, Water vapor and SO_2 Jacobians for Venus

The OCO-2 XCO2 Retrieval Algorithm

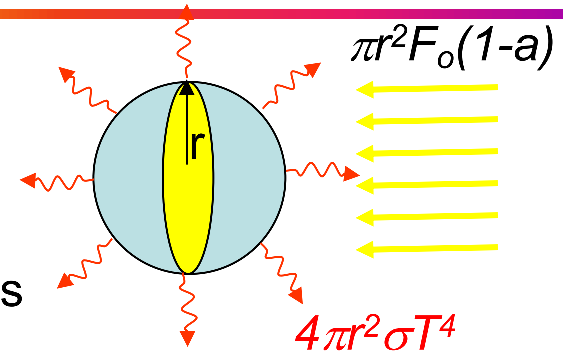


Radiative Forcing of Climate Models

The Simplest Climate Model: Energy Balance of a Planet

In equilibrium, the Planetary Energy balance is given by:

$$\sigma T_e^4 = F_o (1-a) / 4$$



where F_o is the incident solar flux, a is the albedo, and T_e is the effective, globally averaged radiating temperature.

- T_e, denotes the average temperature at the planet's effective emitting surface, which may be the surface or an atmospheric layer where $\tau_{IR} \sim 1$.

	$T_{surface}$	No Greenhouse	Greenhouse Warming
Venus	470 C	-43 C	513 C
Earth	15 C	-17 C	32 C
Mars	-50 C	-55 C	5 C

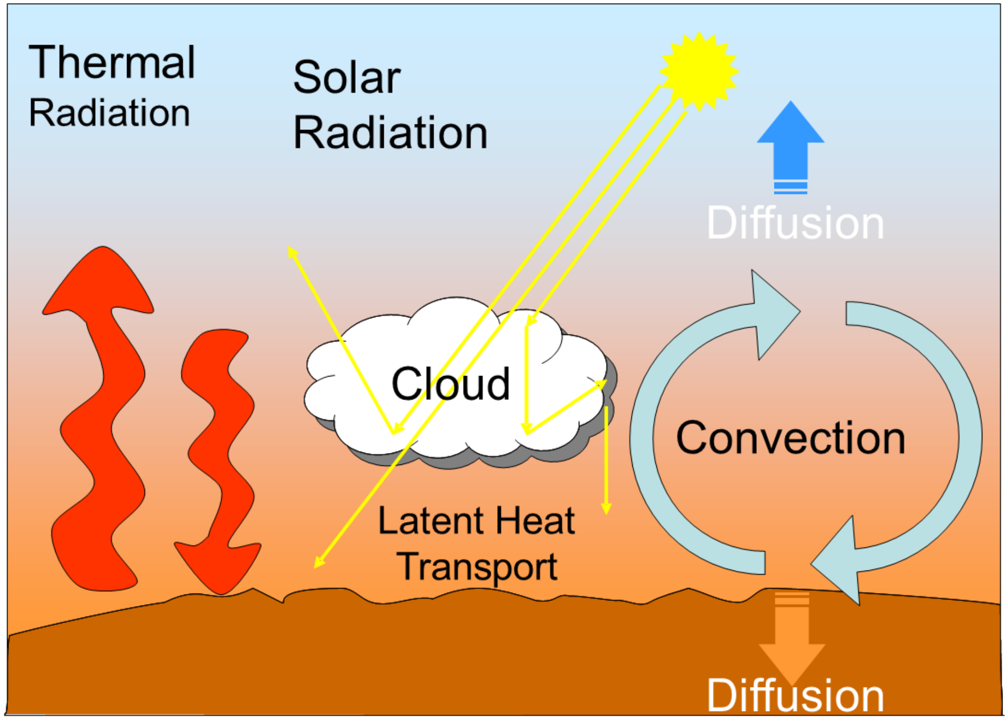
After Table 9.1, Bennet, Shostak, Jakosky, 2003

Radiative processes plays the dominant role in the global scale climate of a planet. Greenhouse effects can be as important as the incident solar flux and surface albedo in determining the surface temperature.

