

ASTR 620: Planetary Processes
Professor Eric Nielsen

Lecture 12: Atmospheres



Logistics

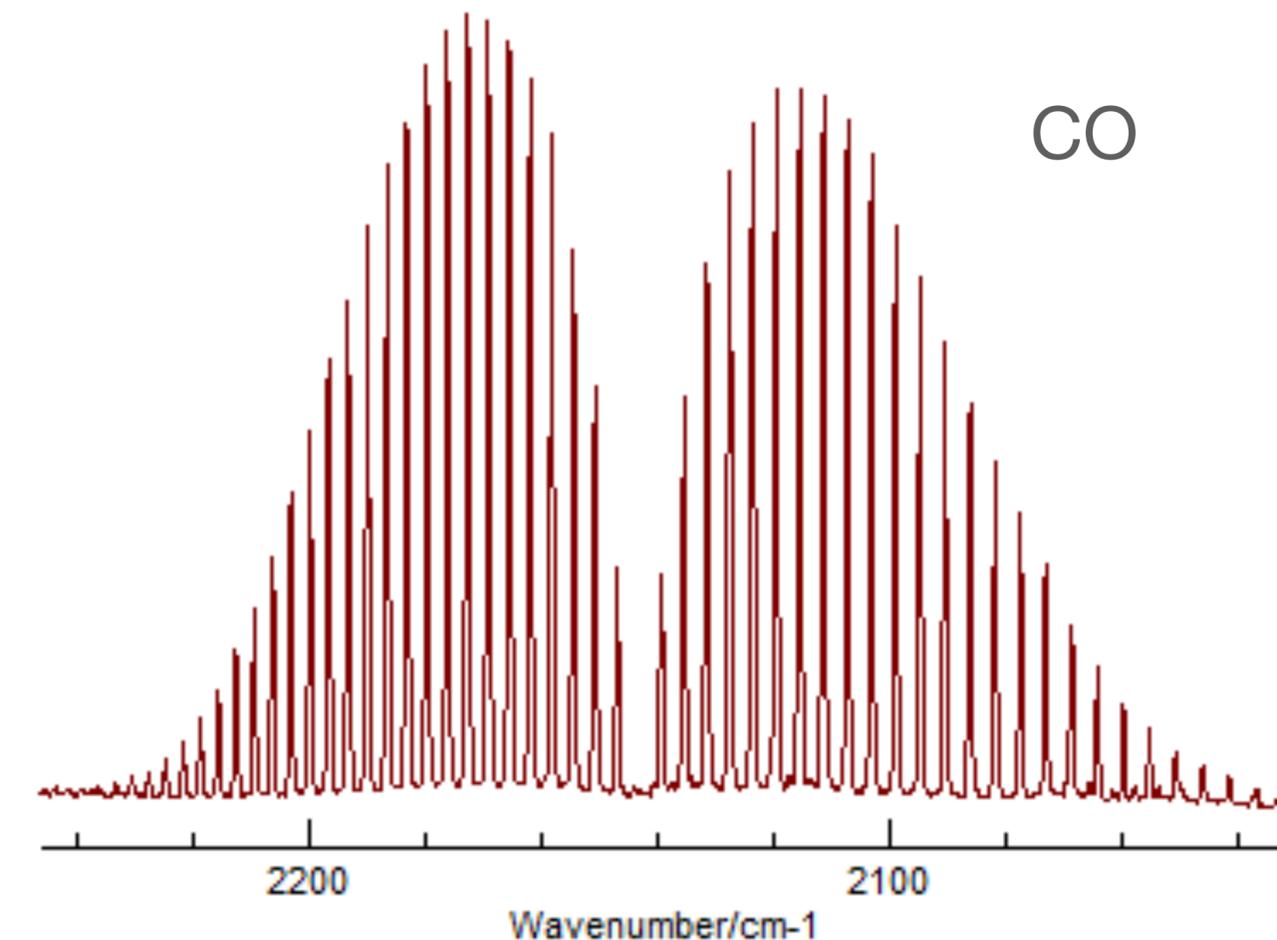
- Masks are encouraged
- No laptops, phones, or other electronic devices during class (I'll let you know in advance if we'll need laptops for an activity) **You may use a tablet to take notes if prefer, but please only use it for note-taking.**
- Remember to bring you response card to class
- Midterm in 7 days: Wednesday, October 5th (here in class)
- Homework 3 due tonight at 11:59pm

Review of the last class

- Which correctly ranks transitions in molecules, from the highest energy transitions to the lowest energy transitions?
 - (A) — (highest) rotational, electron, vibrational (lowest)
 - (B) — (highest) vibrational, rotational, electron (lowest)
 - (C) — (highest) rotational, vibrational, electron (lowest)
 - (D) — (highest) electron, rotational, vibrational (lowest)
 - (E) — (highest) electron, vibrational, rotational (lowest)

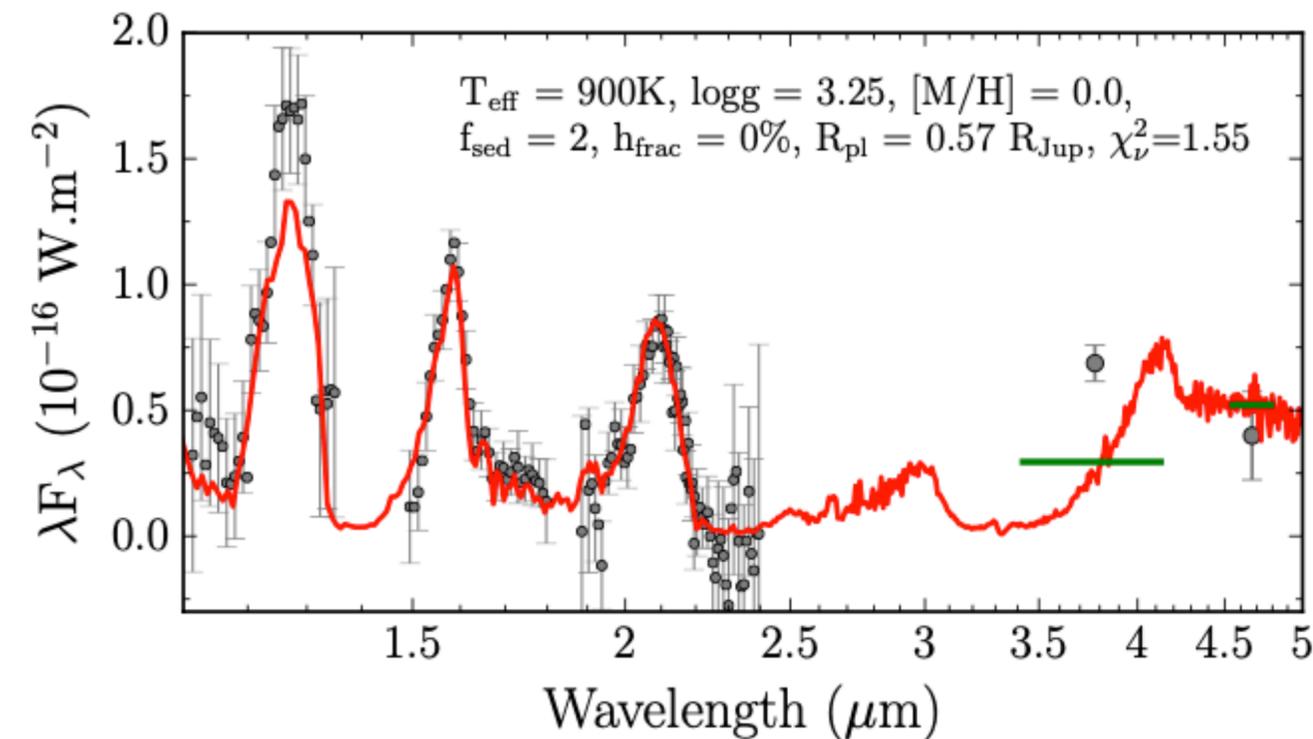
Review of the last class

- What sort of molecular transition does this diagram show?
 - (A) — One vibrational transition and dozens of rotational transitions
 - (B) — One rotational transition and dozens of vibrational transitions
 - (C) — Two vibrational transitions and dozens of rotational transitions
 - (D) — Two rotational transitions and dozens of vibrational transitions
 - (E) — Only rotational transitions



Review of the last class

- What does this spectrum of an exoplanet show, especially blueward of 2.5 microns?
- (A) — Many tightly-spaced emission lines that blend together into a few broad emission bands
- (B) — 3 very broad emission lines
- (C) — Many tightly-spaced absorption lines that blend together into a few broad absorption bands
- (D) — 4 very broad absorption lines



Review of the last class

- What is the wavelength of a transition with an energy (given in wavenumber) of 10cm^{-1} ?
 - (A) — 100 cm
 - (B) — 10 cm
 - (C) — 1 cm
 - (D) — 0.1 cm
 - (E) — 0.01 cm

Review of the last class

- A vibrational line (with no associated rotational transition) has a wavelength of 10^{-4} cm . A rotational line (with no associated vibrational transition) has a wavelength of 1 cm. If both transitions happen simultaneously and a photon is emitted, what is the wavelength of that photon?

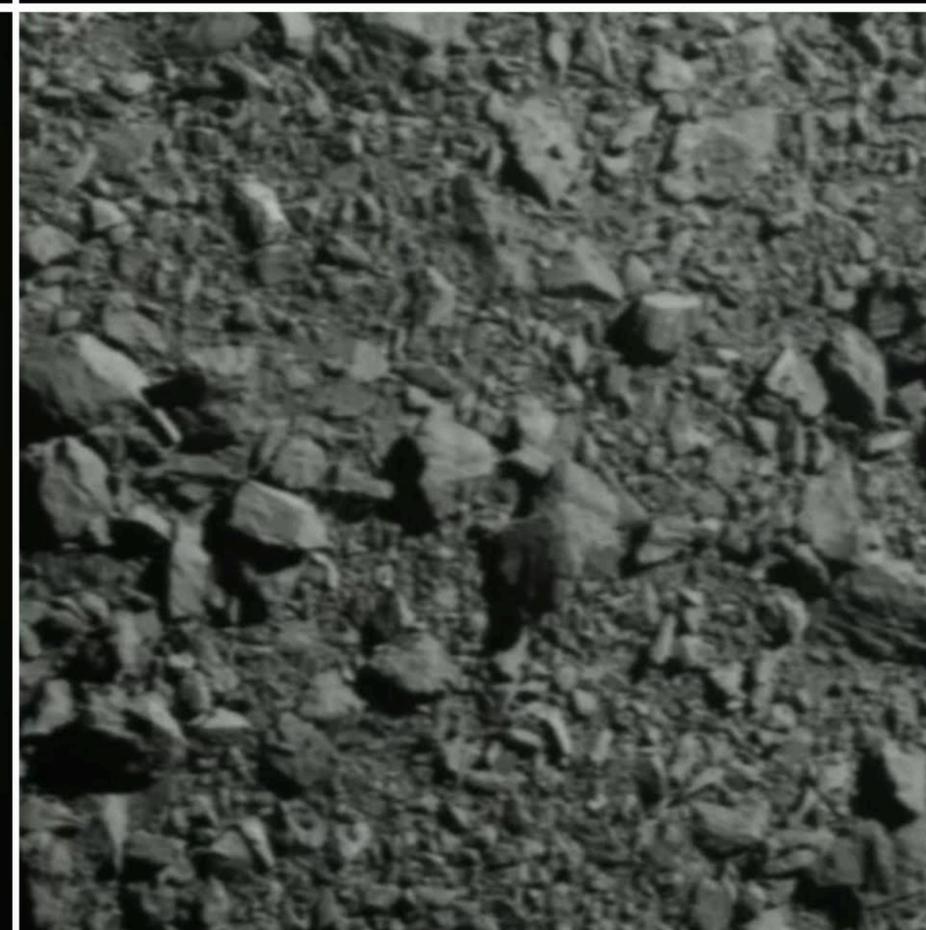
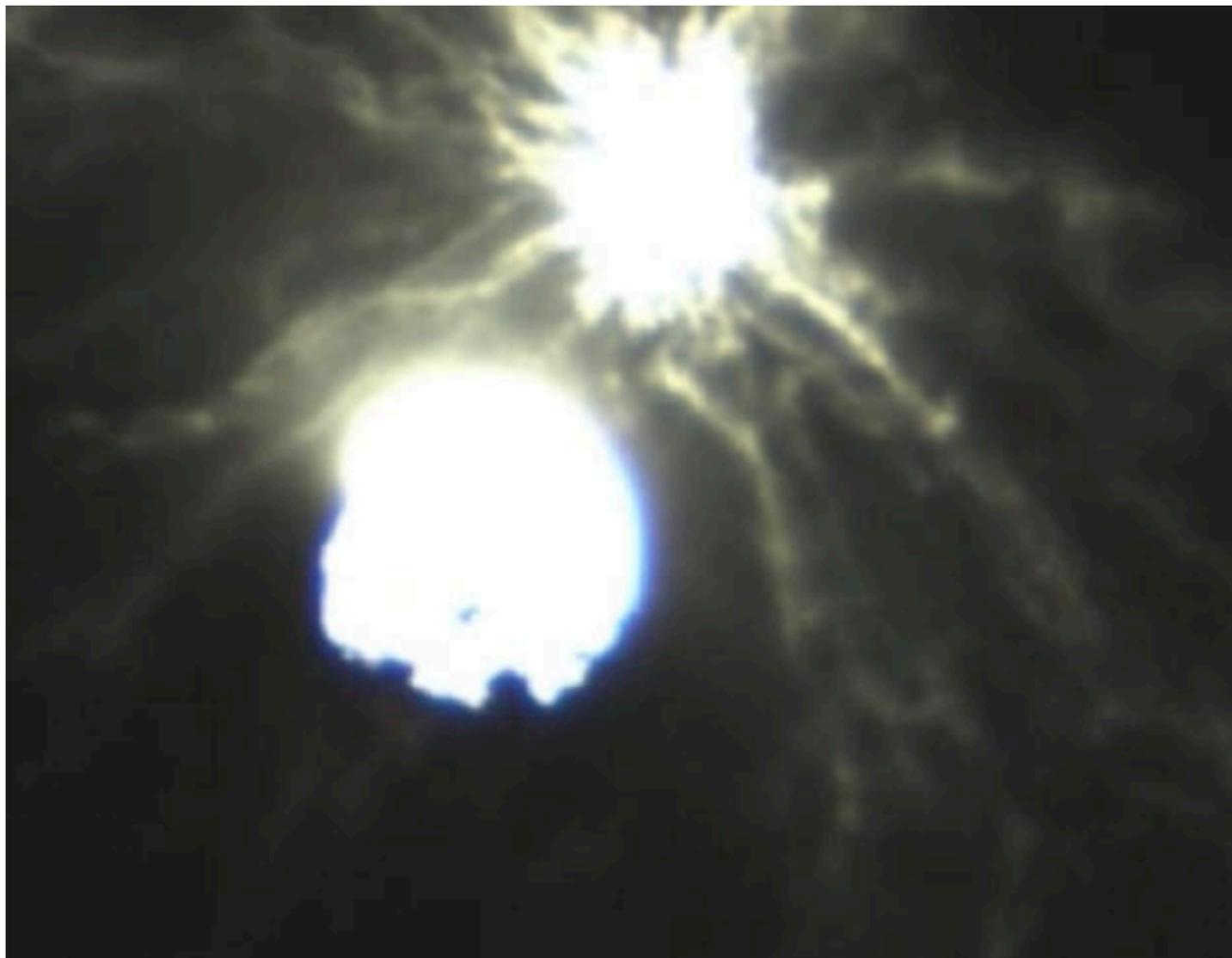
- (A) $1 \text{ cm} + 10^{-4} \text{ cm}$

- (B) $\frac{1}{1 \text{ cm} + 10^{-4} \text{ cm}}$

- (C) $\frac{1}{\frac{1}{1 \text{ cm}} + \frac{1}{10^{-4} \text{ cm}}}$

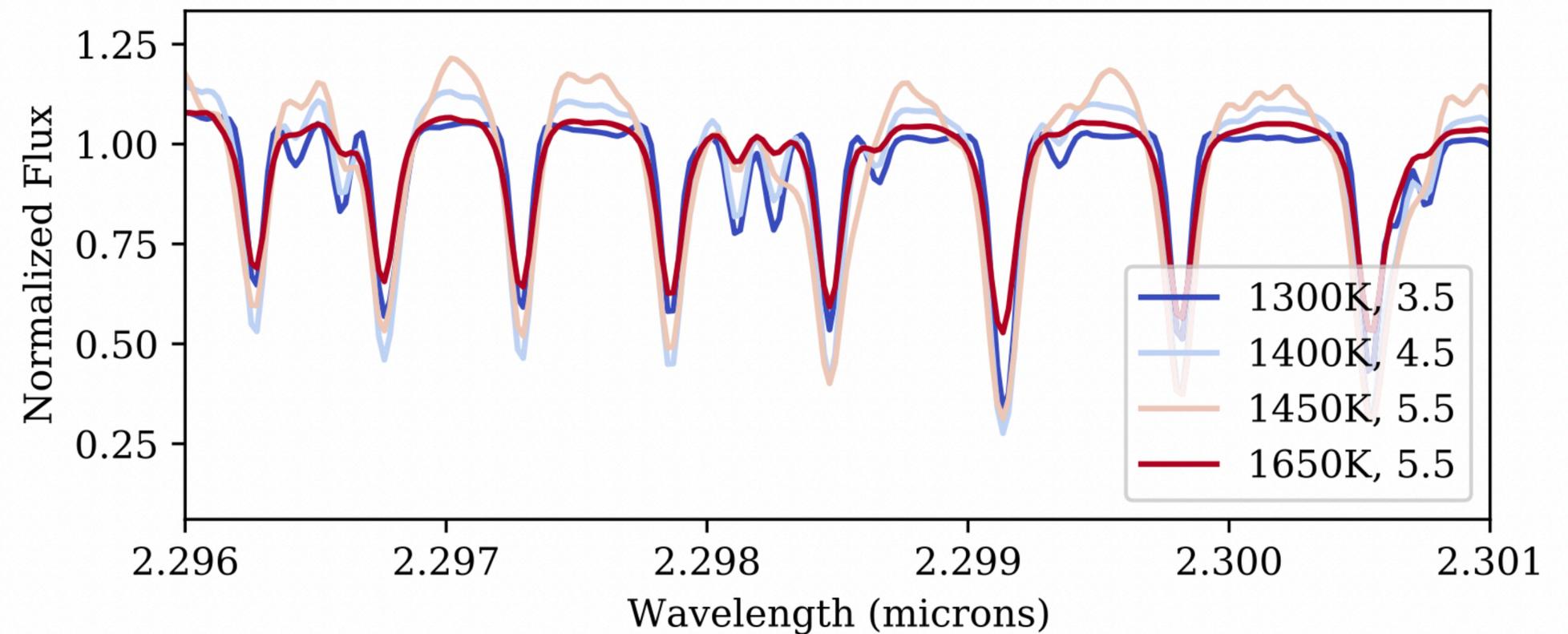
- (D) $\frac{1}{1 \text{ cm}} + \frac{1}{10^{-4} \text{ cm}}$

