

ASTR 620: Planetary Processes
Professor Eric Nielsen

Lecture 15: Atmospheres



Logistics

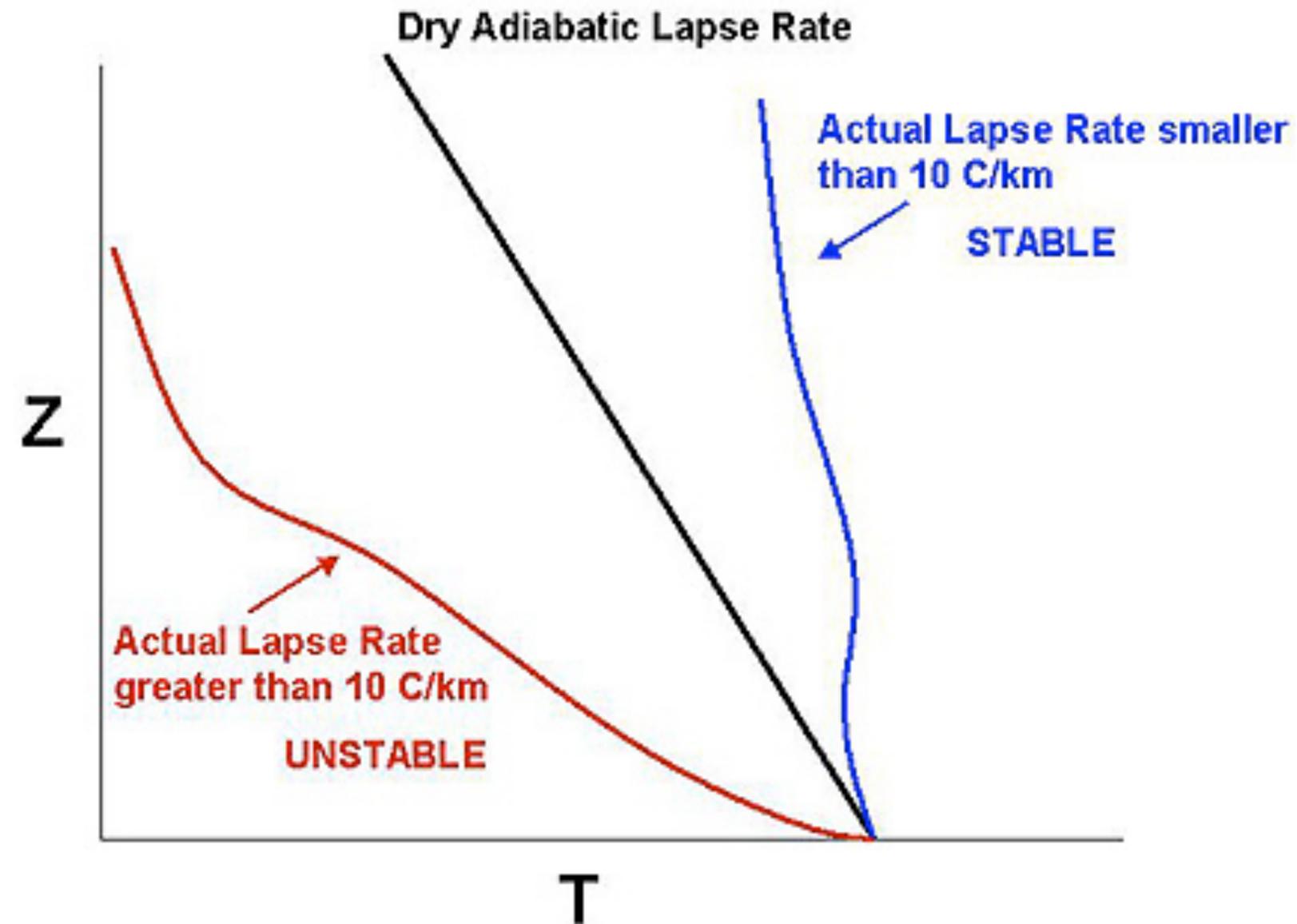
- Masks are encouraged
- No laptops, phones, or other electronic devices during class (I'll let you know in advance if we'll need laptops for an activity) **You may use a tablet to take notes if prefer, but please only use it for note-taking.**
- Remember to bring you response card to class
- Homework 4 due on Wednesday, October 19 at 11:59pm

Review of the last class

- I measure the environmental lapse rate at three locations in an atmosphere:
Location A - environmental lapse rate is steeper (slower change in temperature with height) than adiabatic
Location B: environmental lapse rate is shallower than adiabatic
Location C: environmental lapse rate is equal to adiabatic
- (A) — A: stable, B: unstable, C: neutral
- (B) — A: unstable, B: stable, C: neutral
- (C) — A: neutral, B: stable, C: unstable
- (D) — A: neutral, B: unstable, C: stable
- (E) — A: unstable, B: neutral, C: stable