Climate Models

To illustrate the role of radiative transfer in climate models, we consider a very simple, globally-averaged 1-dimentional climate model

- Three heat transport Processes
  - Radiative Forcing
    - Solar heating
    - Thermal cooling
  - Vertical heat transport by convection and diffusion
  - Latent heat transport
    - Cloud condensation, evaporation, precipitation
- Start from an initial state and march in time to a final, equilibrium state

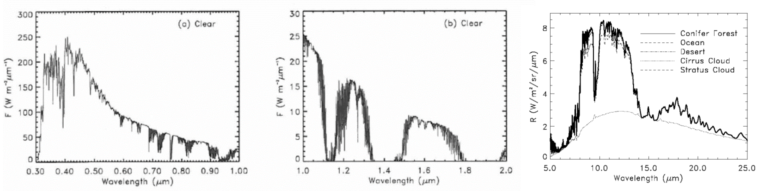


- The solar heating (thermal cooling) rate of any layer in a planetary atmosphere is proportional to the divergence frequency-integrated net solar (thermal) flux in that layer

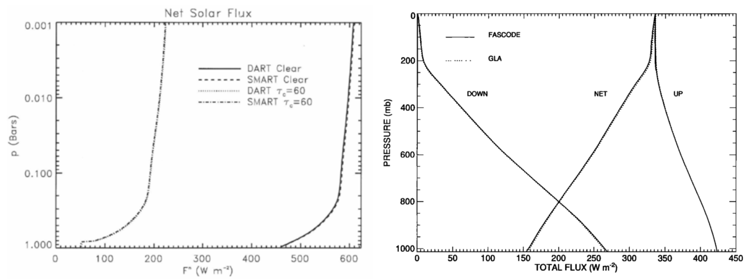
$$\frac{dT}{dt} = \frac{1}{\rho c_p}\frac{dF^{net}}{dz} = \frac{g}{c_p}\frac{dF^{net}}{dp}$$

- The net flux, $F^{net} = F\downarrow - F\uparrow$ is the difference between the total downward and upward flux
- ρ is the atmospheric density, c_p is the specific heat at constant pressure, z is altitude, g is gravitational acceleration, and p is the atmospheric pressure