DART



Molecular spectra: high resolution

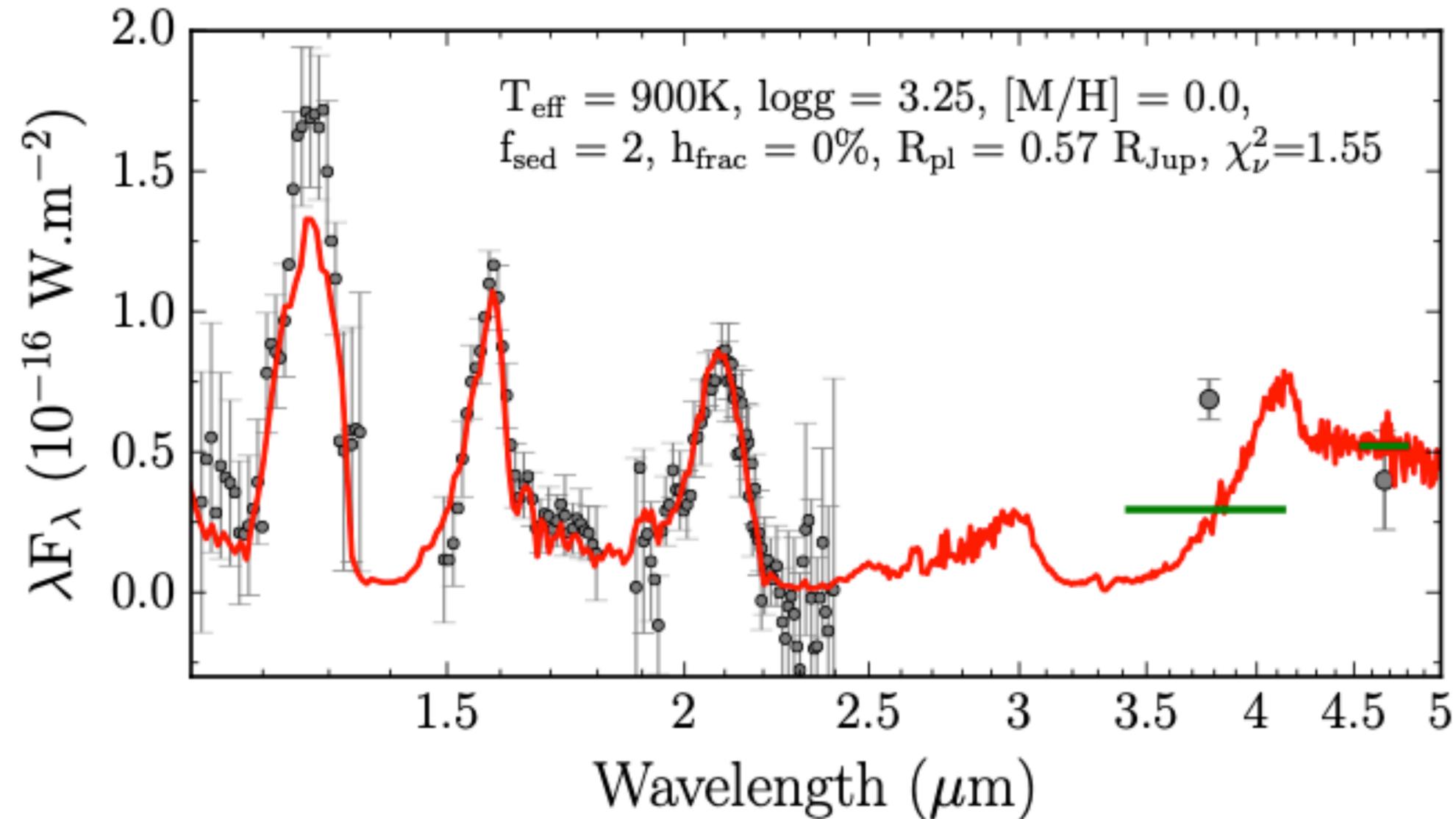
- Each molecule contributes hundreds of closely-spaced lines
- At high resolution, these individual lines can be resolved



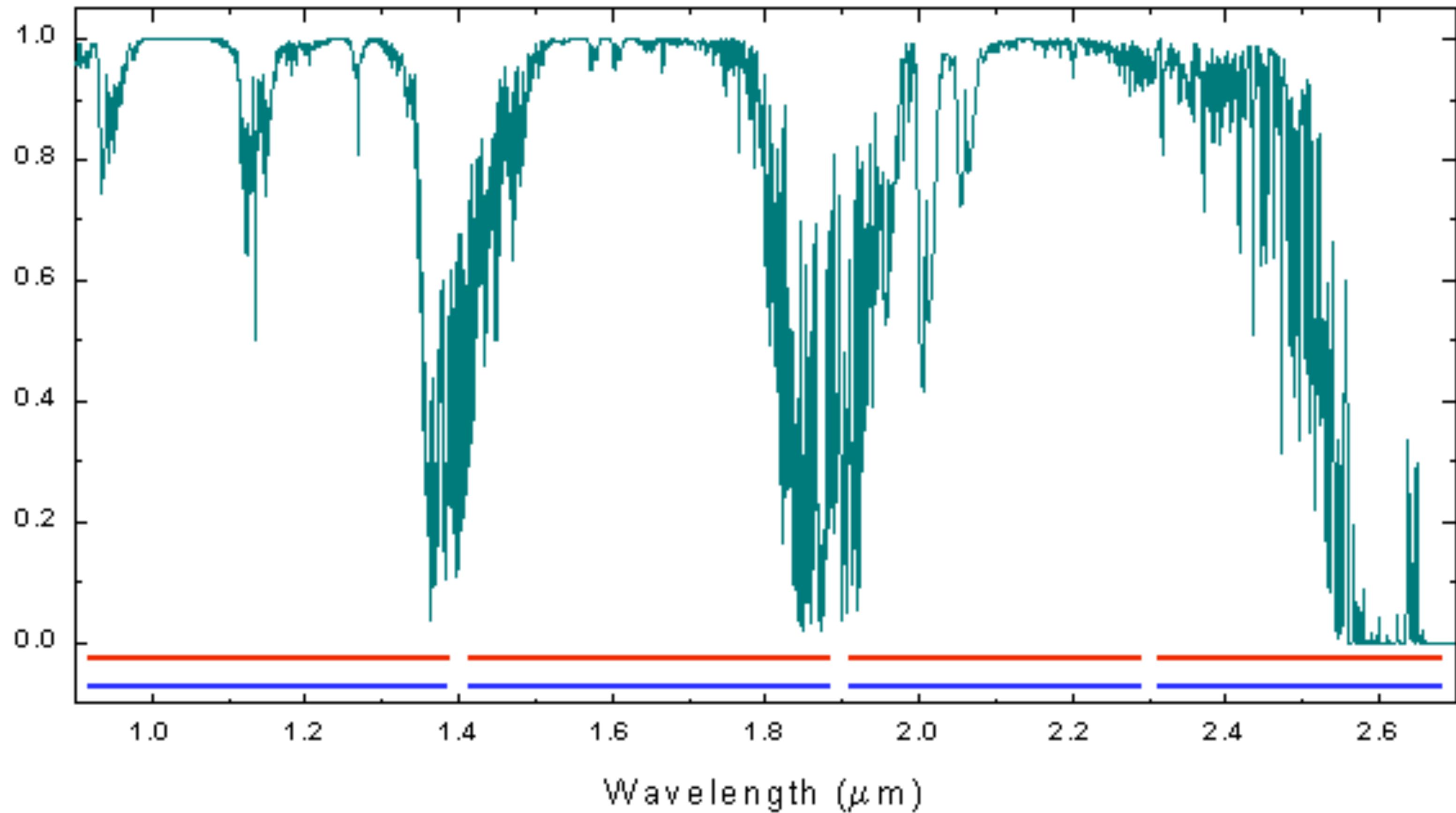
Wang et al. 2021

Molecular spectra: low resolution

- At low resolution, multiple lines blend together to form wide, deep “molecular absorption bands”
- 51 Eri: water, methane are dominant absorbers

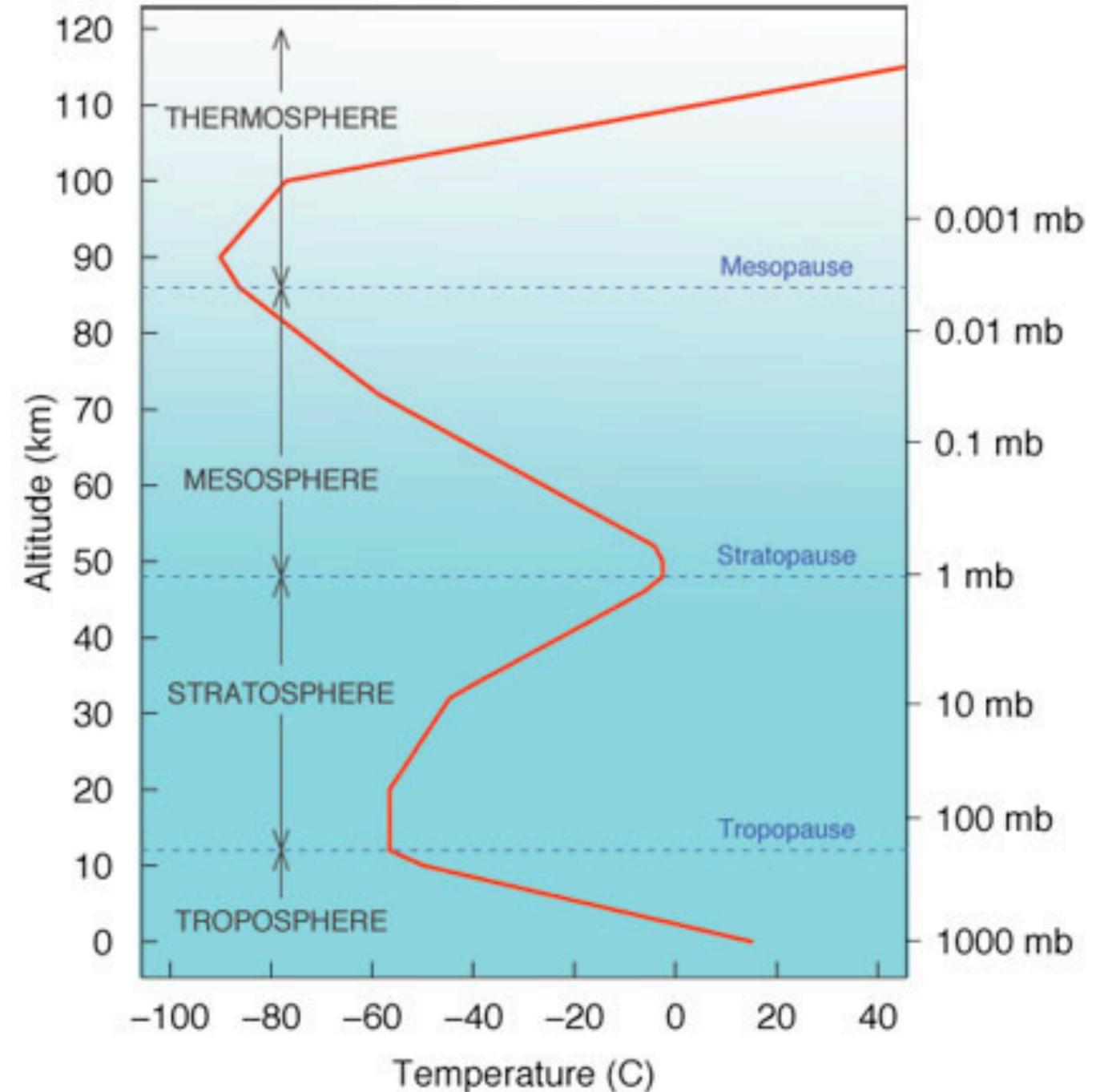


Transmission



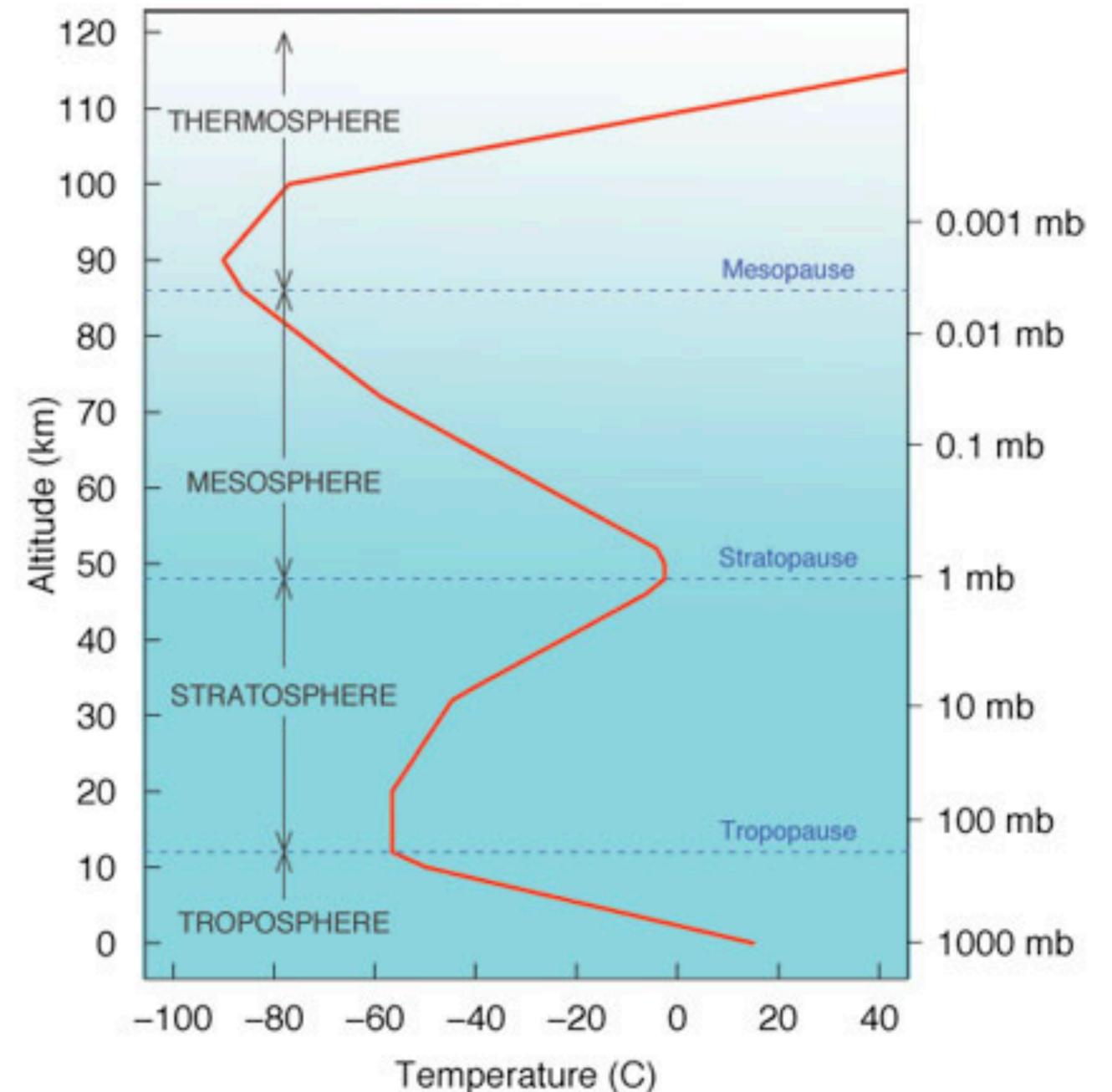
Atmospheric Structure

- Lowest level troposphere, then stratosphere, mesosphere, and thermosphere (with exosphere above thermosphere)
- Boundaries between layers are tropopause, stratopause, and mesopause
- On Earth, boundaries are locations of “temperature inversions”: temperature goes from decreasing with height to increasing with height (or the reverse)