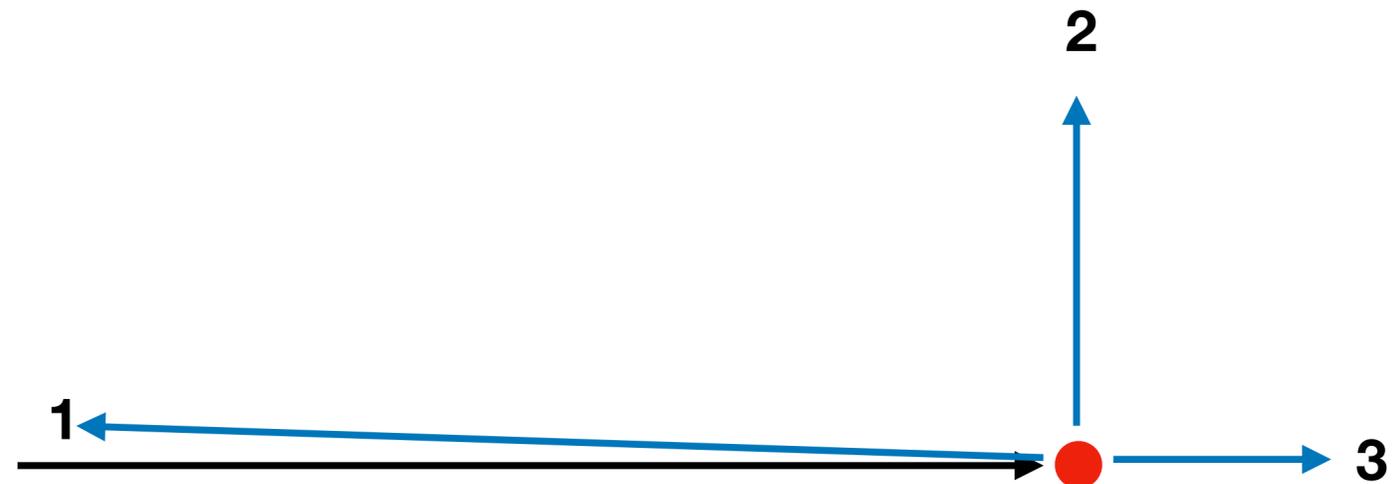
Vertical Stability

- Stable air:
 - slow change in temperature with height
 - suppresses convection
- Unstable air:
 - Rapid change in temperature with height
 - enhances convection
 - caused by surface becoming much warmer than air



Review of the last class

- A beam of light comes in from the left, and scatters off a particle. What scattering angle results in the light observed by observers 1, 2, and 3?
- (A) — 1: 0 degrees 2: 90 degrees, 3: 180 degrees
- (B) — 1: 90 degrees 2: 0 degrees, 3: 180 degrees
- (C) — 1: 180 degrees 2: 90 degrees, 3: 0 degrees
- (D) — 1: 90 degrees 2: 180 degrees, 3: 0 degrees
- (E) — 1: 0 degrees 2: 180 degrees, 3: 90 degrees



Review of the last class

- Three photons scatter off a particle:

Photon 1 has a wavelength much smaller than the particle

Photon 2 has a wavelength about the same size as the particle

Photon 3 has a wavelength much larger than the particle.

What types of scattering phase functions do we expect?

- (A) — Photon 1: mainly forward scattering, Photon 2: mainly back scattering, Photon 3: mostly isotropic scattering
- (B) — Photon 1: mainly back scattering, Photon 2: mainly forward scattering, Photon 3: mostly isotropic scattering
- (C) — Photon 1: mainly forward scattering, Photon 2: mainly isotropic scattering, Photon 3: mostly back scattering
- (D) — Photon 1: mainly isotropic scattering, Photon 2: mainly forward scattering, Photon 3: mostly back scattering
- (E) — Photon 1: mainly back scattering, Photon 2: mainly isotropic scattering, Photon 3: mostly forward scattering

Review of the last class

- Three photons scatter off a particle:

Photon 1 has a wavelength much smaller than the particle

Photon 2 has a wavelength about the same size as the particle

Photon 3 has a wavelength much larger than the particle.

What types of scattering do we expect?

- (A) — Photon 1: Rayleigh Scattering, Photon 2: Geometric Optics, Photon 3: Mie Scattering
- (B) — Photon 1: Geometric Optics, Photon 2: Rayleigh Scattering, Photon 3: Mie Scattering
- (C) — Photon 1: Rayleigh Scattering, Photon 2: Mie Scattering, Photon 3: Geometric Optics
- (D) — Photon 1: Mie Scattering, Photon 2: Rayleigh Scattering, Photon 3: Geometric Optics
- (E) — Photon 1: Geometric Optics, Photon 2: Mie Scattering, Photon 3: Rayleigh Scattering

Review of the last class

- A red photon (8000 Angstroms) and a blue photon (4000 angstroms) both encounter a nitrogen molecule in our atmosphere. Which statement is correct?
 - (A) — The blue photon is 2x more likely to scatter
 - (B) — The red photon is 2x more likely to scatter
 - (C) — The blue photon is 8x more likely to scatter
 - (D) — The red photon is 8x more likely to scatter
 - (E) — The blue photon is 16x more likely to scatter

Review of the last class

- An object's brightness temperature is:
 - (A) — The temperature I would measure if I touched it to a thermometer
 - (B) — The temperature of a blackbody that has identical specific intensity to the object
 - (C) — The temperature of a blackbody that has equal luminosity to the object
 - (D) — The temperature required for incoming flux and outgoing flux to perfectly balance

Temperatures

- Brightness Temperature (T_b): the temperature that a blackbody would have in order to produce the observed radiation at some particular frequency
- Effective Temperature (T_{eff}): if you can integrate the flux from a source over all frequencies, then effective temperature is the temperature of a blackbody that would have the same total luminosity
- Equilibrium Temperature (T_{eq}): temperature derived by balancing incoming solar radiation (mostly visible) and outgoing radiation (mostly thermal infrared)