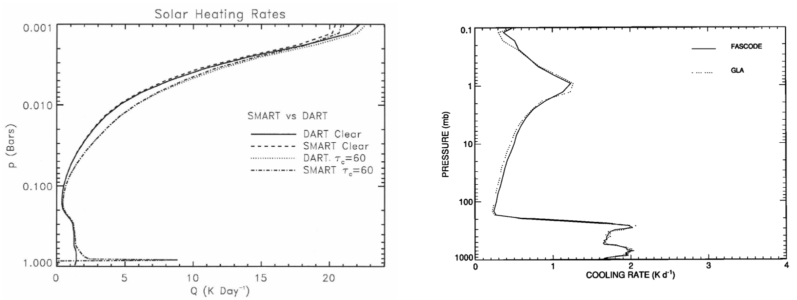
Generate Fluxes at all Levels & λs



Integrate over solar and thermal λ

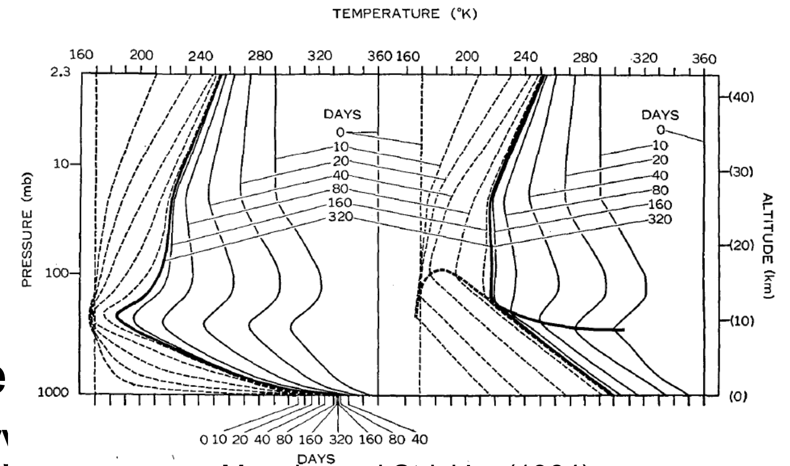


Compute Flux Divergence

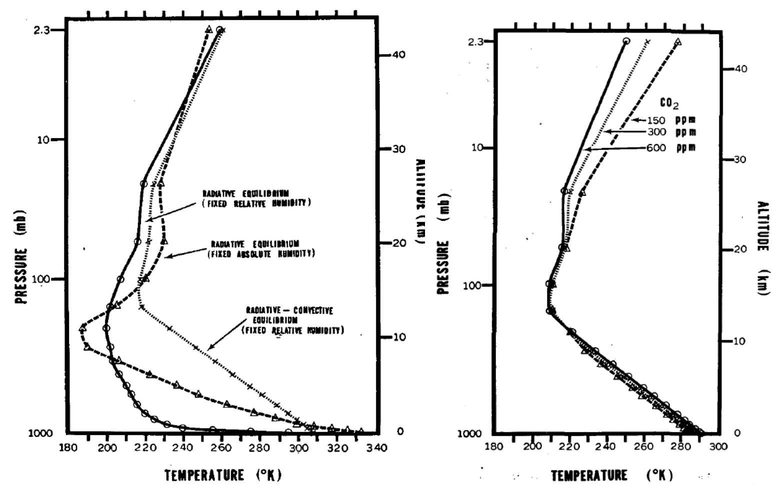


Early Work: Manabe and Strickler (1964); Manabe and Wetherald (1966)

- These early works used simple empirical band models for CO_2, H_2O, and O_3, fit to available, low-resolution laboratory data
- These radiative transfer models were coupled to an innovative "convective adjustment" scheme, which simulated the vertical heat transport by convection in dry and moist atmospheres
  - The globally-averaged radiative-convective equilibrium temperature profile was derived from an initial state, using time marching
  - Interestingly, the computational methods (convective adjustment, time marching) are in use today
    - Predicted doubling CO_2 would raise surface temperature by 2.3 °C.
    - Current estimates are 1.5-4.5 °C