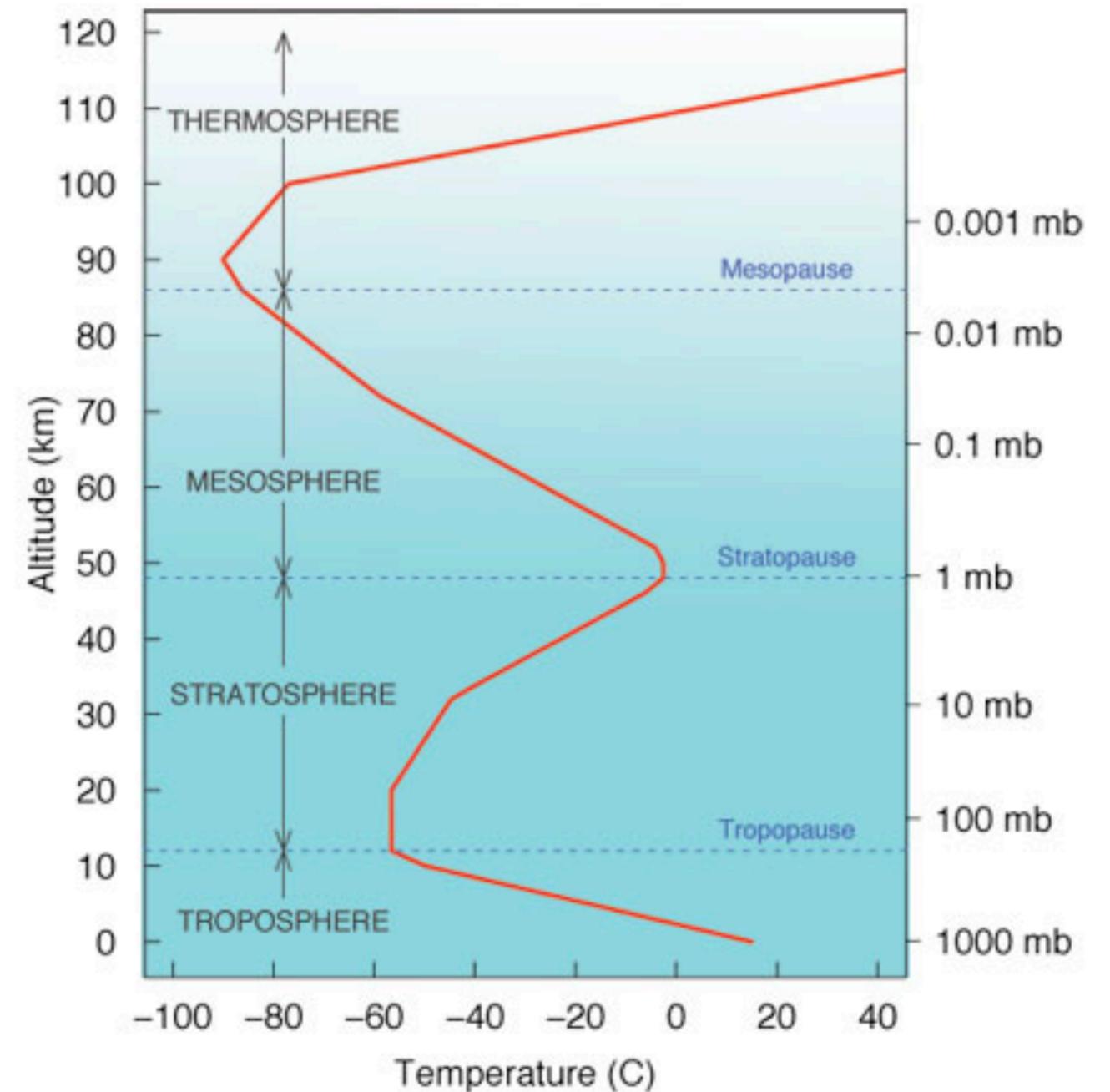
Atmospheric Structure

- What physical processes govern the pressure/temperature profiles?
 - Are they the same for all planetary atmospheres?
 - How do they compare to a stellar atmosphere?
- Understanding TP profiles of solar system planets (and exoplanets) gives us insight into formation/evolution of planetary atmospheres



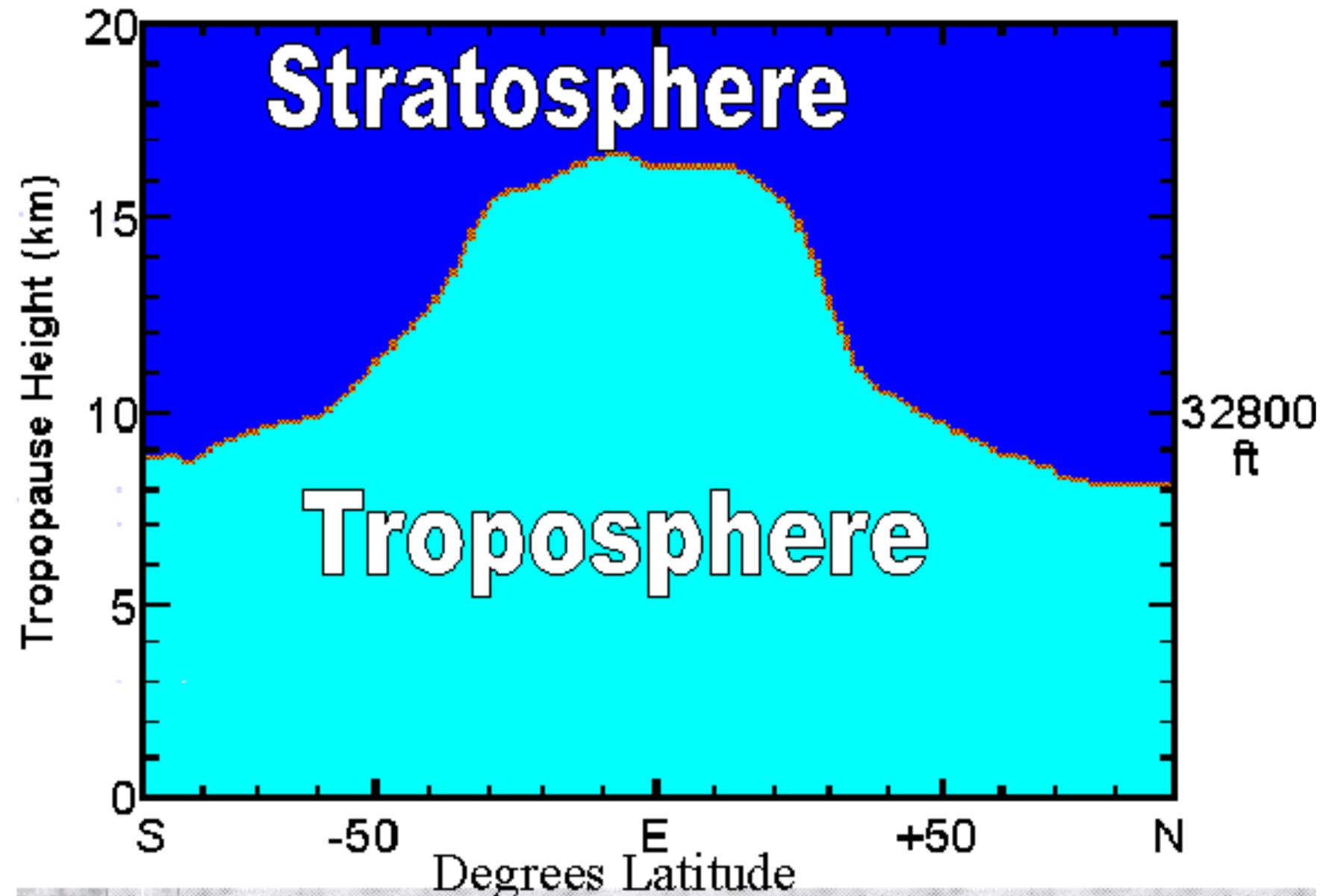
Atmospheric Structure

- Three methods for energy transport, most efficient given local conditions will dominate:
 - Conduction — dominates in compressed regions
 - Radiation — dominates in less dense regions
 - Convection — dominates when temperature gradient allows



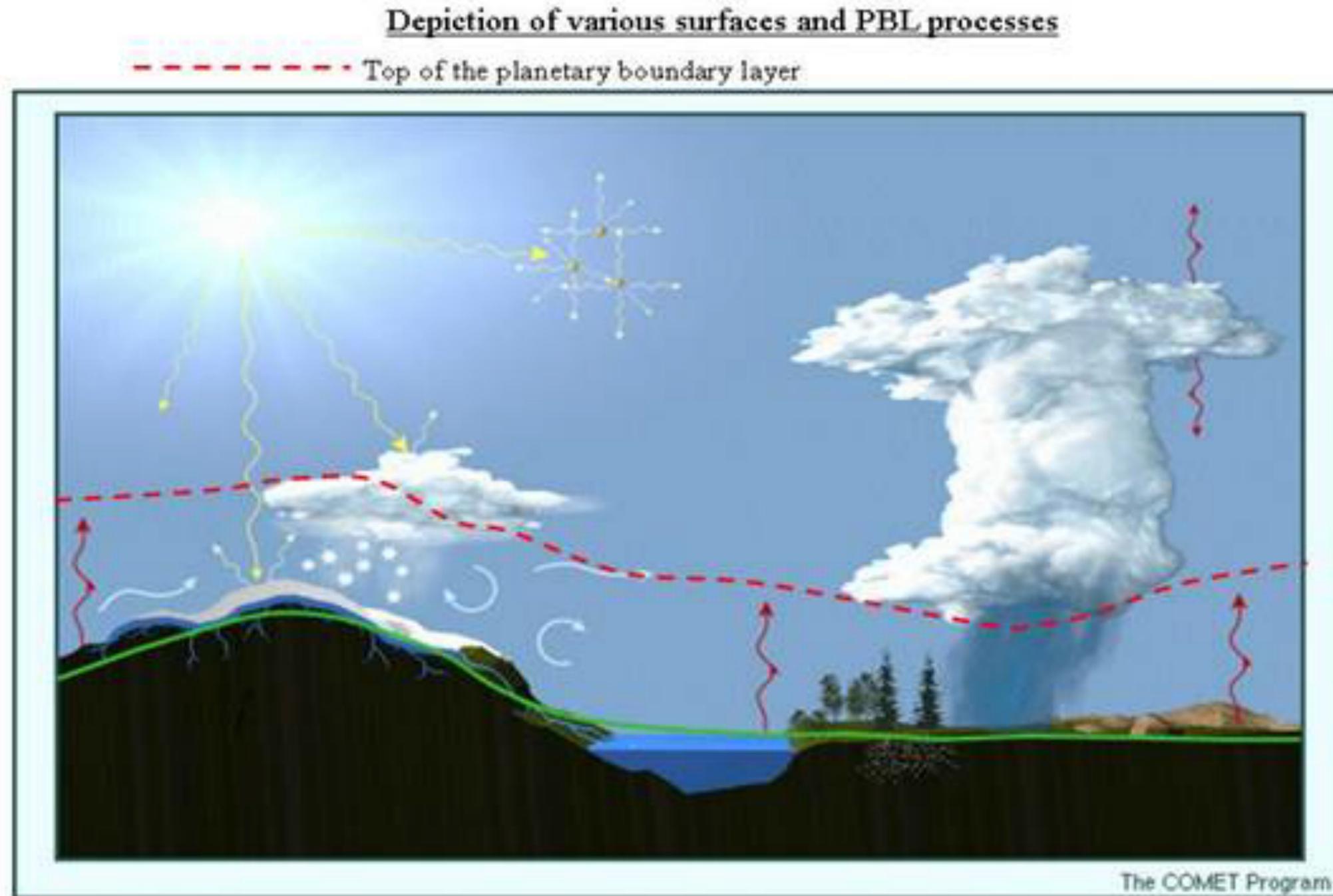
Troposphere (0-10 km)

- Contains ~75% of atmospheric gas
- Maximum altitude varies with latitude
 - highest maximum altitude at the tropics, where convection is strong
- Fuzzy boundary: it can be defined thermally, dynamically, or chemically



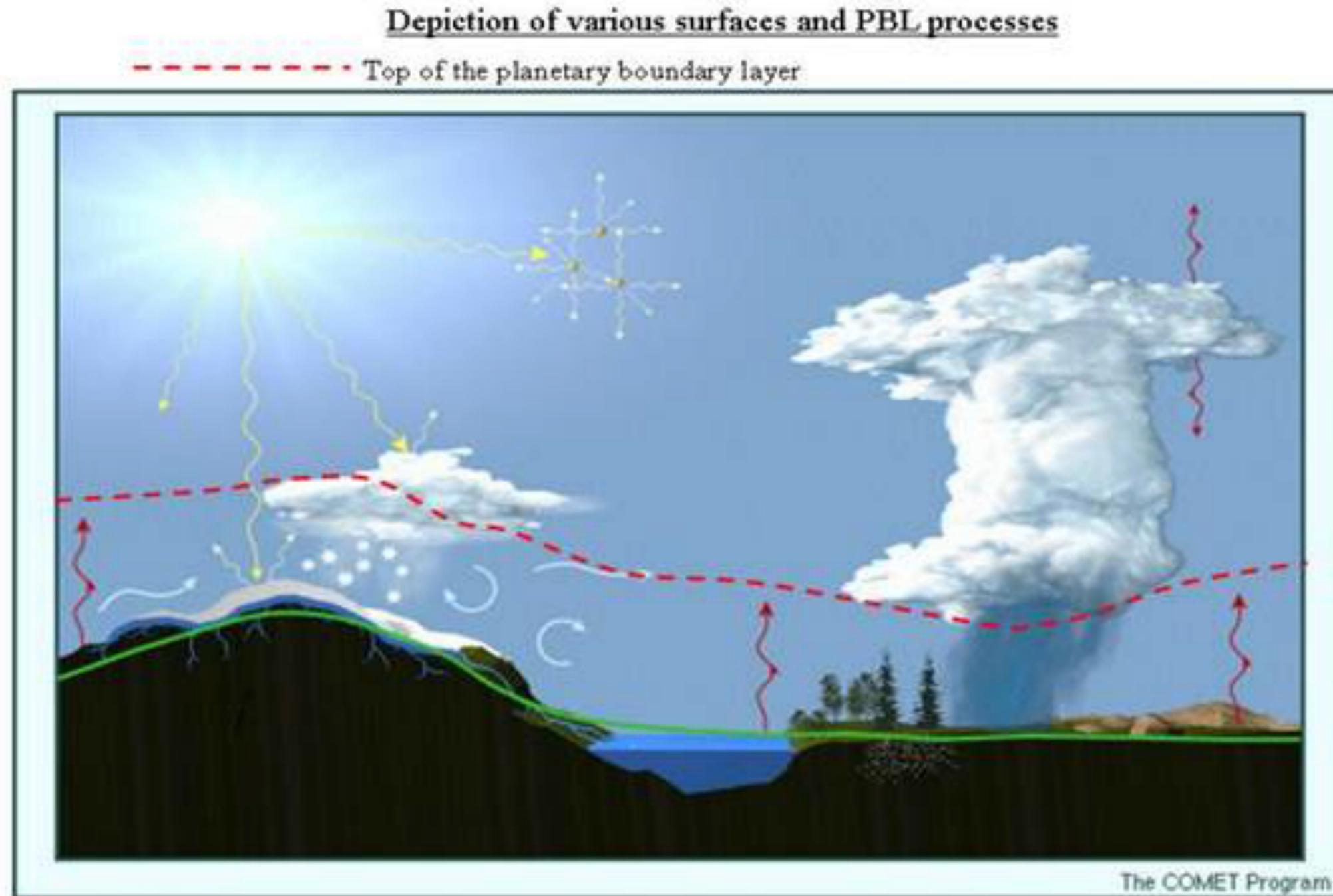
Planetary Boundary Layer (0-0.3km to 0-3km)

- Lowest layer of the troposphere
- Height above surface varies between 300m and 3km
 - Influenced by convection
 - varies diurnally (day-to-night)



Planetary Boundary Layer (0-0.3km to 0-3km)

- PBL directly influenced by contact with planetary surface
- Responds to changes in how much sunlight the surface receives rapidly (~hours)
- Flow velocity, temperature, moisture show rapid variations (turbulence) and vertical mixing is strong
- PBL winds are affected by surface drag
 - winds in the “free troposphere” above are determined by pressure gradients