Radiative Equilibrium Equation

- Calculate the temperature an object should be based on its size, distance from the Sun, and reflectivity
- This lets us:
 - determine expected physical state of volatiles
 - determine upper limit for an object's size
 - identify presence of excess energy at surface



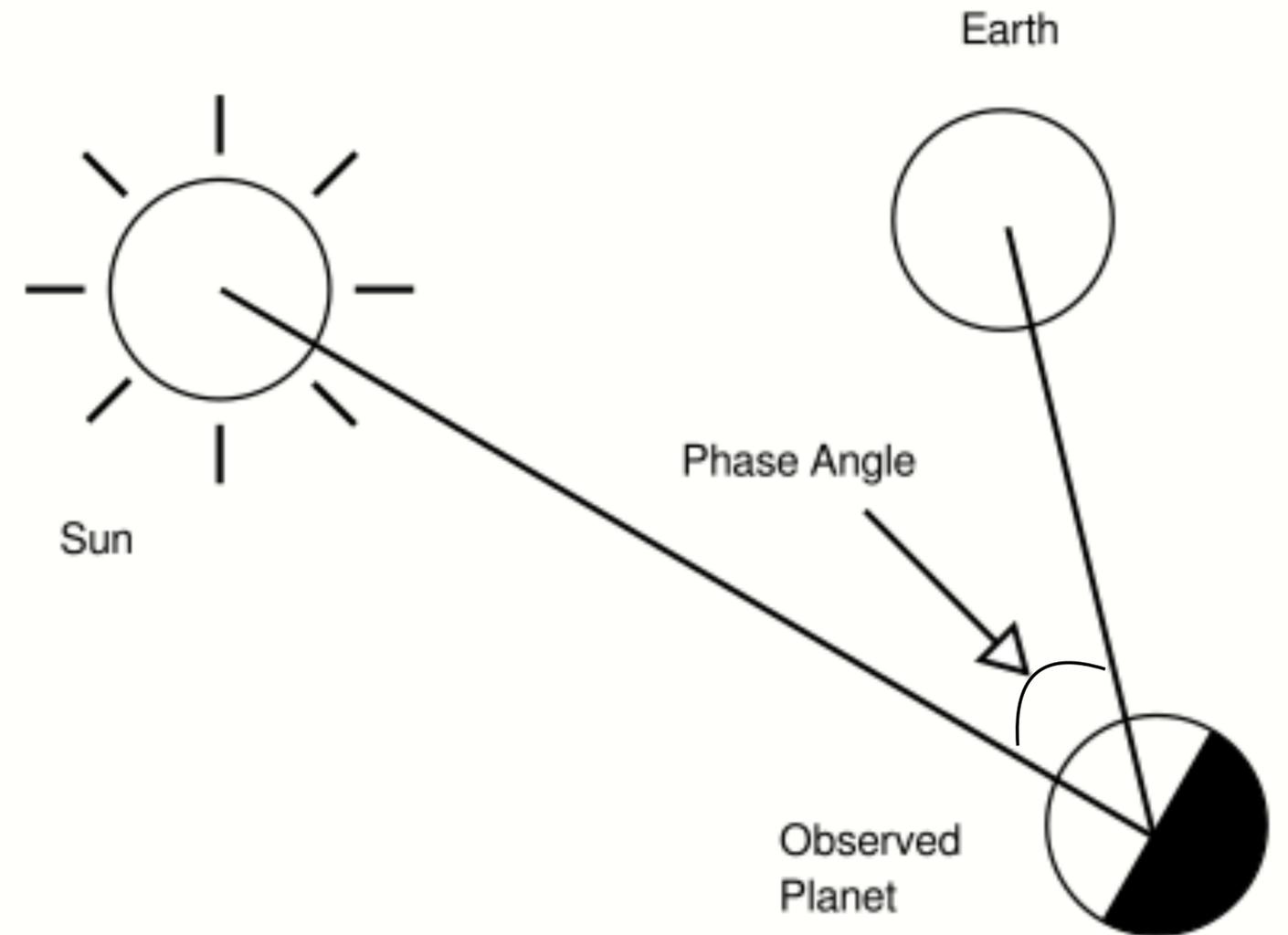
Albedo

- Albedo: fraction of incoming radiation that is reflected (and scattered) back out into space
- Monochromatic albedo: A_ν
- Integrated over all frequencies = Bond albedo: A_b