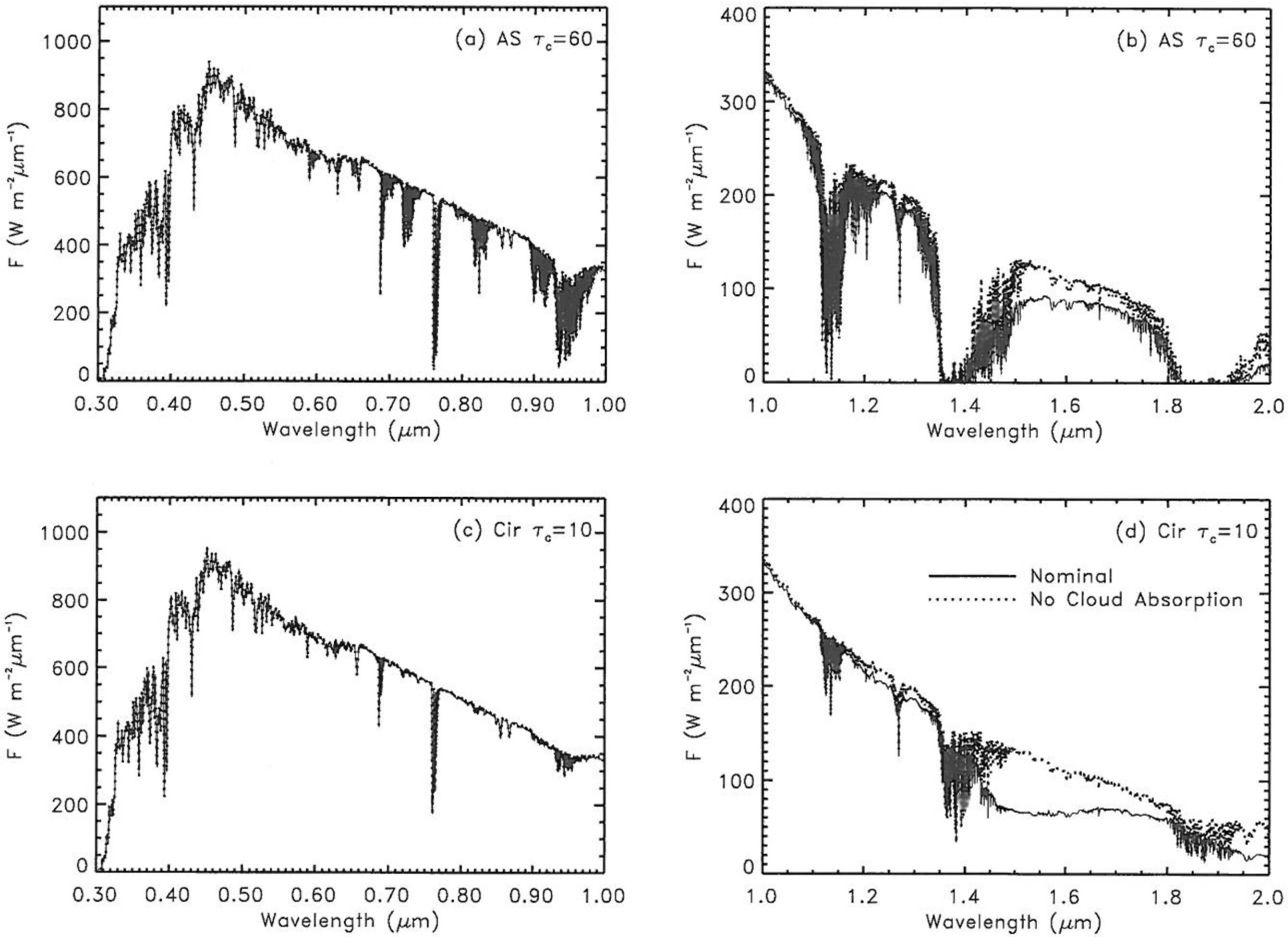


Manabe and Strickler (1964)



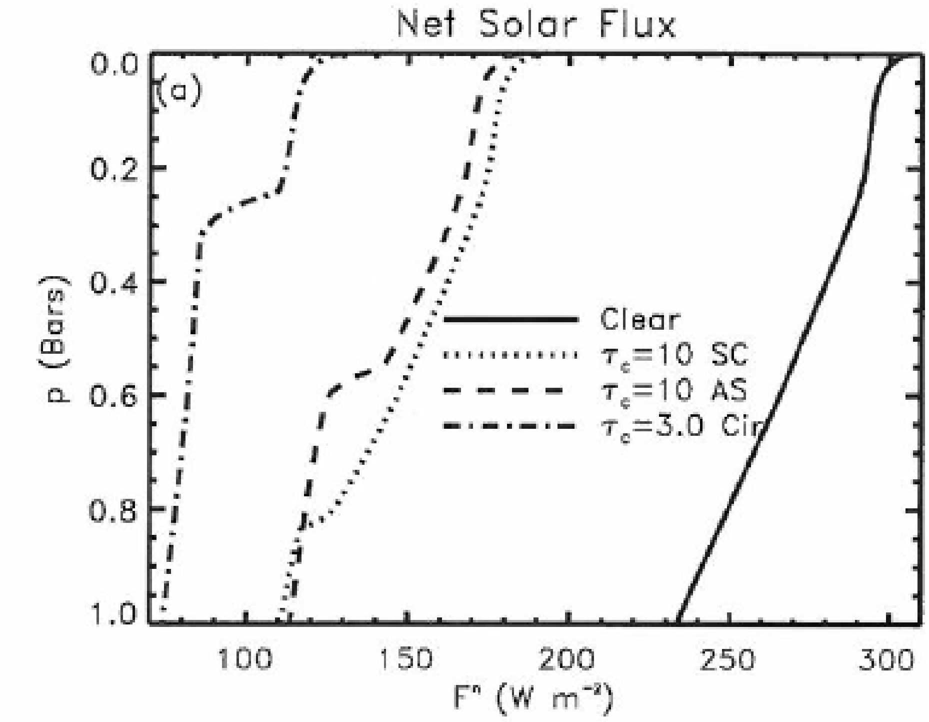
Manabe and Wetherald (1966)