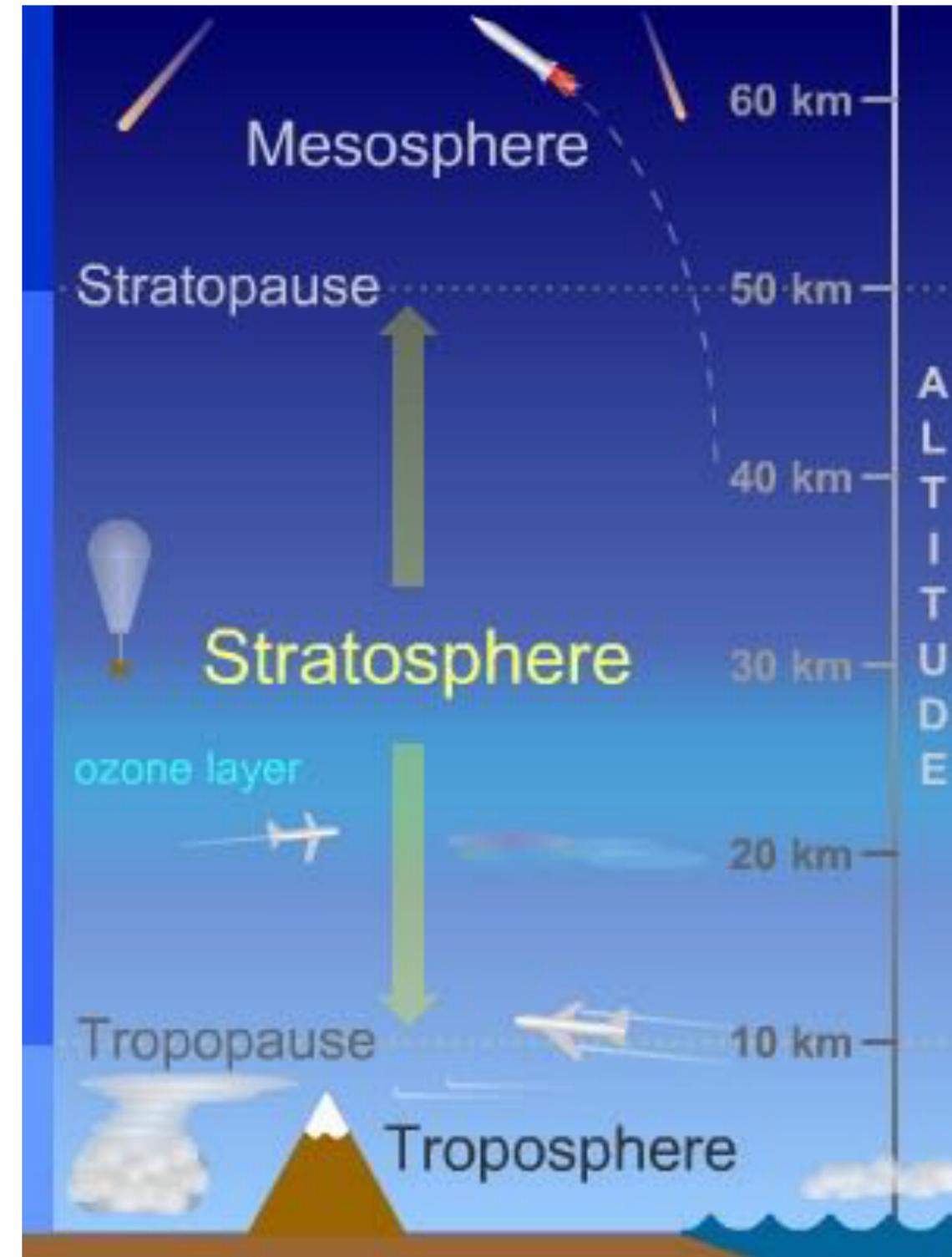
Troposphere (0-10 km)

- Energy transport by convection and radiation, vertical mixing layer



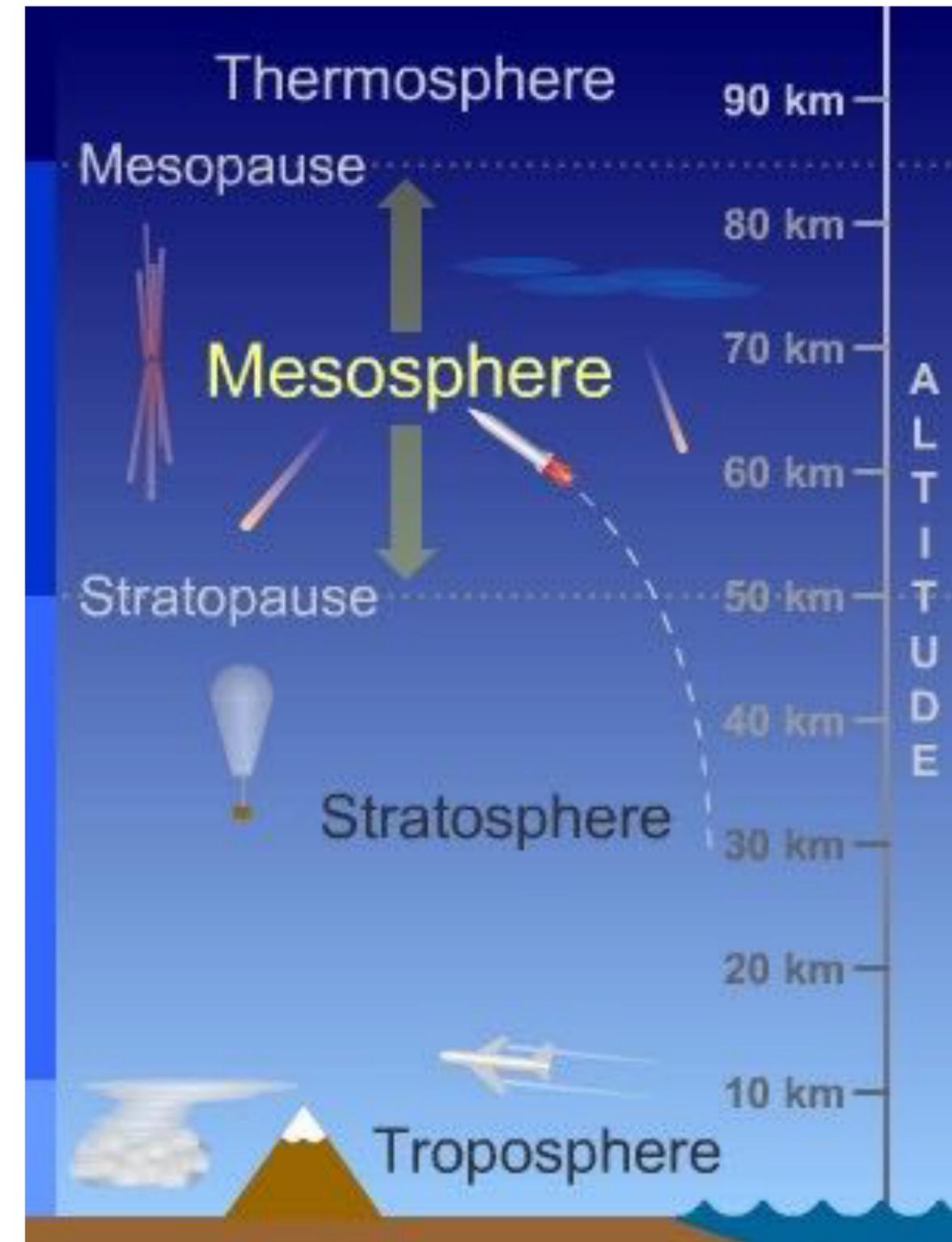
Stratosphere (10-50 km)

- Ozone (O_3) absorption of UV photons
- Ozone absorbs widely in UV and IR
- Bonds break: $O_3 \rightarrow O_2 + O$
- Excess energy from this reaction goes into local kinetic energy: heating source
- Result is a temperature inversion (T increases with height in the stratosphere)



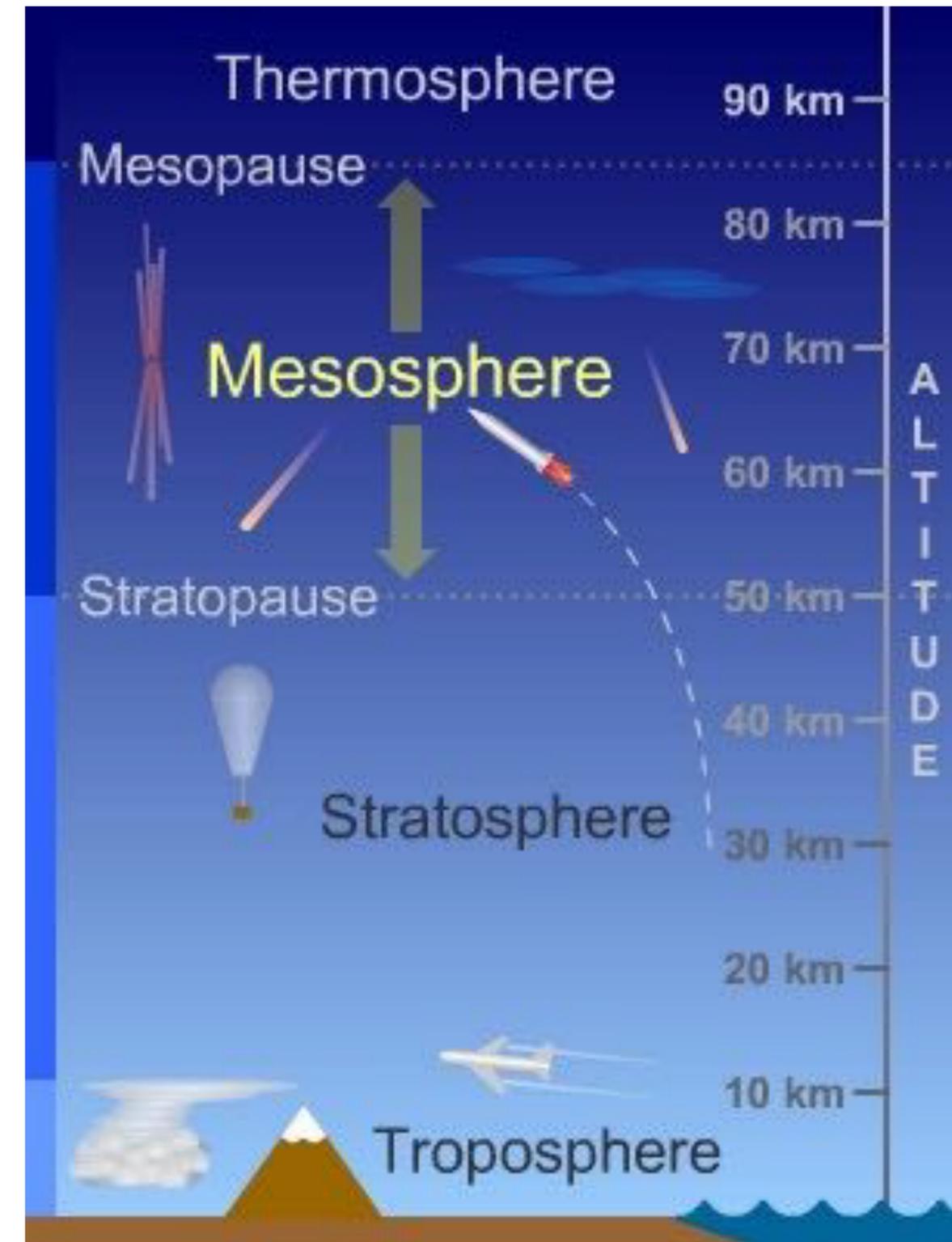
Mesosphere (50-85 km)

- Decrease in O₃ absorption of UV photons
- Increase in cooling rate of carbon dioxide
- At high densities (low altitudes) carbon dioxide is a greenhouse gas:
 - absorbs infrared radiation from below, then collides with oxygen or nitrogen and transfers that energy
- At low densities (high altitude) collisions are less frequent, and the reverse happens:
 - carbon dioxide absorbs energy through collisions, and radiates that energy to space before the next collision



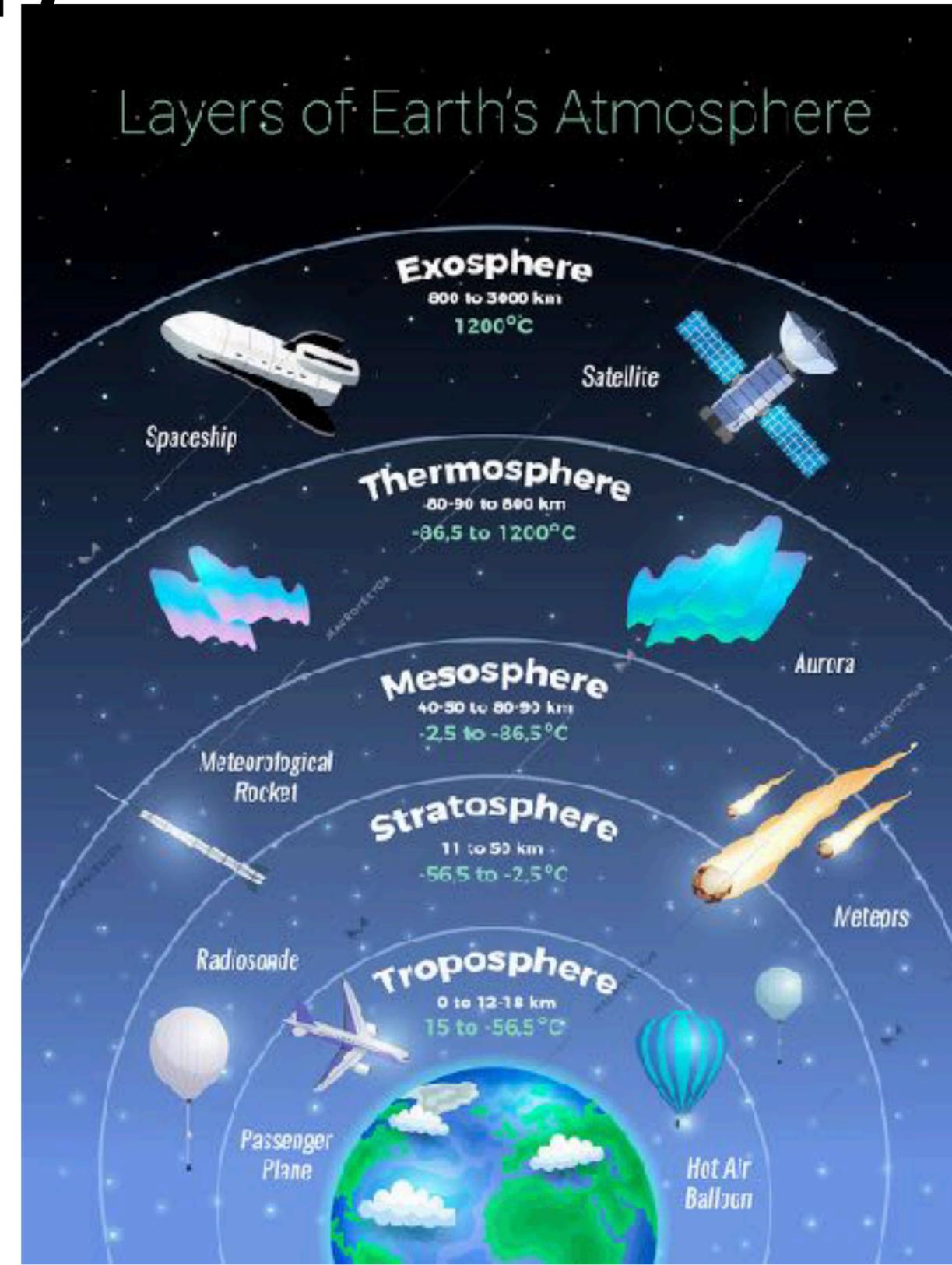
Thermosphere (85-800 km)

- Heating due to O₂ photolysis, ionization
 - Most XUV and X-rays from the Sun are absorbed in the thermosphere
- Thickness of this layer is a function of solar activity
- Average kinetic energy of particles is high
- Absorption of UV photons can boost particles to escape velocity
 - From space, see a big Lyman-alpha cloud leaving Earth
- Satellites orbit in the thermosphere
- Aurora originate here



Exosphere (800-3000km)

- The beginning of “space”
- some satellites orbit here

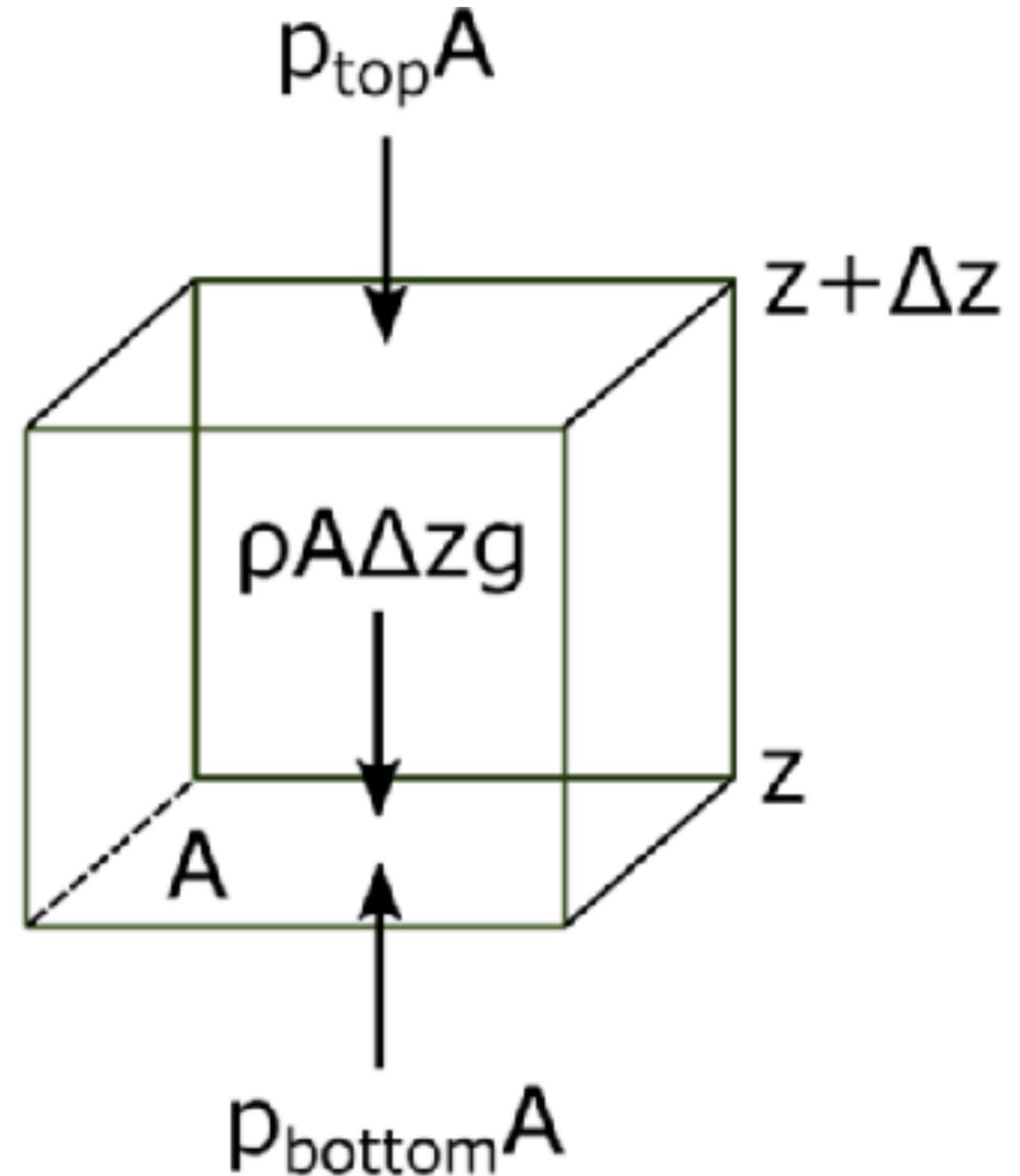


Break

05:00

Vertical structure

- Defined as the distribution of Pressure (P), Temperature (T), density (ρ), and mean molecular weight (μ) as a function of r (or z)
- Start with hydrostatic equilibrium: atmospheric structure is not currently changing
 - Pressure of the atmosphere below a parcel of gas supports the weight of that parcel of gas
- Pressure = F/A , so $F = PA$