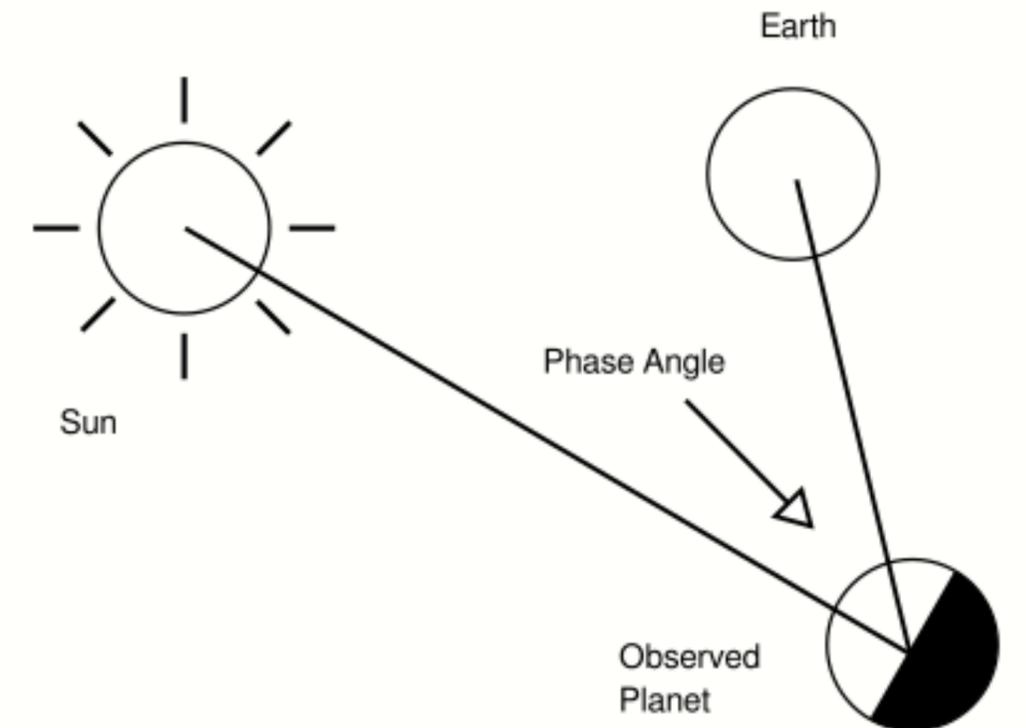
Phase Angle

- To characterize how a body scatters incident light, need to consider the phase angle:
 - angle from light source to object of interest to observer
 - for example: Sun to Jupiter to our telescope on Earth
- Note: NOT the same convention as scattering angle



Response Card Question

- From a telescope on Earth, we observe a planet in our Solar System at a phase angle of 160 degrees. Which planet did we observe?
 - (A) — Venus
 - (B) — Mars
 - (C) — Jupiter
 - (D) — Saturn

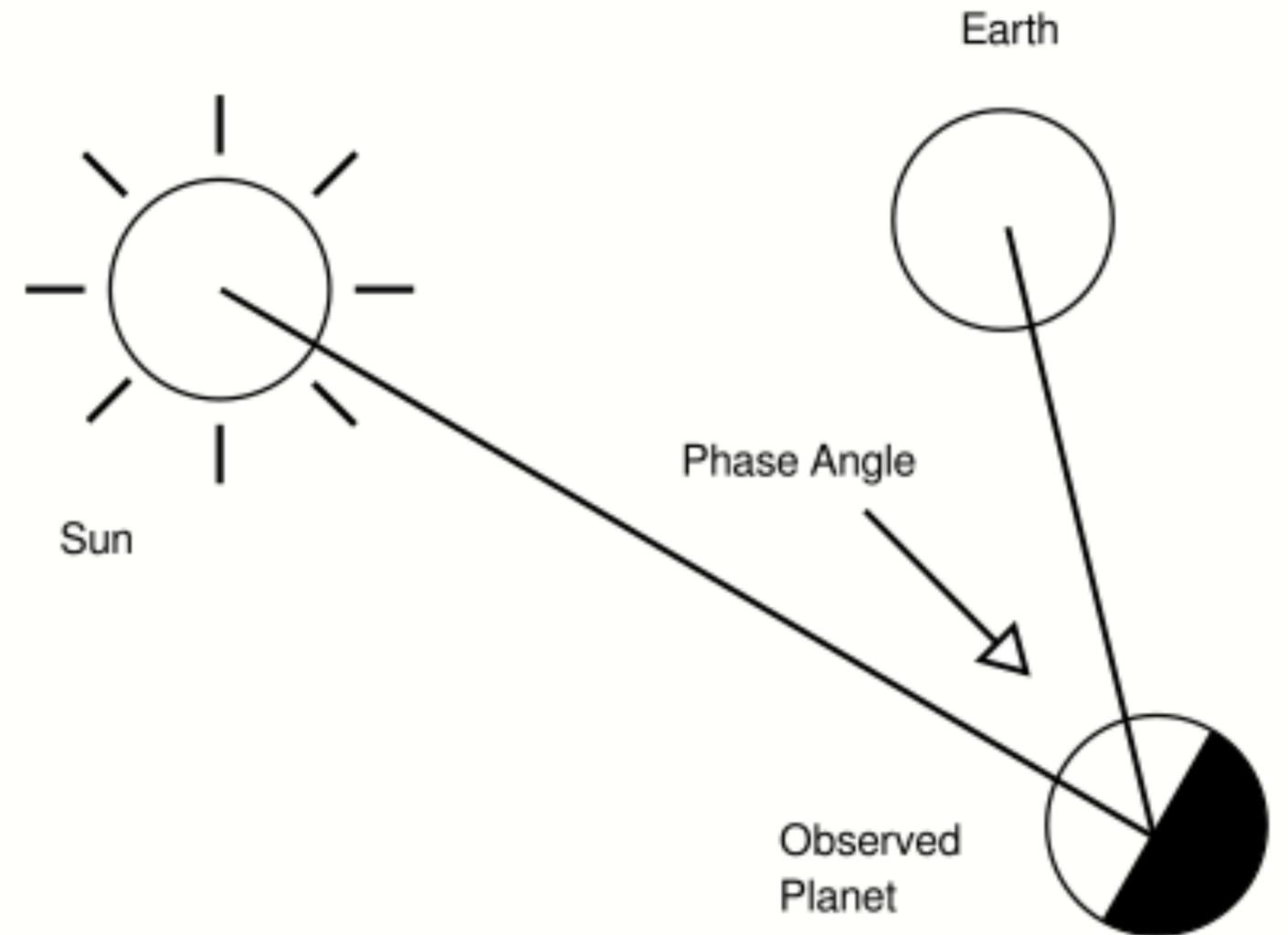


Phase Integral

- The phase integral (q_{ph}) integrates over the phase angle to find the total amount of scattering+reflectance:

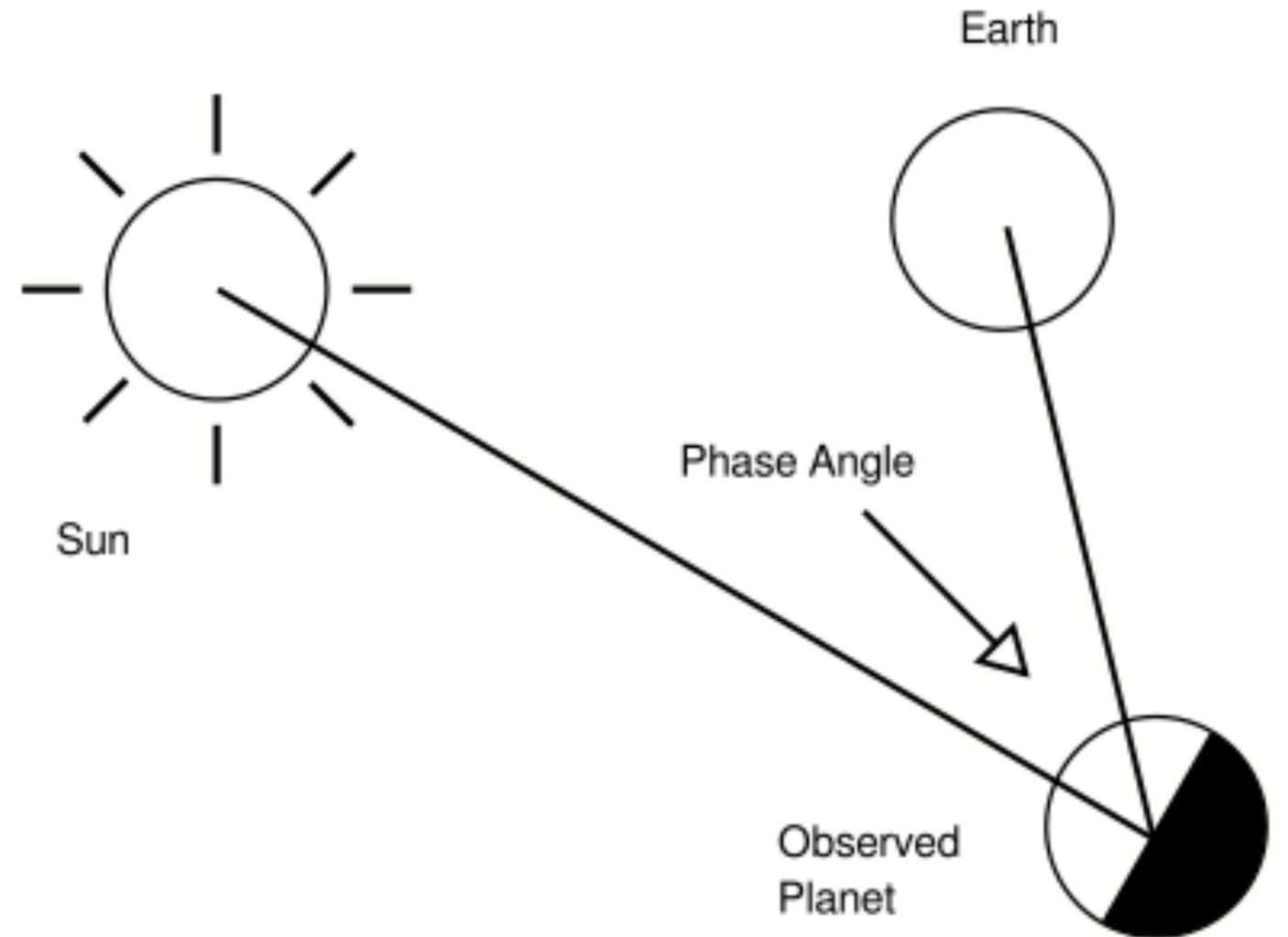
$$q_{ph} = 2 \int_0^\pi \frac{F(\phi)}{F(\phi = 0)} \sin \phi d\phi$$

- Can measure q_{ph} for Mercury, Venus, and the Moon from Earth
 - Need a spacecraft for the outer planets