Impact of Clouds on Solar Heating Rates

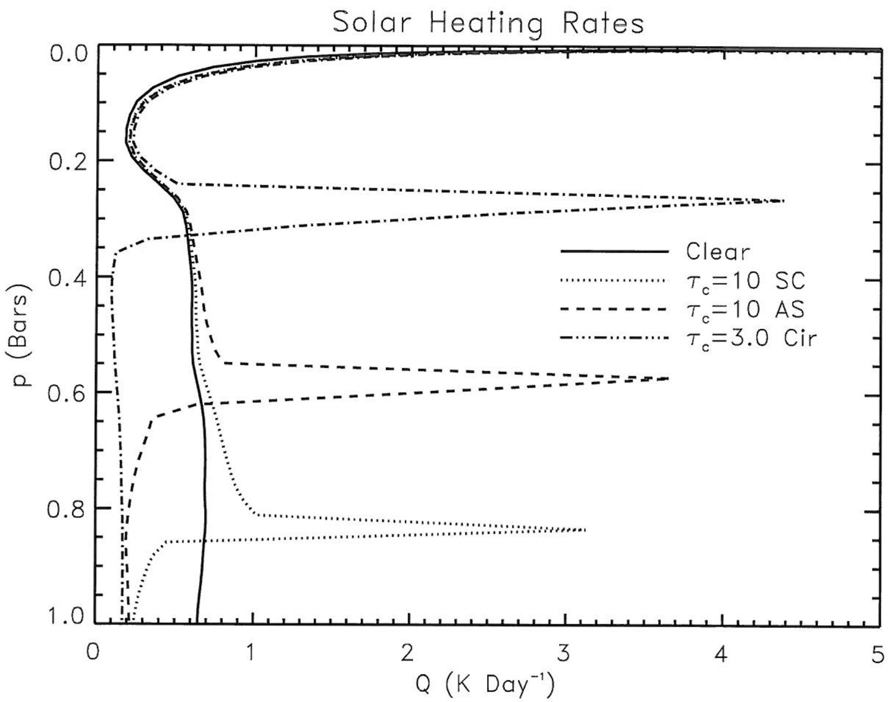


The impact of absorption by cloud particles. Clouds absorb little solar radiation at visible wavelengths, but absorb weakly at near infrared wavelengths.