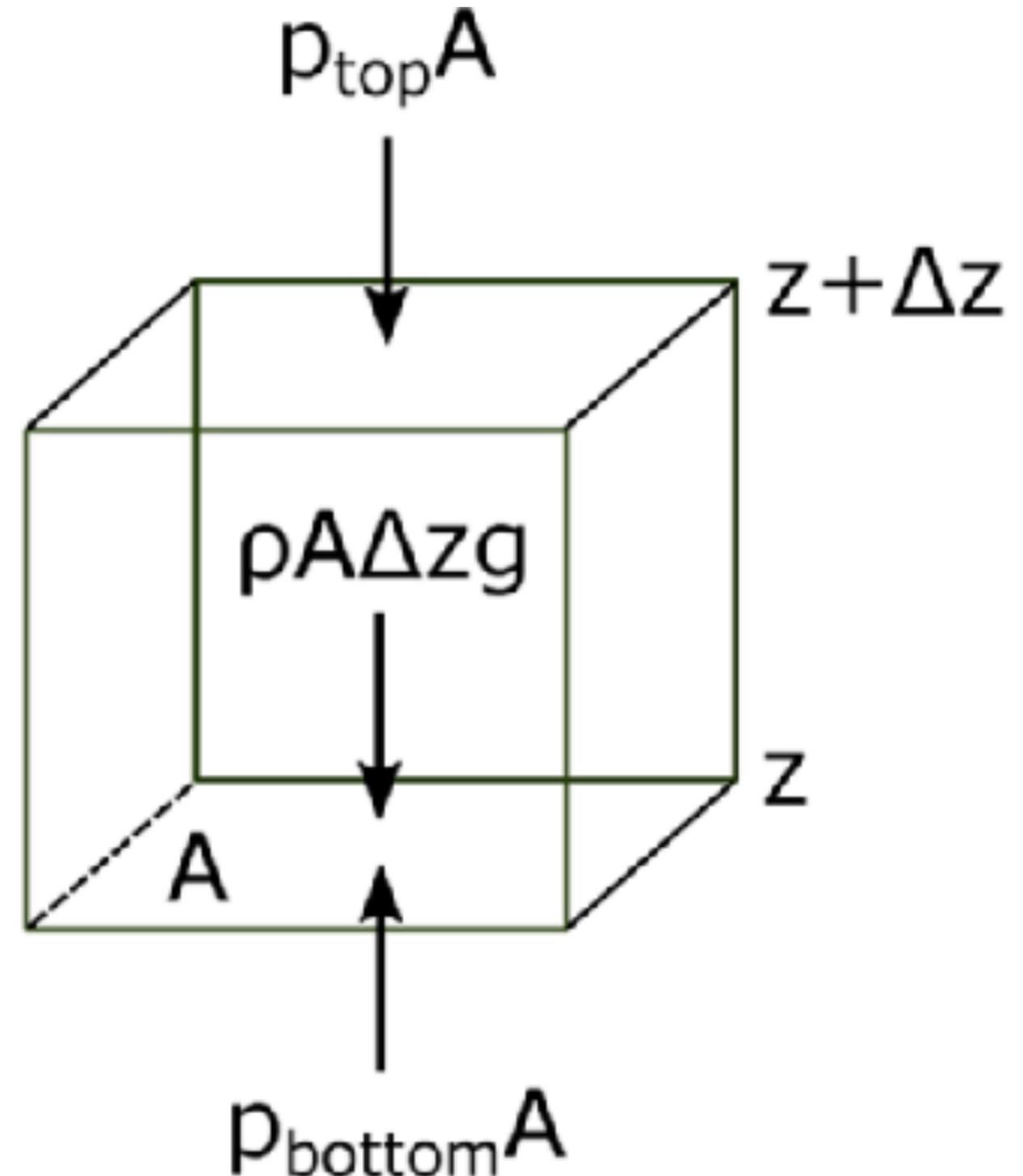


Vertical structure

- There are 3 forces on this parcel of air:
 - Pressure coming from above: $-P_{\text{top}}A$
 - Pressure coming from below: $P_{\text{bottom}}A$
 - Weight of the gas in the parcel: $-\rho Vg$
- Volume of the box is $V = A\Delta z$
- In hydrostatic equilibrium, the 3 forces sum to 0 (the gas in the box is neither rising nor falling):

$$F_{\text{top}} + F_{\text{bottom}} + F_{\text{weight}} = 0$$

$$-P_{\text{top}}A + P_{\text{bottom}}A - \rho g A \Delta z = 0$$



Vertical structure

- $-P_{top}A + P_{bottom}A - \rho g A \Delta z = 0$

$$\Delta P = \rho g \Delta z$$

- Or, if we make Δz very small:

$$dP = \rho g dz$$

- More generally:

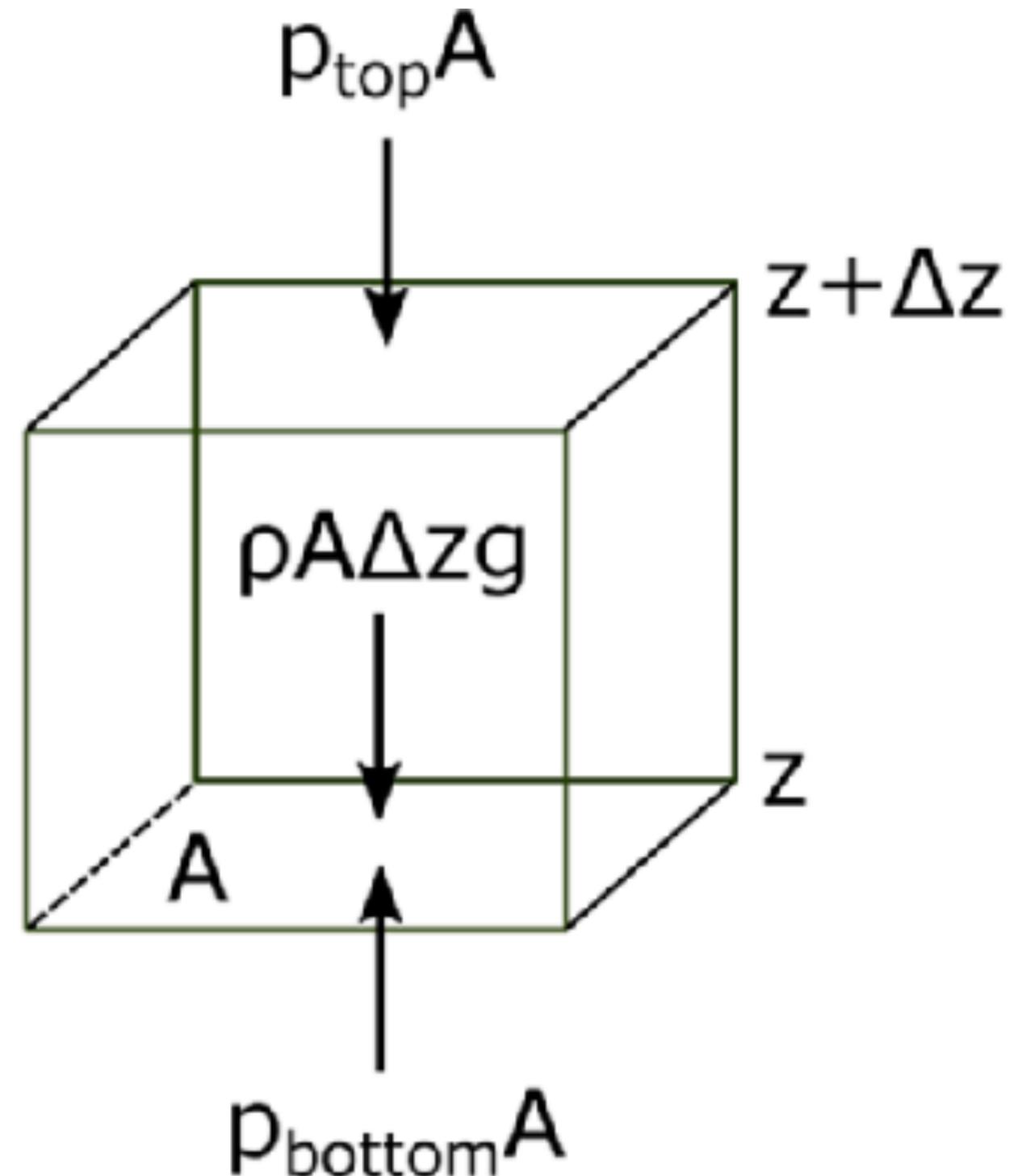
$$\frac{dP}{dr} = g(r)\rho = -\frac{GM}{r^2}\mu N$$

- M: mass of planet

- μ : mean molecular weight (mass/particle)

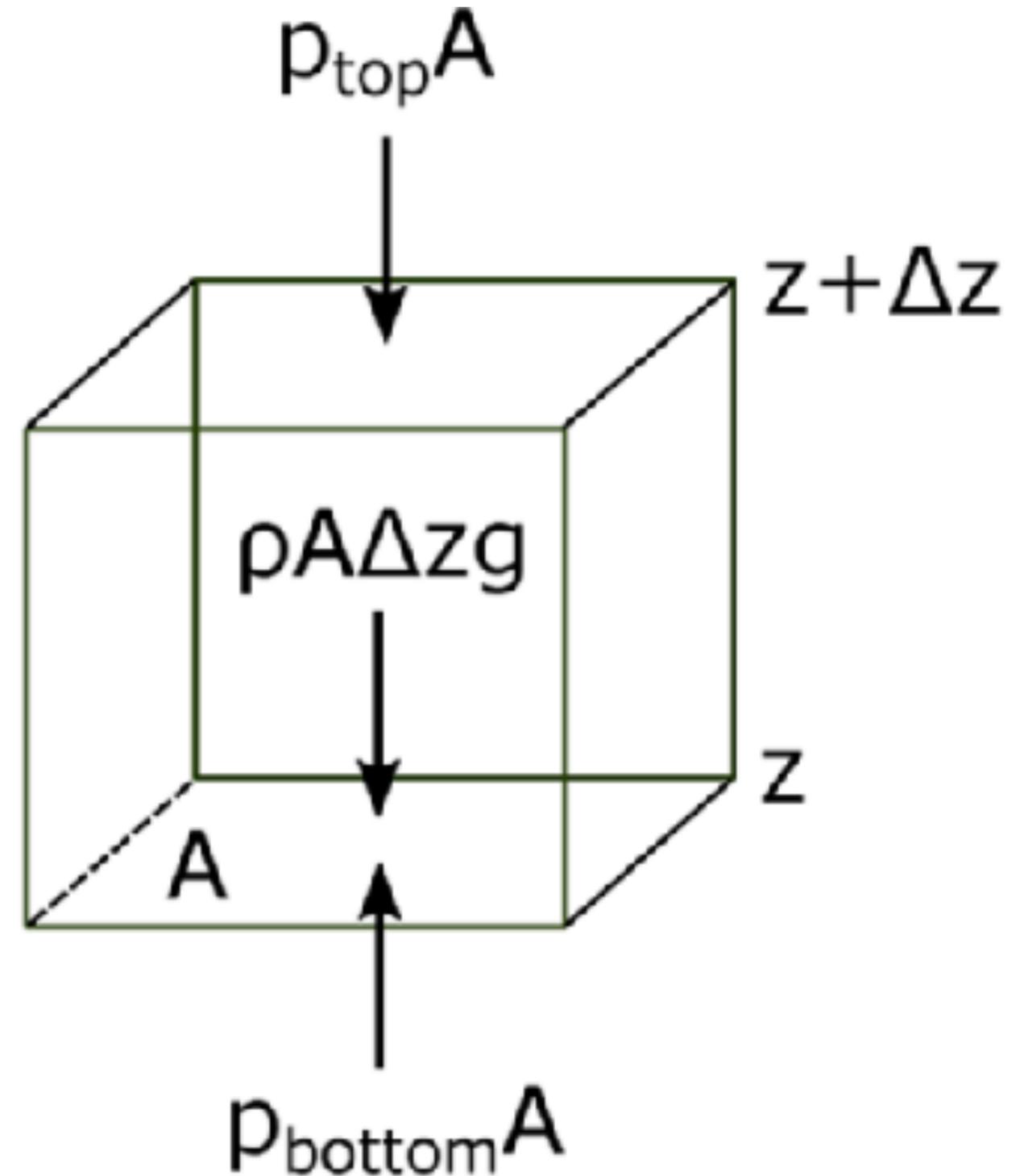
- N: number density

- ρ : mass density



Vertical structure

- $\frac{dP}{dr} = g(r)\rho = -\frac{GM}{r^2}\mu N$
- If $\Delta r \ll r$, $g(r) = \text{constant}$
- With an equation of state, we can relate pressure and density
 - For planetary atmospheres, we can use the ideal gas law
- $P = NkT$ or $P = \rho RT$
- (R is the gas constant for a given atmospheric composition)



Vertical structure

- $\frac{dP}{dr} = g(r)\rho = -\frac{GM}{r^2}\mu N$

- $P = NkT$

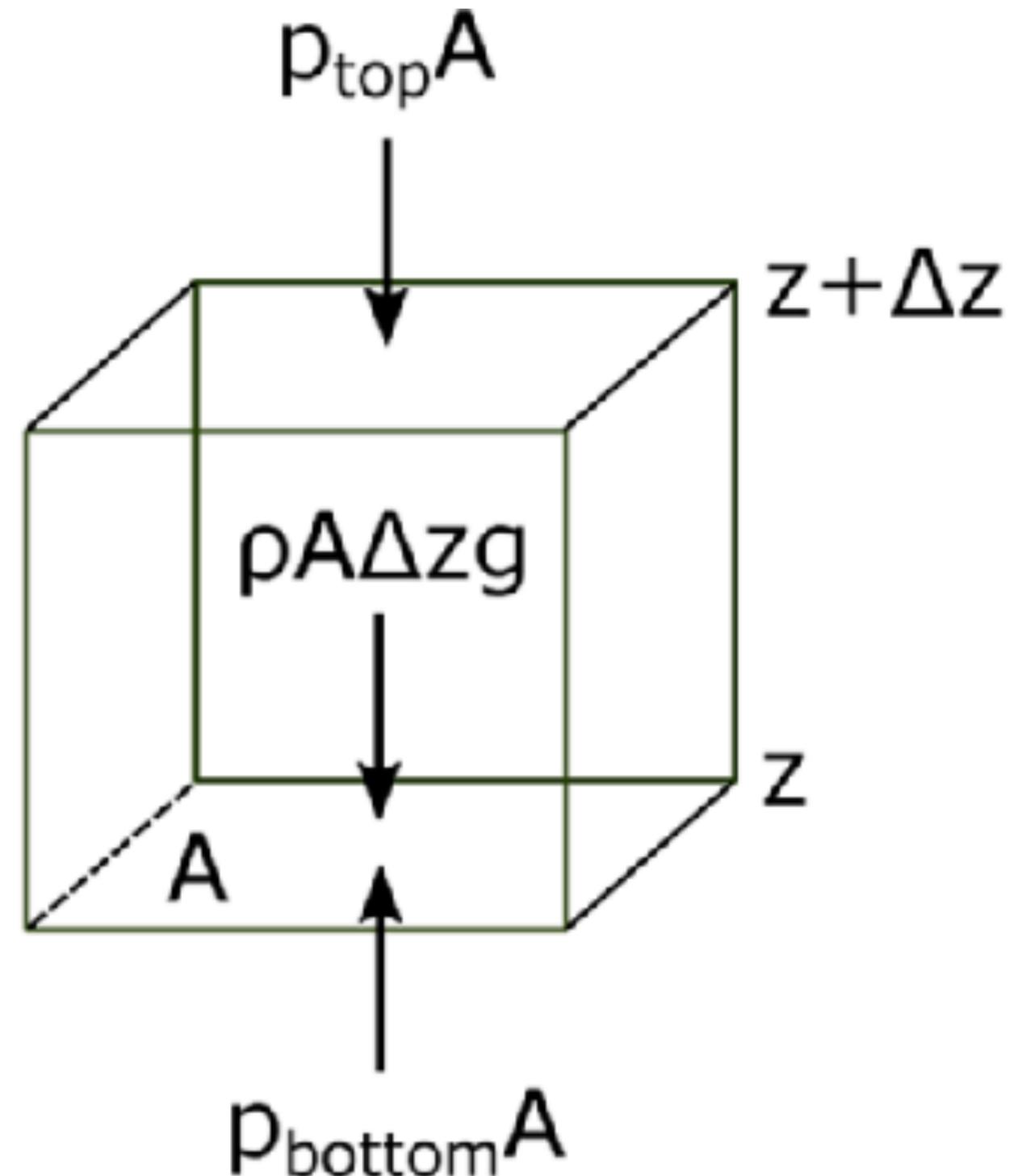
- $\frac{dP}{P} = -\frac{GM}{r^2}\mu\frac{dr}{kT} = -\frac{GM\mu}{kT}\frac{dr}{r^2}$