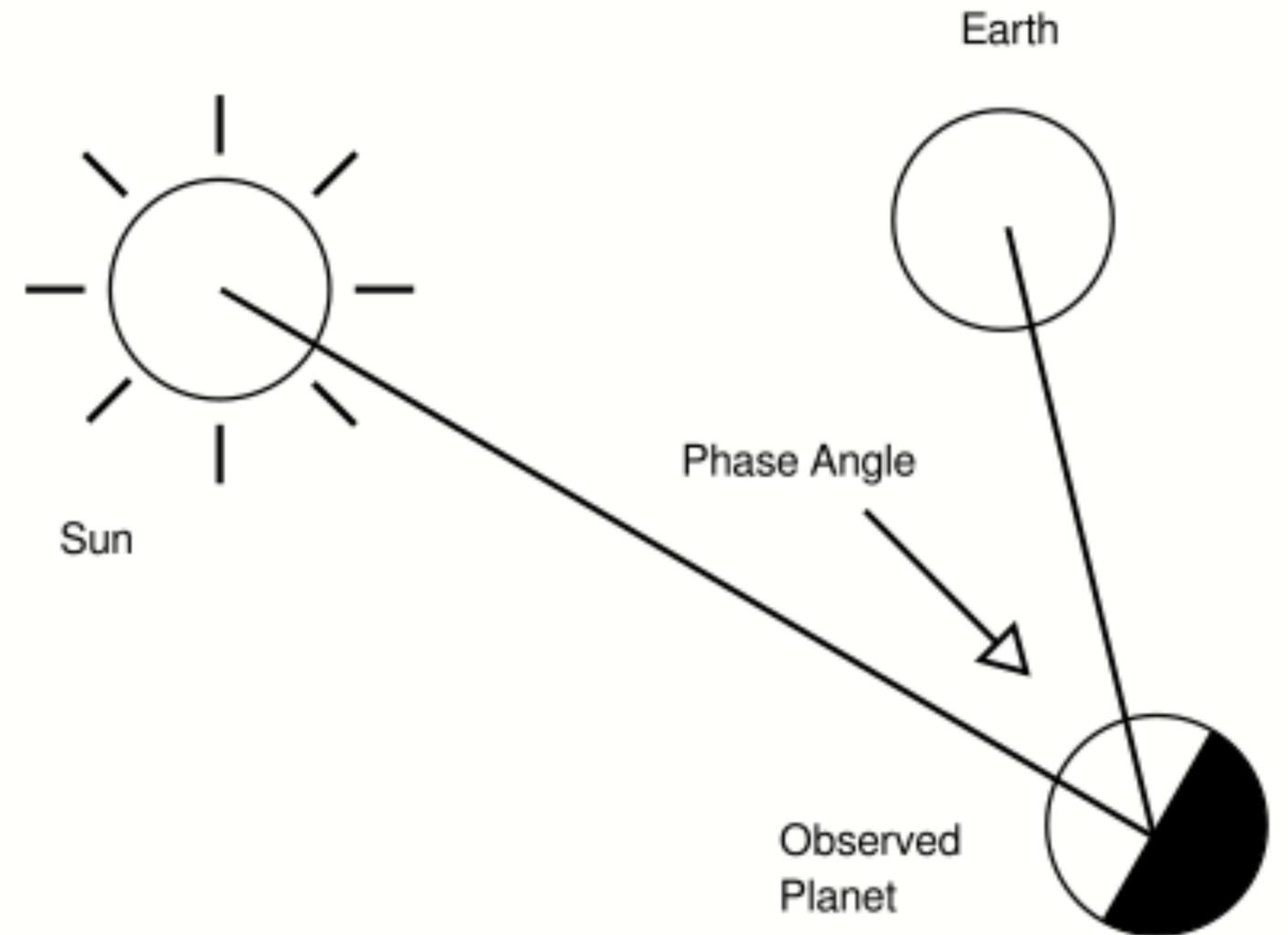
Albedo

- $A_b = A_0 q_{ph}$
- A_b : bond albedo
- A_0 : geometric albedo (“head-on” reflectance)
- Geometric albedo is the ratio of actual brightness at zero phase angle to that of an idealized, flat, fully reflecting, diffusely scattering surface/atmosphere:
 - A Lambertian sphere
 - (a ping-pong ball)



Emissivity

- Ratio of energy radiated by a surface to energy radiated by a blackbody at same temperature
 - A true blackbody has $\epsilon = 1$
 - Everything else has $\epsilon < 1$
- $\epsilon_{\nu} = 1 - A_{\nu}$



Equilibrium Temperature

- Assume the same amount of energy that goes into a planet in a second also leaves that planet in a second
 - The planet is not currently warming or cooling
- $E_{in} = E_{out}$
- Energy in is the flux from the Sun at the distance (d) of the planet, multiplied by the cross-sectional area of the planet, multiplied by the fraction of that light that's not reflected/scattered:

$$E_{in} = \frac{L_{\odot}}{4\pi d^2} \pi R^2 (1 - A_b)$$



Equilibrium Temperature

- If we assume the temperature is uniform across the surface, energy out is the flux of a blackbody at the equilibrium temperature, multiplied by the surface area of the planet, multiplied by the emissivity:

$$E_{out} = \sigma T_{eq}^4 4\pi R^2 \epsilon$$

- Setting these two equal:

$$E_{in} = E_{out} = \sigma T_{eq}^4 4\pi R^2 \epsilon = \frac{L_{\odot}}{4\pi d^2} \pi R^2 (1 - A_b)$$

$$T_{eq} = \left(\frac{L_{\odot} (1 - A_b)}{16\pi\sigma\epsilon d^2} \right)^{\frac{1}{4}}$$



In Class Activity: Equilibrium Temperature

- $T_{eq} = \left(\frac{L_{\odot}(1 - A_b)}{16\pi\sigma\epsilon d^2} \right)^{\frac{1}{4}}$

- Stefan-Boltzmann Constant: $\sigma = 5.67 \times 10^{-5} \frac{\text{erg}}{\text{cm}^2 \text{s K}^4}$

- (1) What is the equilibrium temperature of Earth?
- (2) What is the equilibrium temperature of Pluto (at 40 AU)?



In Class Activity: Equilibrium Temperature

- $T_{eq} = \left(\frac{L_{\odot}(1 - A_b)}{16\pi\sigma\epsilon d^2} \right)^{\frac{1}{4}}$

- Stefan-Boltzmann Constant: $\sigma = 5.67 \times 10^{-5} \frac{erg}{cm^2 s K^4}$

- (1) What is the equilibrium temperature of Earth?