Solar Fluxes and Heating Rates in Clear and Cloudy Conditions

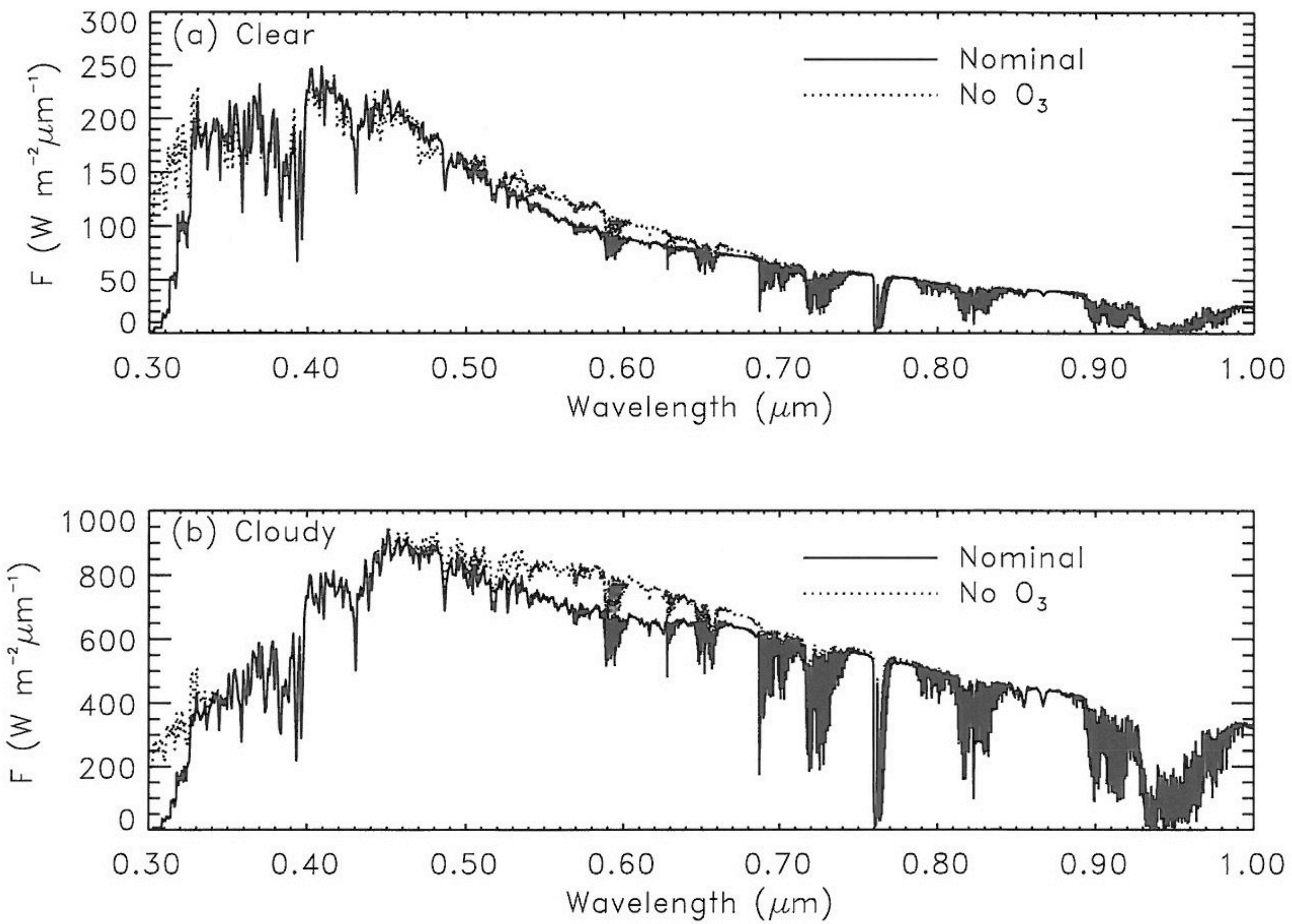


Net solar fluxes in clear and cloudy atmospheres with nominal mid-latitude summer (MLS) water vapor mixing ratios, ocean surface albedos (~5%) and global-annual-average illumination conditions.



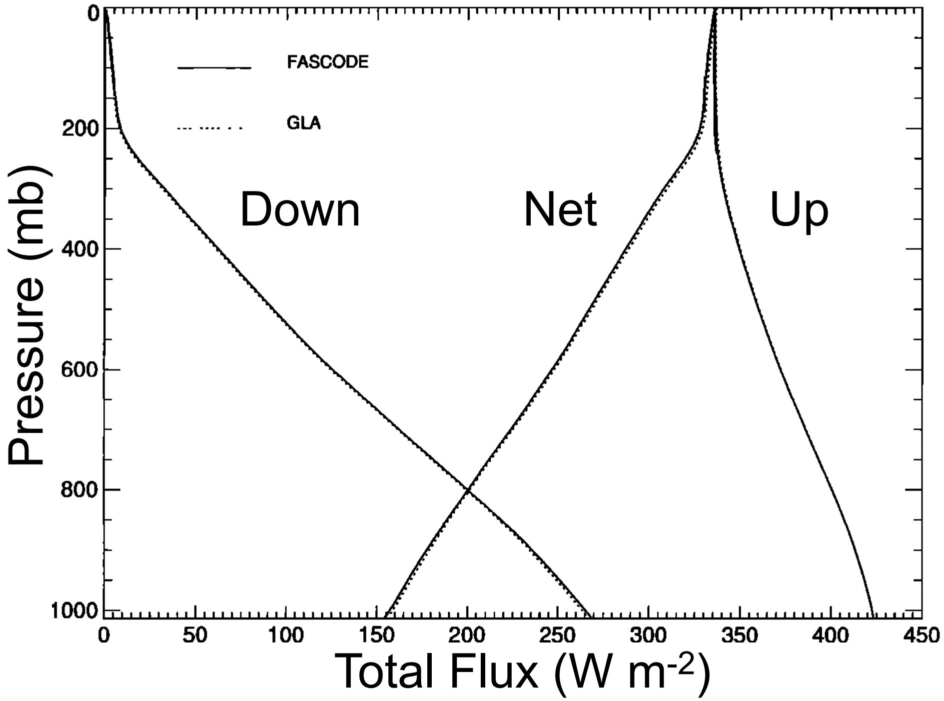
Tropospheric solar heating rates for clear atmospheres and atmospheres with moderately-thick stratocumulus (SC, τ_c=10), altostratus (AS, τ_c=10), and cirrus (Cir, τ_c=3) clouds and global-annual-average illumination conditions.