- If we assume the size scales we're considering are much smaller than the radius r (so g is a constant, and T and μ are constants):

- $\frac{dP}{P} = -\frac{g\mu}{kT}dr = -\frac{dr}{H}$

- Pressure scale height:

$$H = \frac{kT}{\mu g}$$



Vertical structure

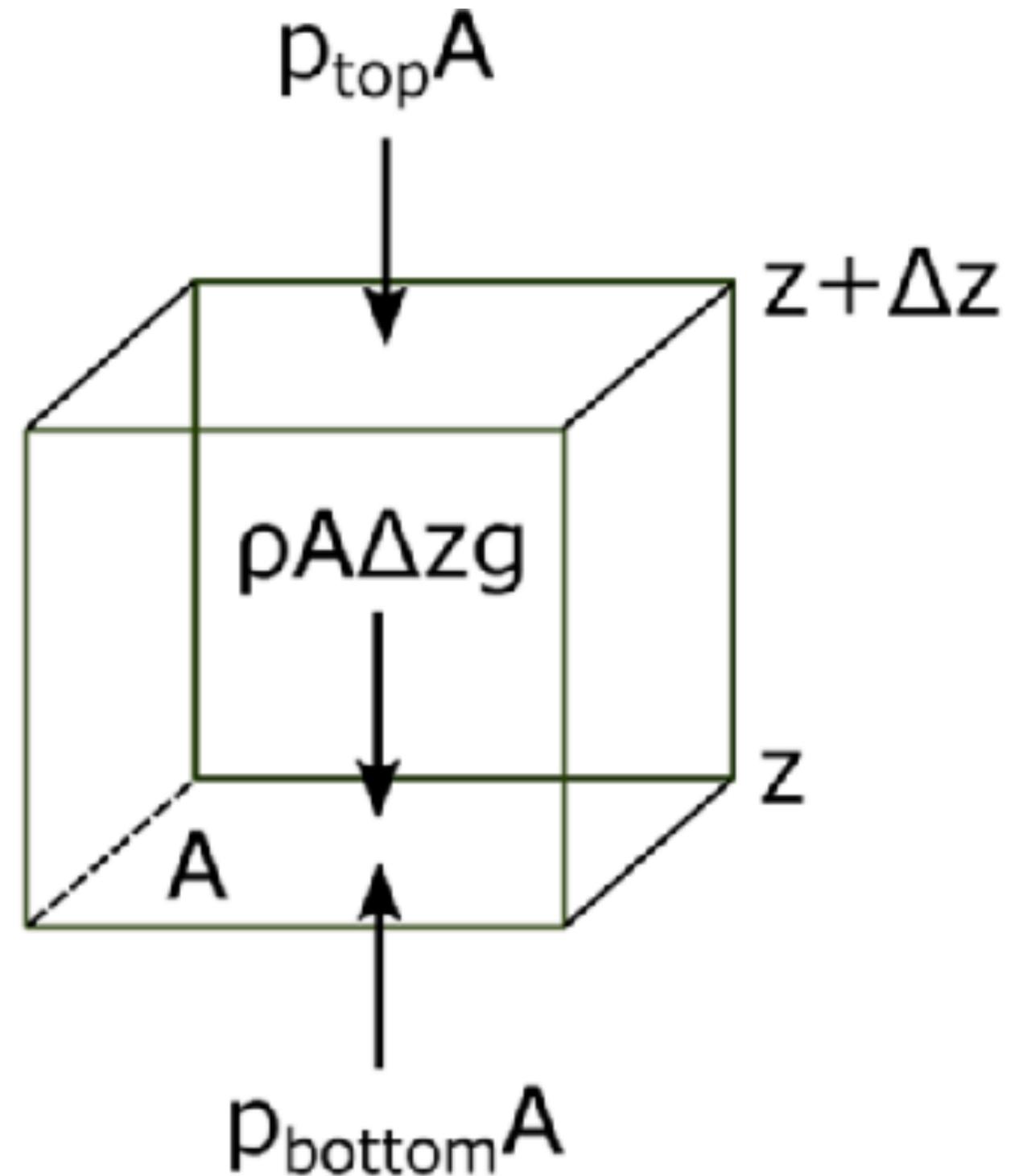
- $\frac{dP}{P} = -\frac{dr}{H}$

- Integrate:

$$\ln P(r) - \ln P(r_0) = -\frac{1}{H}(r - r_0)$$

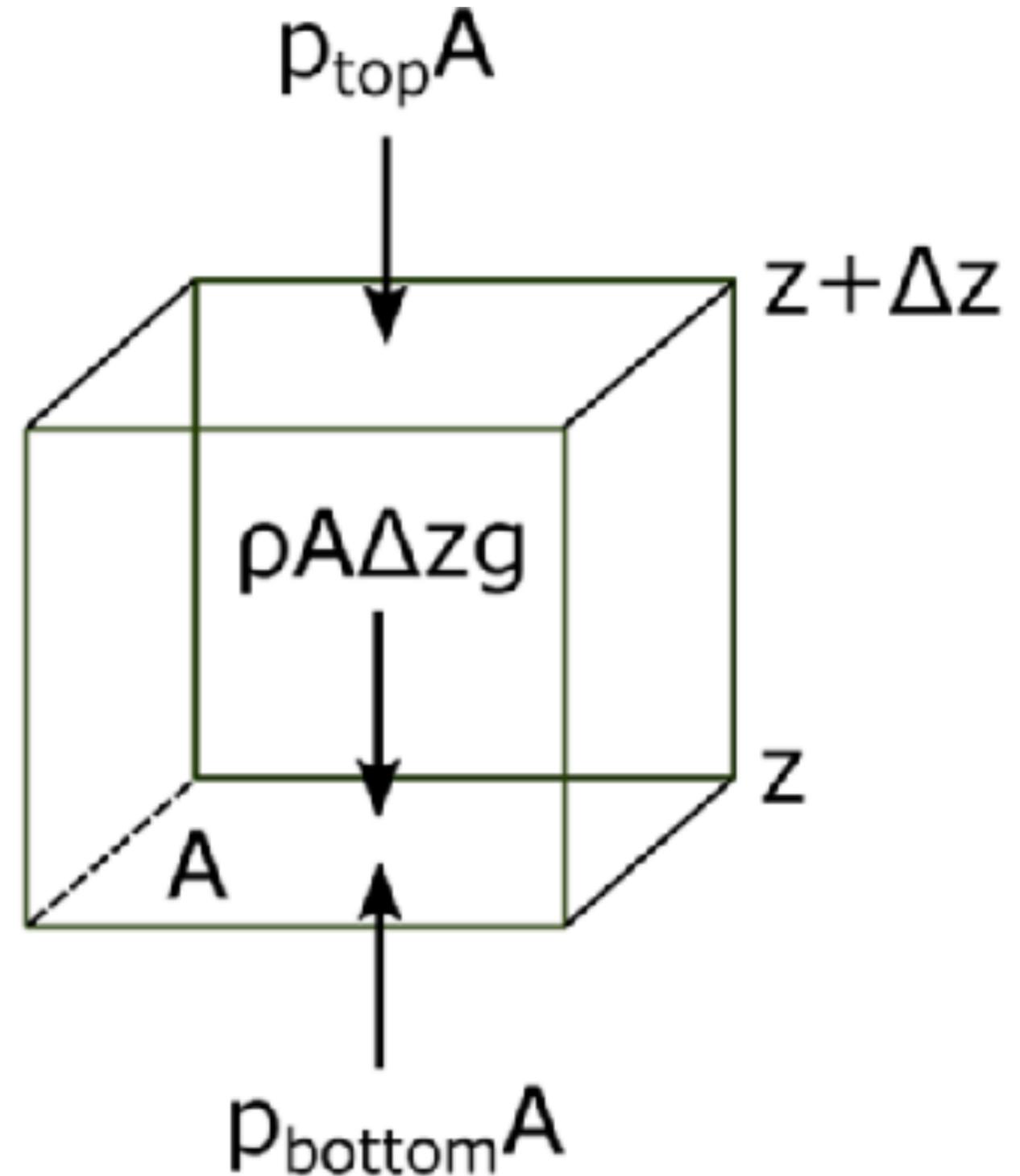
$$\ln \frac{P(r)}{P(r_0)} = -\frac{(r - r_0)}{H}$$

$$P(r) = P(r_0)e^{-\frac{r-r_0}{H}}$$



Vertical structure

- $P(r) = P(r_0)e^{-\frac{r-r_0}{H}}$
- Exponent is negative: pressure decreases with height
 - Lower altitudes have to support the weight of more atmosphere above them
- Pressure drops off exponentially:
 - Go up one scale height, and pressure has dropped by $1/e$
- Scale height near Earth's surface: about 8 km



Mean molecular weight

- μ : average mass per particle
- Calculate using a weighted average of atmospheric constituents:
- $$\mu = \sum w_i m_i$$
- w_i : number fraction of constituent i
- m_i : mass of constituent i

Mean molecular weight

- $\mu = \sum w_i m_i$
- Example: Dry air on Earth is 78% nitrogen (N₂) and 21% oxygen (O₂), 1% argon, and a tiny fraction of everything else (Carbon dioxide, Neon, ...)
- What is the mean molecular weight (in amu) of dry air on Earth?
- $\mu_{\oplus} = (0.78)(14) + (0.21)(16) + (0.01)(40) = 14.7$

Response Card Question

- What is the mass of Jupiter, compared to the mass of Earth and the Sun?
- (A) — 100 times less than the Sun, 30 times more than the Earth
- (B) — 1000 times less than the Sun, 30 times more than the Earth
- (C) — 100 times less than the Sun, 300 times more than the Earth
- (D) — 1000 times less than the Sun, 300 times more than the Earth

Response Card Question

- What is the radius of Jupiter, compared to the radius of Earth and the Sun?
 - (A) — 10 times less than the Sun, 10 times more than the Earth
 - (B) — 10 times less than the Sun, 100 times more than the Earth
 - (C) — 100 times less than the Sun, 10 times more than the Earth
 - (D) — 100 times less than the Sun, 100 times more than the Earth
 - (E) — 1000 times less than the Sun, 100 times more than the Earth

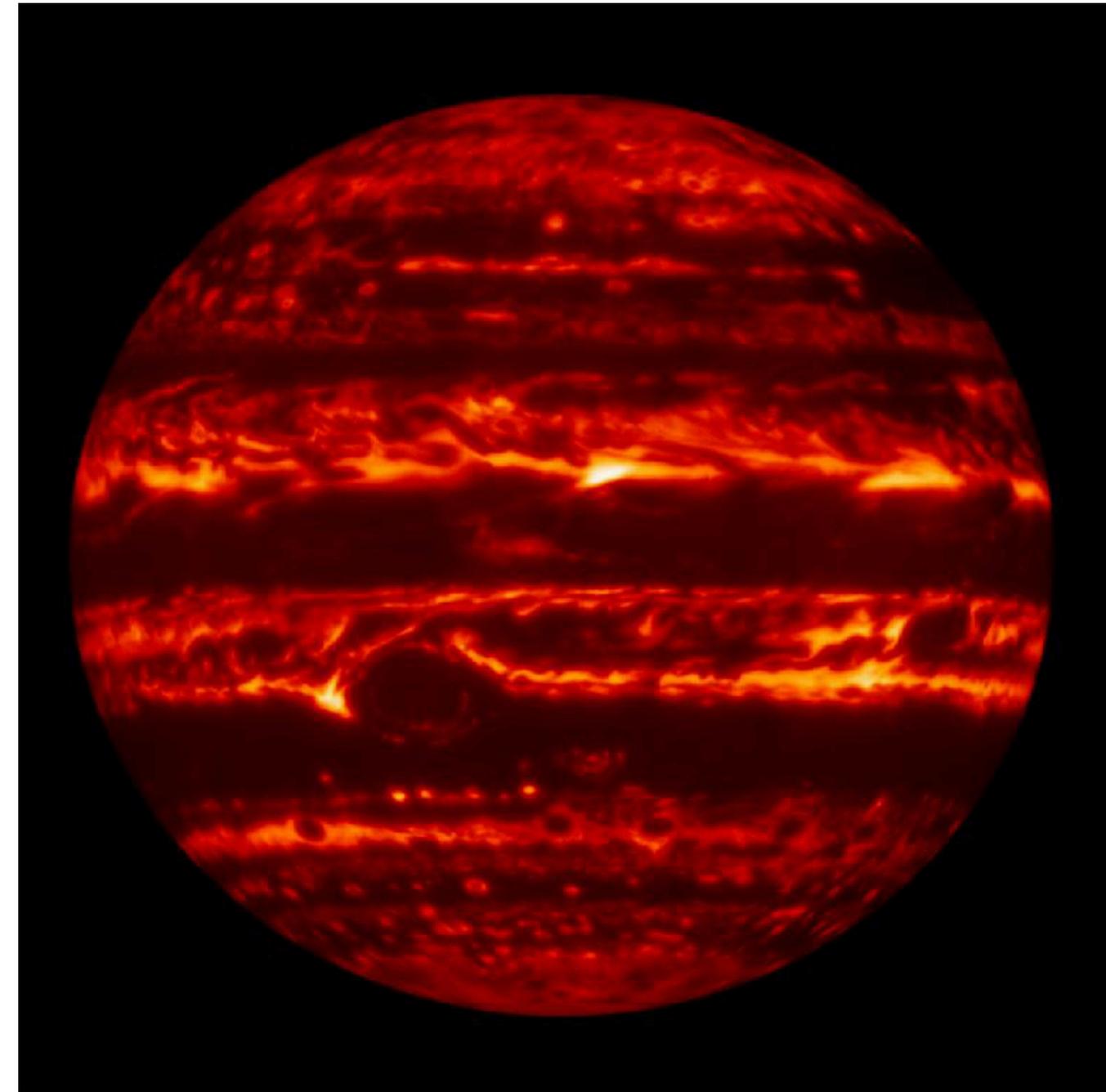
Order of Magnitude: Scale Height of Jupiter's upper atmosphere

$$H = \frac{kT}{\mu g} \quad \mu = \sum w_i m_i \quad k = 1.38 \times 10^{-16} \frac{\text{cm}^2 \text{g}}{\text{s}^2 \text{K}}$$
$$m_p = 1.7 \times 10^{-24} \text{g}$$

- Galileo Entry probe measured abundances (number fractions):

H₂ — 84.2% He — 15.6% CH₄ — 0.2%

- For Jupiter's upper atmosphere, above the uppermost cloud decks ($r = R_{\text{Jup}}$), $T = 122\text{K}$:
- (1) What is the mean molecular weight at this part of Jupiter's atmosphere, in amu? In grams?
- (2) What is the surface gravity of Jupiter at this location?
- (3) What is the pressure scale height, in km?



Order of Magnitude: Scale Height of Jupiter's upper atmosphere

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- (1) What is the mean molecular weight at this part of Jupiter's atmosphere, in amu? In grams?

- Ok, H₂ has 2 nucleons, He has 4.