- Assume albedo of Earth is about a half, and emissivity is about 1. Earth is 1AU from the Sun, then we just plug in numbers:

$$T_{eq} = \left(\frac{L_{\odot}(1 - A_b)}{16\pi\sigma\epsilon d^2} \right)^{\frac{1}{4}} = \left(\frac{(4 \times 10^{33} \text{ erg/s})(1 - (0.5))}{16\pi(5.67 \times 10^{-5} \text{ erg/cm}^2/\text{s/K})(1)(1.5 \times 10^{13} \text{ cm})^2} \right)^{\frac{1}{4}}$$

$$T_{eq} = \left(\frac{2 \times 10^{33}}{16 \times 3 \times 6 \times 2 \times 10^{-5+26}} \right)^{\frac{1}{4}} = \left(\frac{2 \times 10^{33}}{600 \times 10^{21}} \right)^{\frac{1}{4}} = \left(\frac{1}{300} 10^{12} \right)^{\frac{1}{4}} = (3 \times 10^9)^{\frac{1}{4}} = (30 \times 10^8)^{\frac{1}{4}} = 2.5 \times 10^2 = 250K$$

In Class Activity: Equilibrium Temperature

- $T_{eq} = \left(\frac{L_{\odot}(1 - A_b)}{16\pi\sigma\epsilon d^2} \right)^{\frac{1}{4}}$

- (2) What is the equilibrium temperature of Pluto (at 40 AU)?

- Let's assume emissivity and albedo stay about the same, so the only thing that changes is the distance.

$$T_{eq} \propto \frac{1}{\sqrt{d}} = \frac{1}{\sqrt{40}} \approx \frac{1}{6}$$

So the equilibrium temperature on Pluto will be 6 times smaller than that on Earth:

$$T_{eq} = \frac{250K}{6} = 40K \quad (\text{bring a jacket})$$

Respond Card Question

- Earth has an equilibrium temperature of (about) 300 K. What is the equilibrium temperature of a (hypothetical) Earth-like planet orbiting Saturn ($a=10$ AU)?
 - (A) — 900 K
 - (B) — 600 K
 - (C) — 300 K
 - (D) — 100 K
 - (E) — 30 K

$$T_{eq} = \left(\frac{L_{\odot}(1 - A_b)}{16\pi\sigma\epsilon d^2} \right)^{\frac{1}{4}}$$

Response Card Question

- We find an Earth-like exoplanet orbiting a star with 1/100 the luminosity of our Sun but the planet has the same equilibrium temperature as Earth. What is the distance between this exoplanet and its star?
 - (A) — 100 AU
 - (B) — 10 AU
 - (C) — 1 AU
 - (D) — 0.1 AU
 - (E) — 0.01 AU

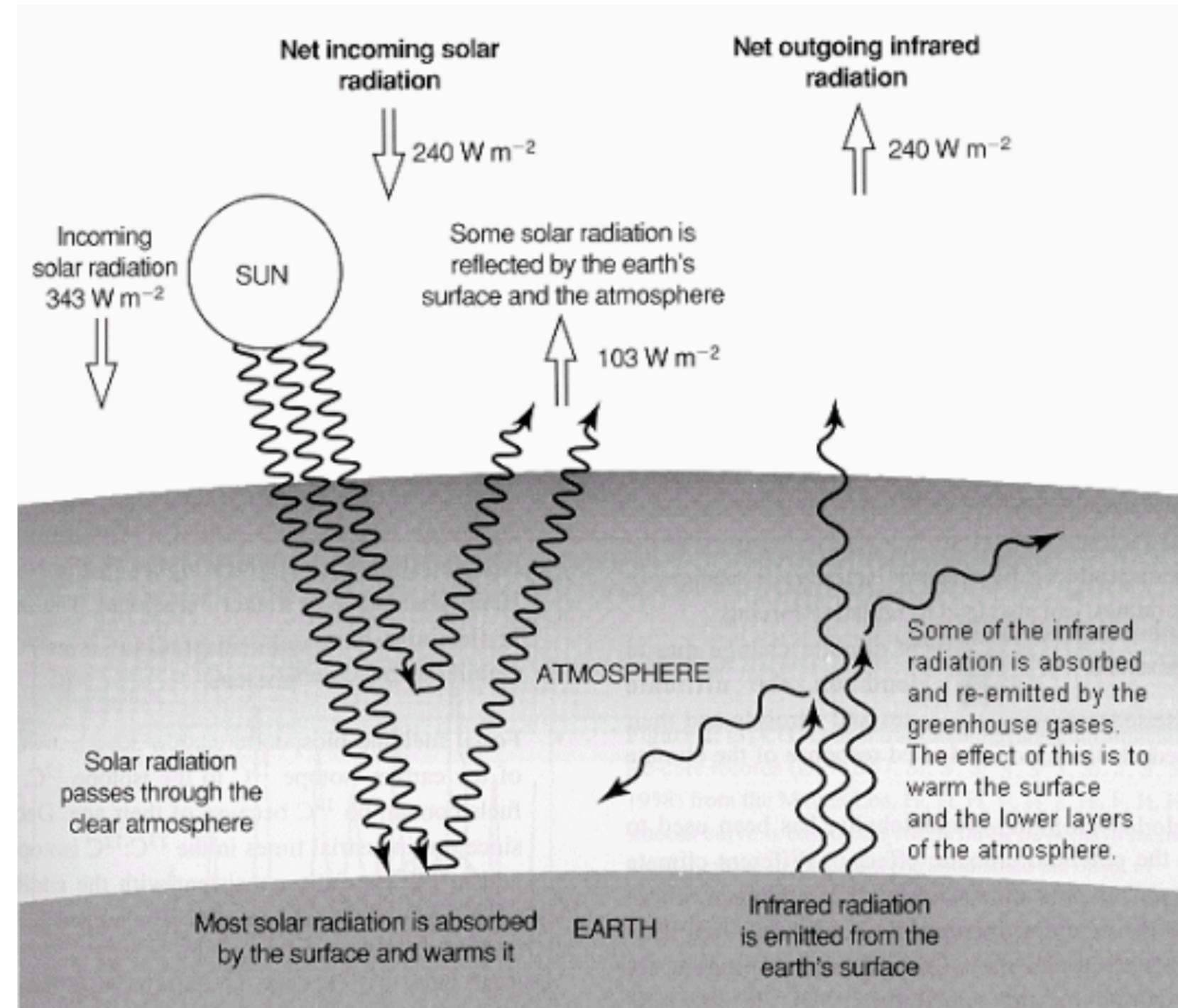
$$T_{eq} = \left(\frac{L_{\odot}(1 - A_b)}{16\pi\sigma\epsilon d^2} \right)^{\frac{1}{4}}$$