Impact of Clouds on Ozone Absorption

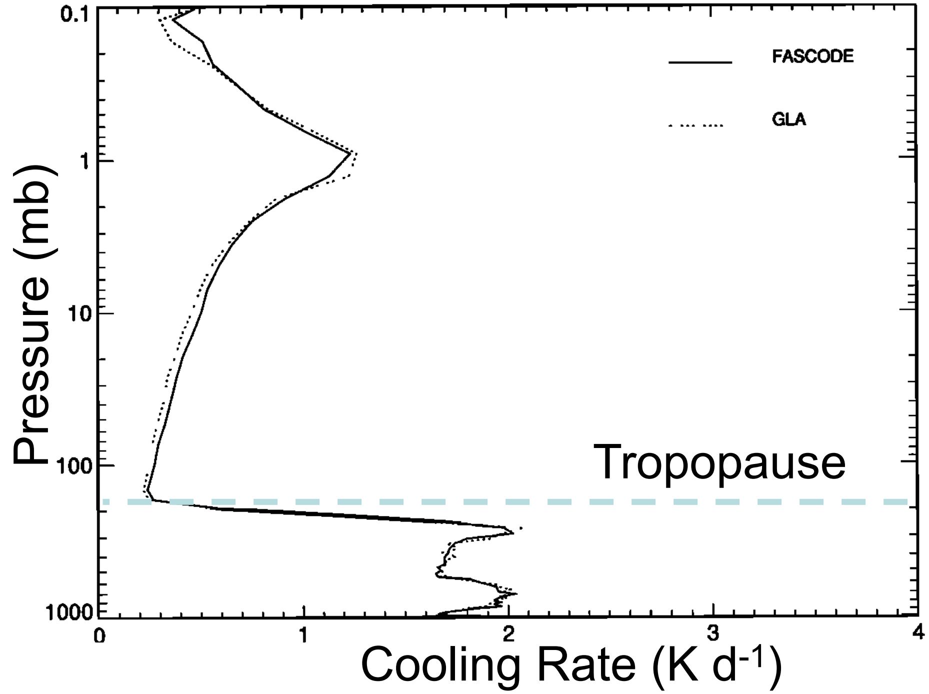


Clouds and high surface albedos can enhance ozone absorption at wavelengths where ozone cross sections are small by increasing the fraction of the flux that traverses the ozone layer twice