Methane? 4 from each of the hydrogens, 12 from carbon, so 16 total

$$\mu = (0.842)(2) + (0.156)(4) + (0.002)(16) = 1.7 + 0.6 + 0.032 = 2.3 \text{ amu}$$

- Converting to grams, just multiply by the mass of the proton: $\mu = 2.3 \times 1.7 \times 10^{-24} \text{g} = 4 \times 10^{-24} \text{g}$

Order of Magnitude: Scale Height of Jupiter's upper atmosphere

- (2) What is the surface gravity of Jupiter at this location?
- Jupiter is 10x larger than Earth, and 1/1000 as massive as the Sun

- $R = 10 \times 6 \times 10^8 \text{ cm} = 6 \times 10^9 \text{ cm}$ $M = 10^{-3} \times 2 \times 10^{33} \text{ g} = 2 \times 10^{30} \text{ g}$

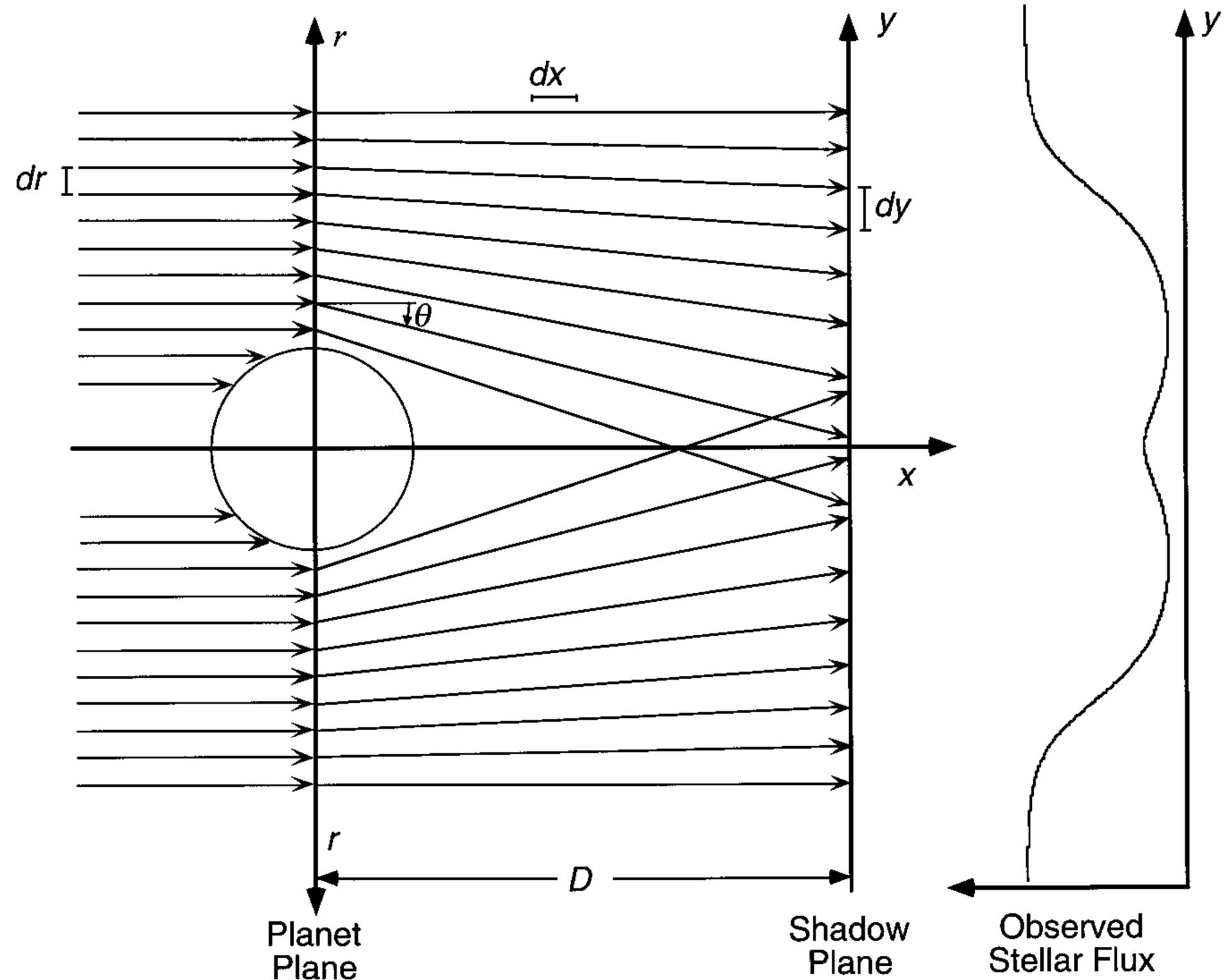
$$g = \frac{GM}{R^2} = \frac{(7 \times 10^{-8})(2 \times 10^{30})}{(6 \times 10^9)^2} = \frac{14 \times 10^{22}}{36 \times 10^{18}} = \frac{1}{2} 10^4 = 5 \times 10^3 \frac{\text{cm}}{\text{s}^2}$$

- (3) What is the pressure scale height, in km?

$$H = \frac{kT}{\mu g} = \frac{(1 \times 10^{-16})(100)}{(4 \times 10^{-24})(5 \times 10^3)} = \frac{10^{-14}}{20 \times 10^{-21}} = 0.5 \times 10^6 = 5 \times 10^5 \text{ cm} = 5 \text{ km}$$

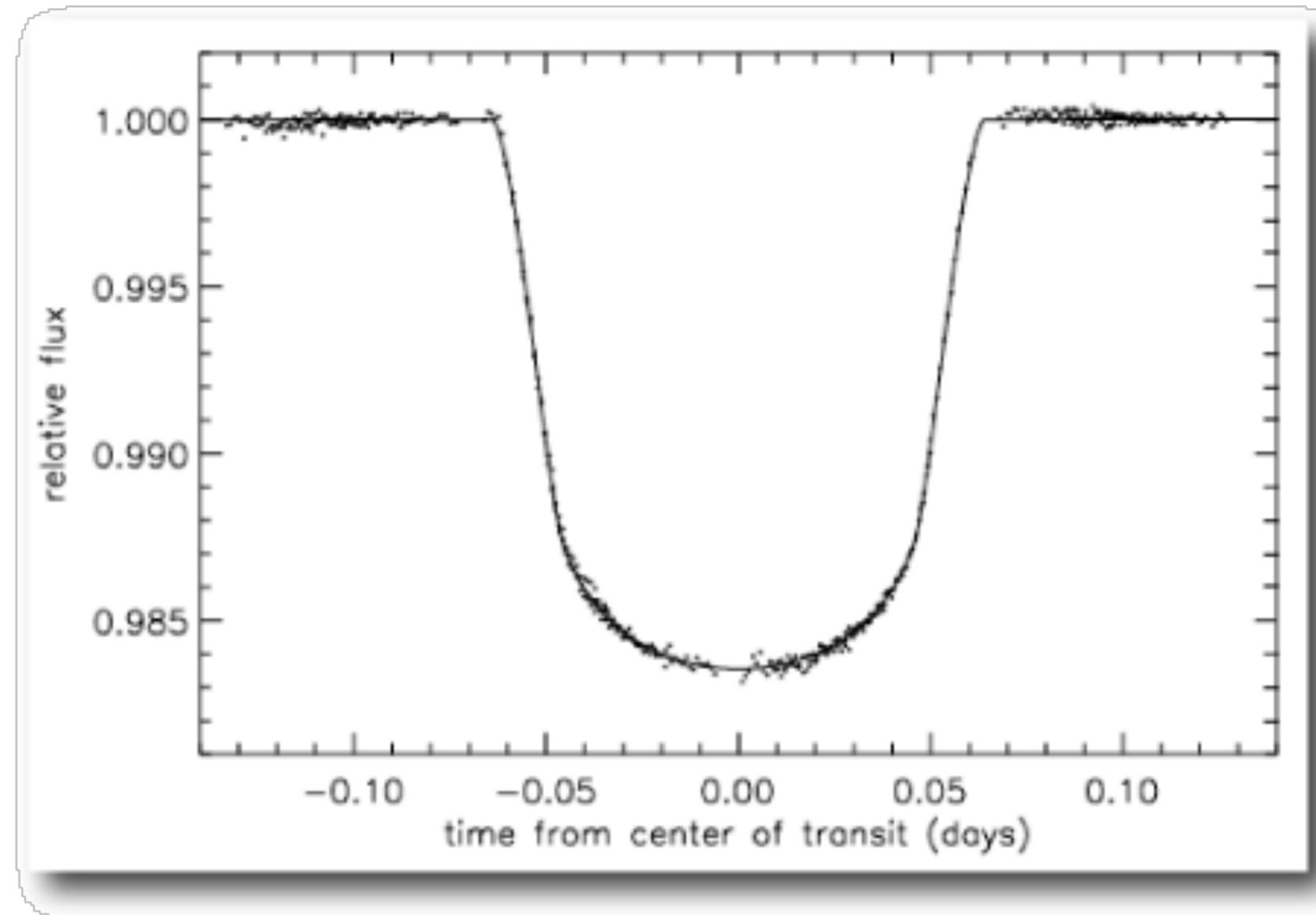
Occultations

- Multiple types of occultation data:
 - ground-based stellar occultation
 - occultation of radio signals from spacecraft
 - solar occultations
 - stellar occultation observed from spacecraft



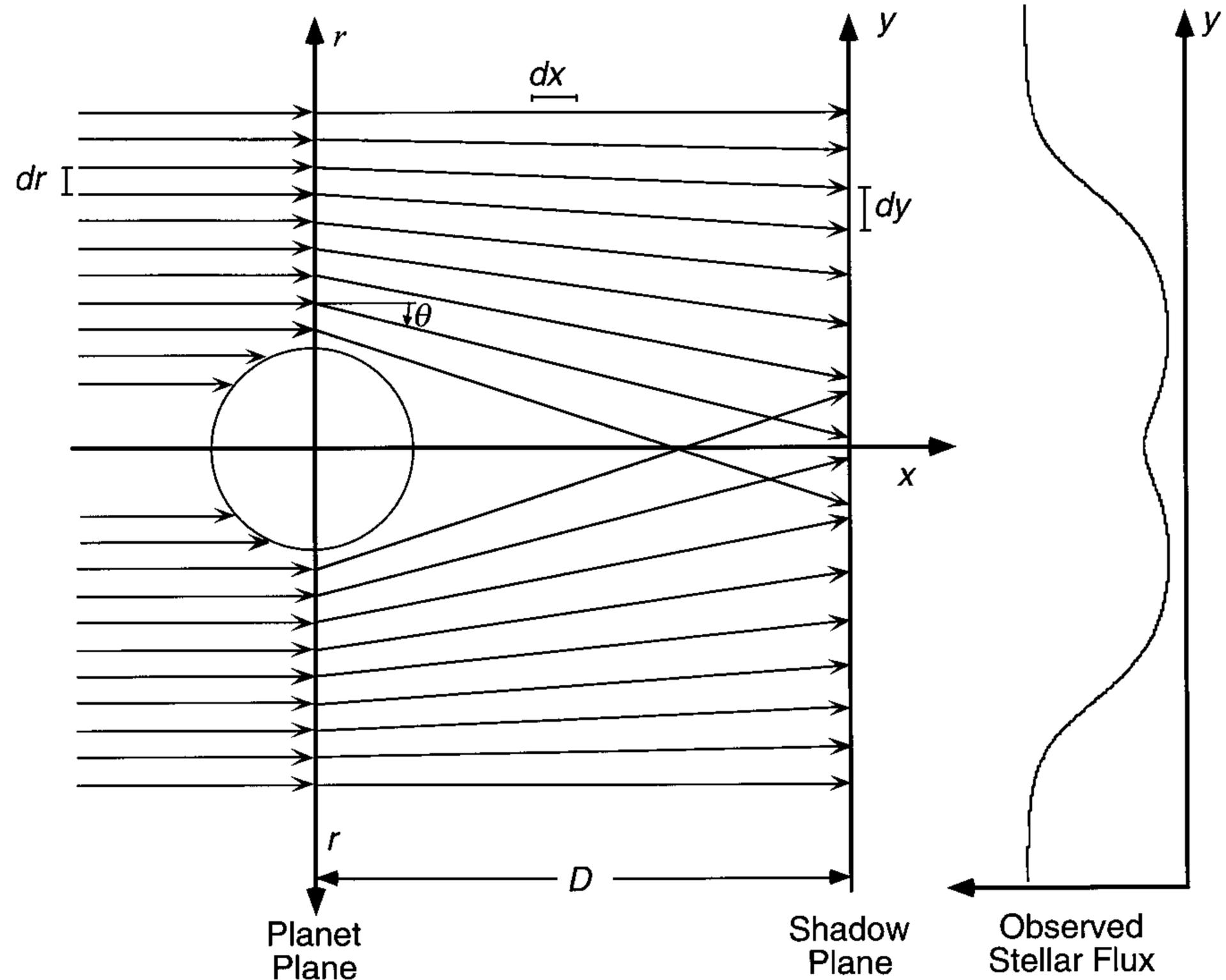
Transit spectroscopy

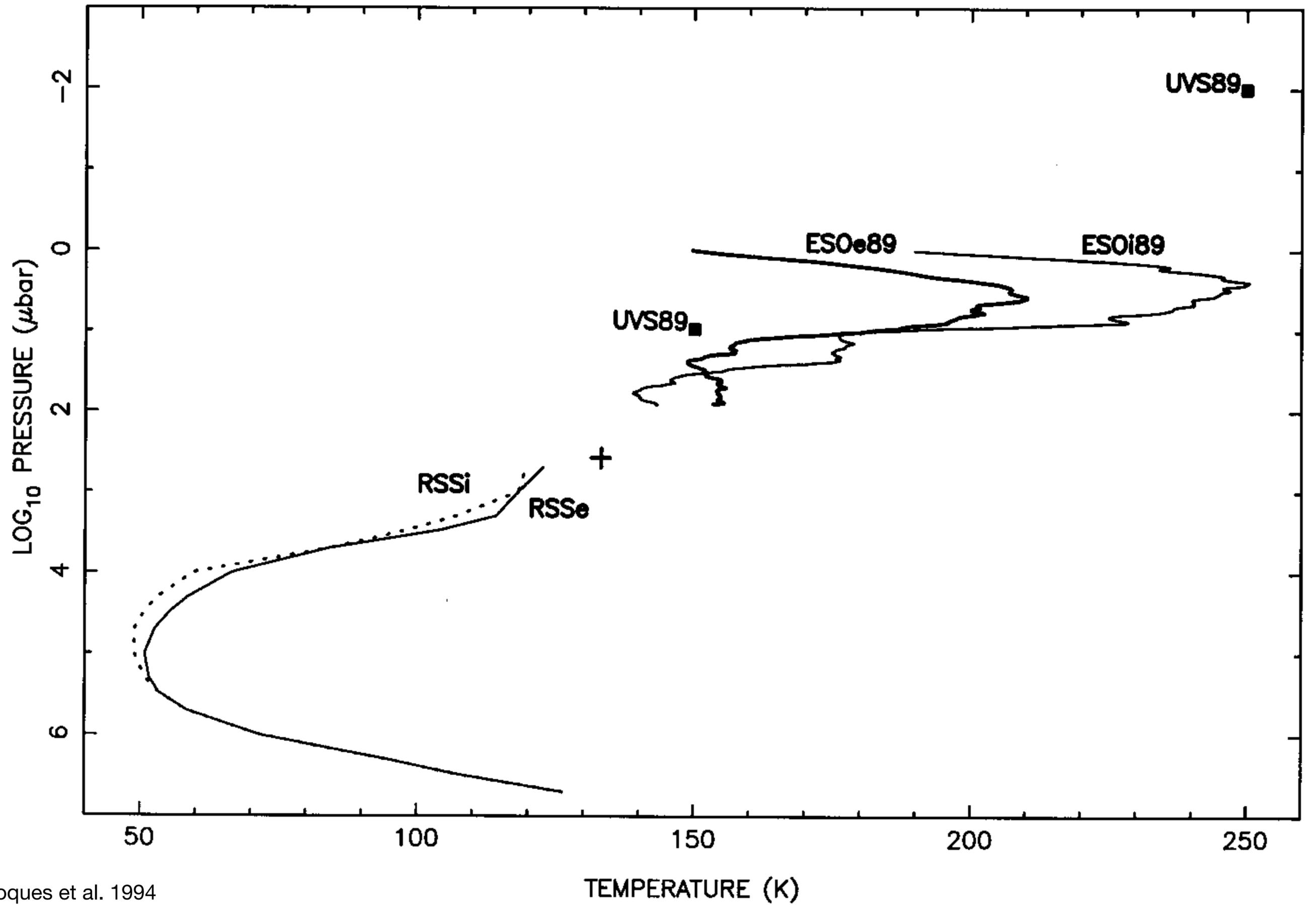
- One way to take spectra of exoplanets is transit spectroscopy (the other is direct imaging)
- For favorable orbit configurations, the planet passes between its host star and us, the observer
- Taking spectra during transit (and carefully subtracting off all the light from the star) can reveal a spectrum of the planet