Thermal Fluxes and Cooling Rates

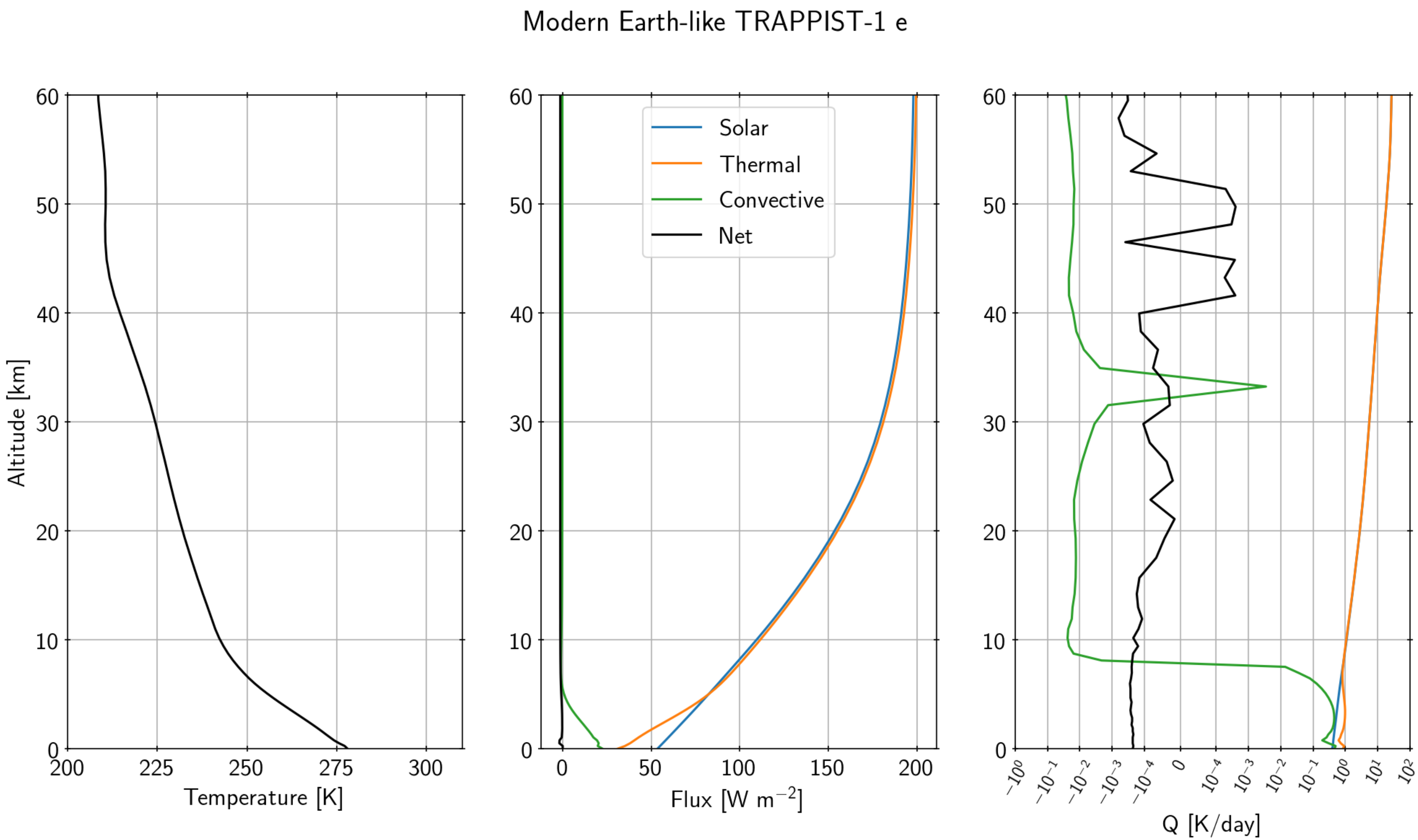


Clear sky upward, downward, and net thermal fluxes for a Mid-Latitude Summer atmosphere. Thermal fluxes are very sensitive to the thermal structure as well as the atmospheric optical properties.



Thermal cooling rates for a Mid-Latitude Summer atmosphere.

Global Radiative – Convective Equilibrium in Exoplanet Atmospheres



Global average thermal structure of an exoplanet (Trappist-1e) if it has an Earth-like atmosphere.

Brief Summary of the Territory Covered

We took a quick tour through:

- The solar and thermal components of the electromagnetic spectrum

- Interactions of solar and thermal radiation with the surface and atmosphere
  - Surface reflectance and bi-directional reflection distribution function
  - Scattering by airborne particles
  - Absorption and scattering by atmospheric gases

- Briefly introduced the equation of transfer and methods for calculating the solar and thermal radiative transfer in scattering, absorbing, emitting planetary atmospheres

- Touched on few applications including remote sensing and climate modeling