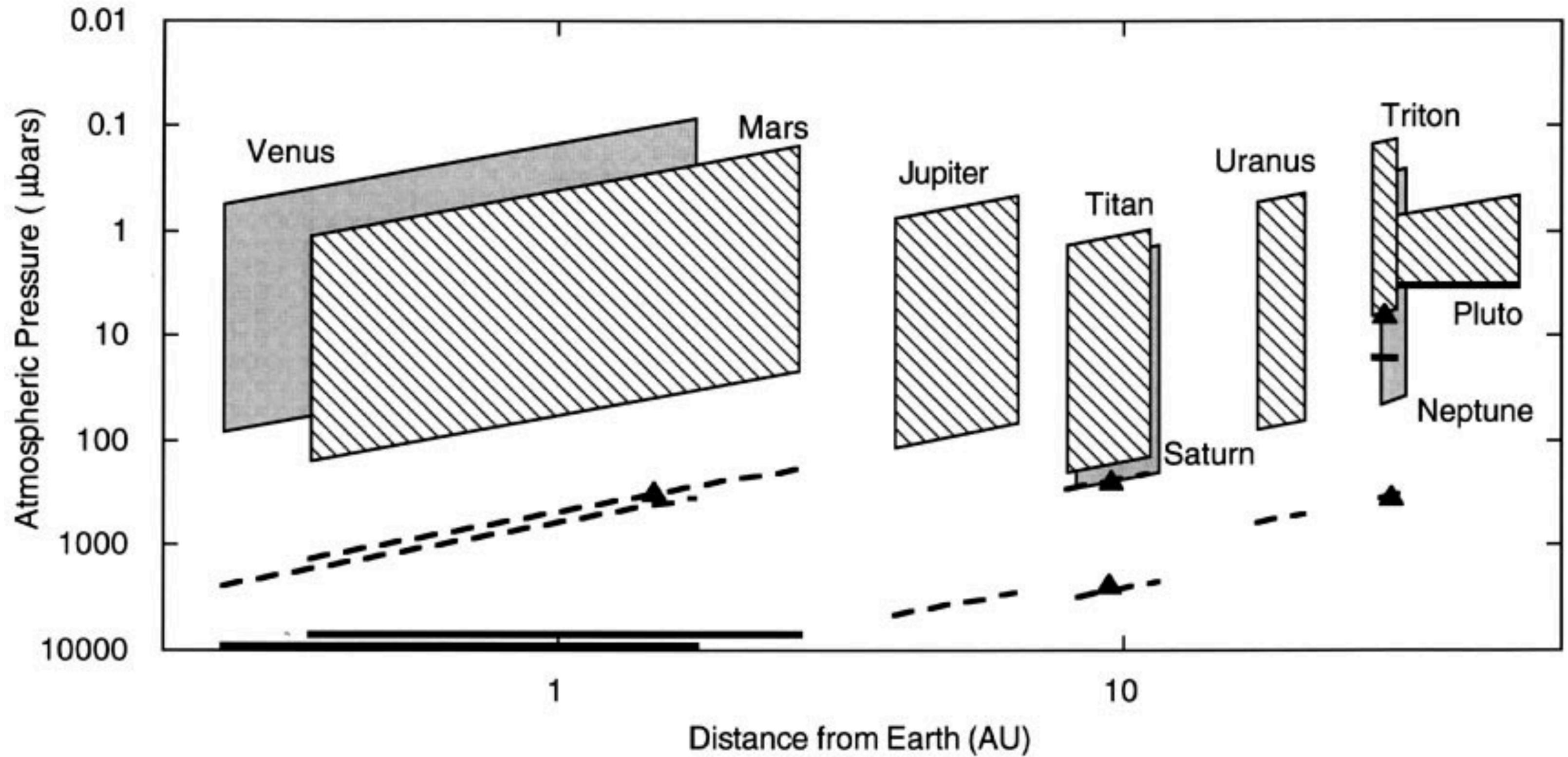


Occultations

- Need to reconstruct path of observer through shadow plane
- Can extract scale height info to first order
- If we know/assume composition (μ), can derive profiles of temperature, pressure, and number density
- Need simultaneously observations at multiple wavelengths to characterize extinction

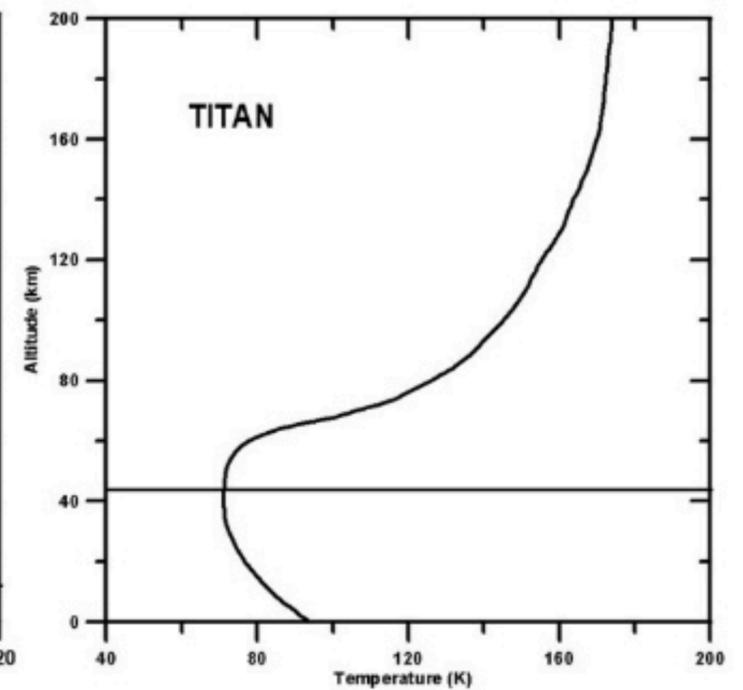
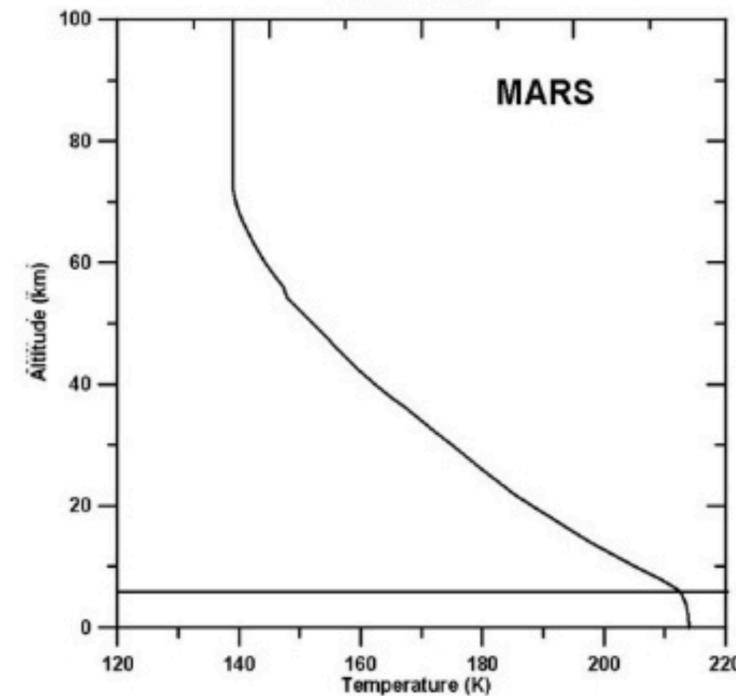
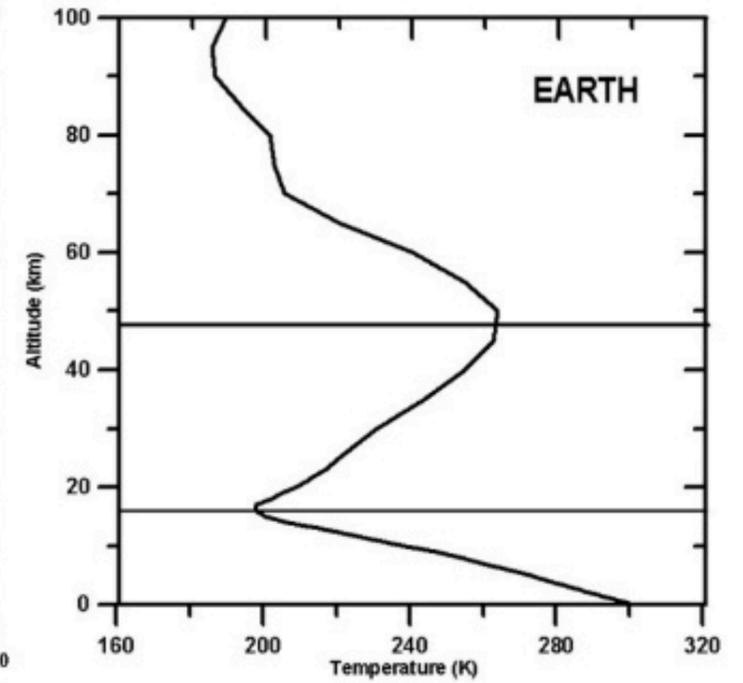
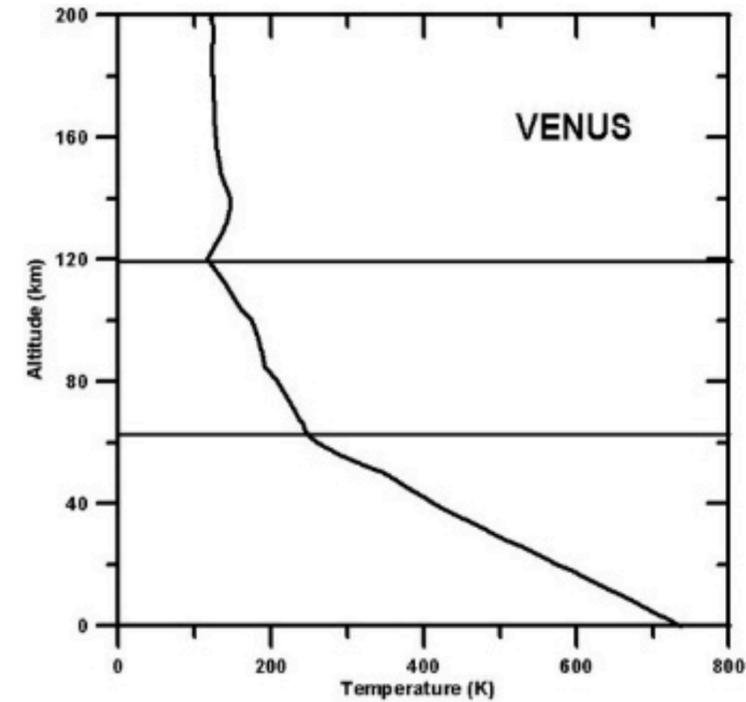






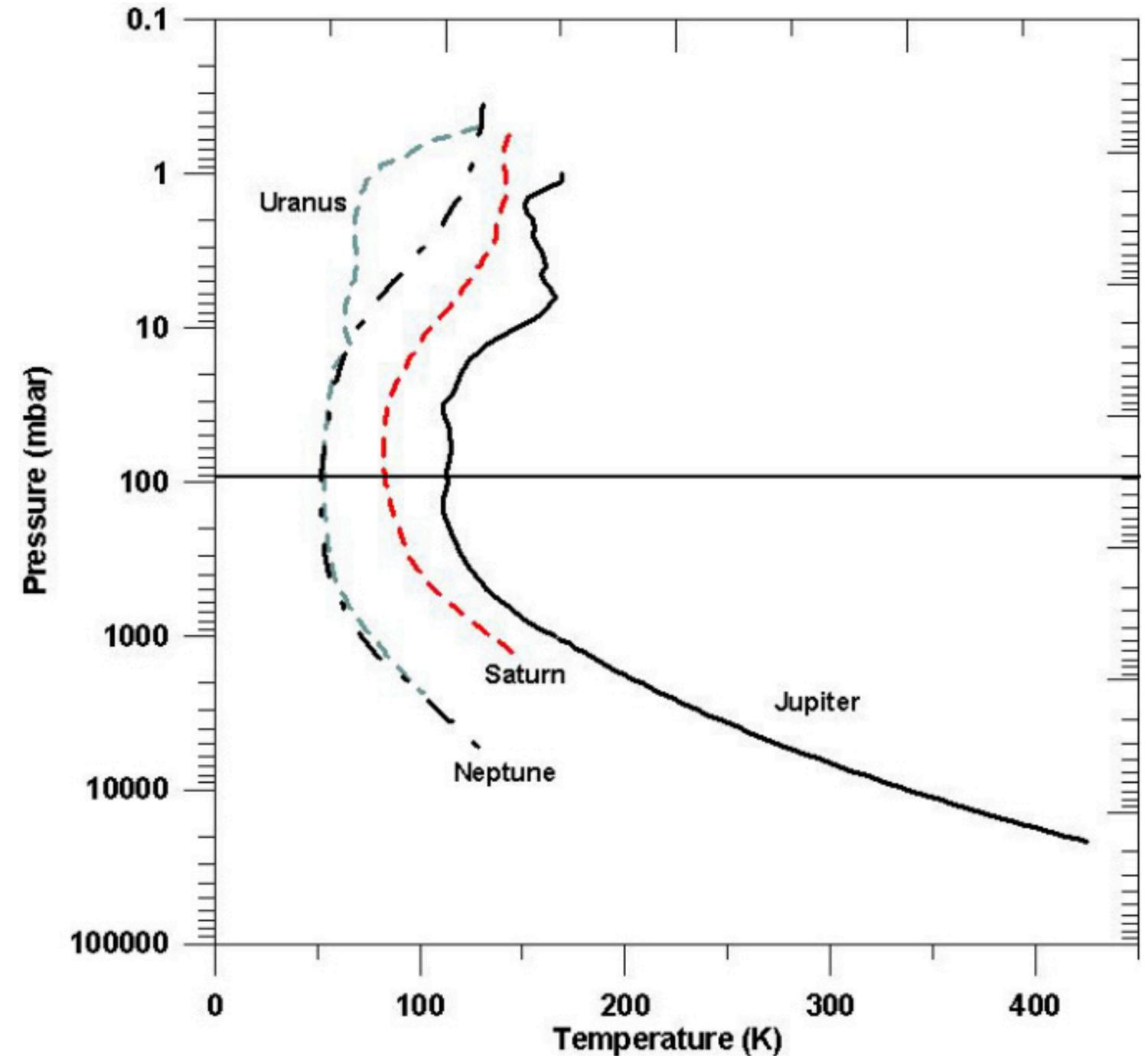
Temperature/Pressure Profiles: Terrestrial bodies

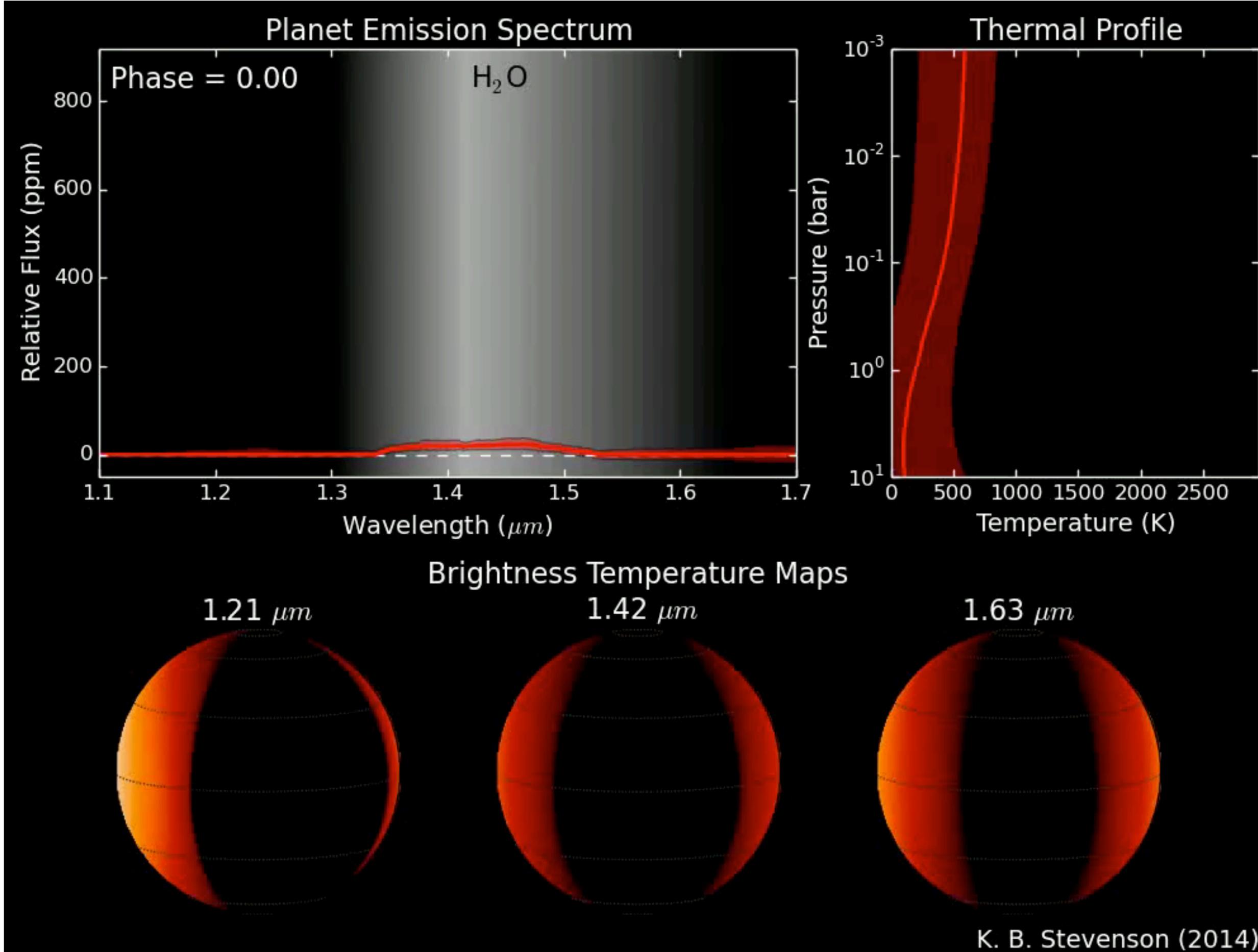
- Venus: only 2.6% of incident solar flux reaches surface
 - no stratosphere, extensive mesosphere
- Mars: No stratosphere, extensive mesosphere
- Titan: Extensive stratosphere due to absorption by hazes, hydrocarbons



Temperature/Pressure Profiles: Giant Planets

- Stratosphere due to absorption by hazes, hydrocarbons, then isothermal mesosphere





WASP-43b

K. B. Stevenson (2014)

For next time

- Reading: de Pater & Lissaeuer Chaper 3, 3.2.3.4
- Homework 3 due tonight at 11:59pm