Break

05:00

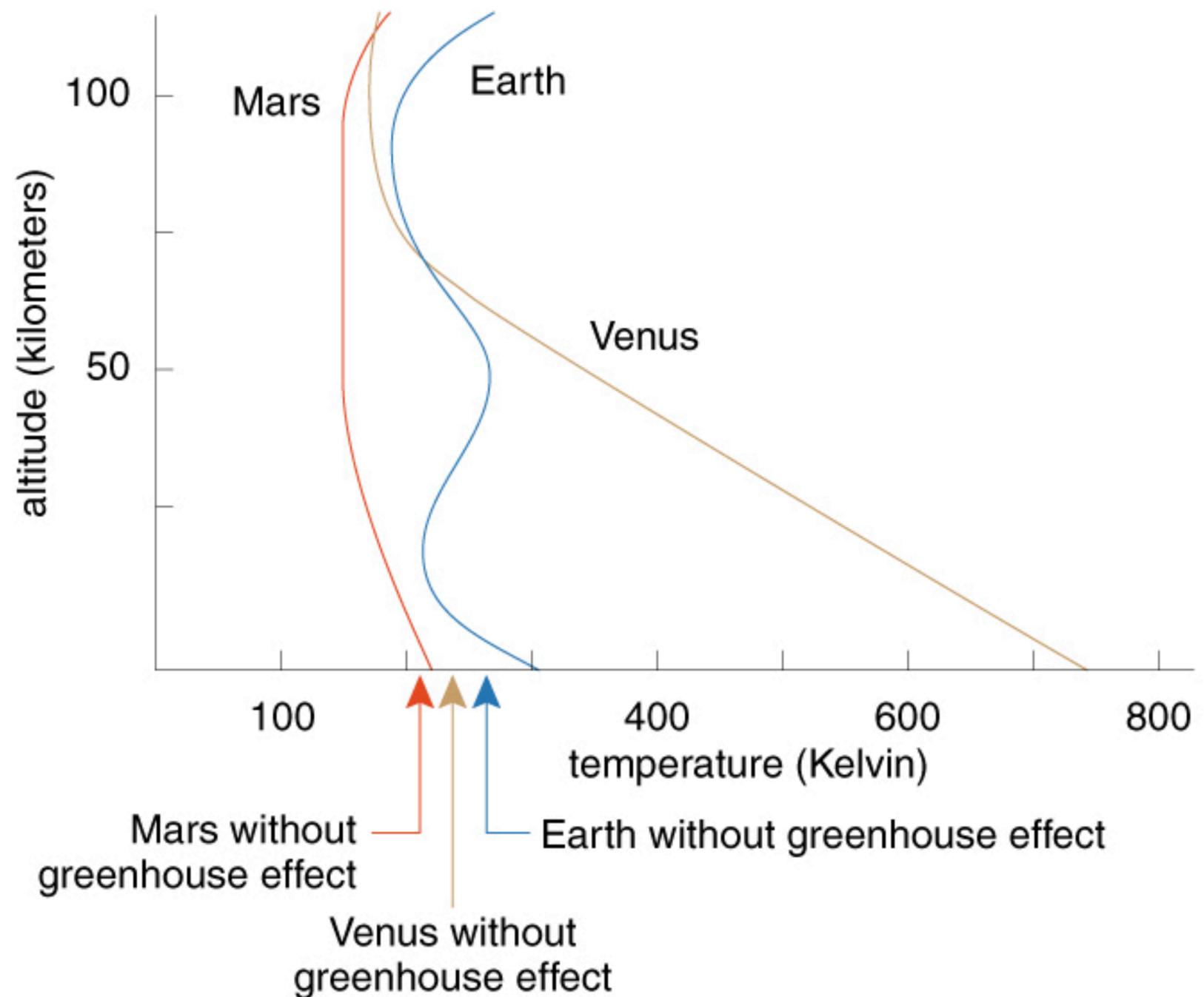
Earth's Energy Budget

- For all the solar energy that is received at Earth:
 - 40% is reflected to space
 - 40% is absorbed by ground (25% re-radiated to atmosphere)
 - 18% absorbed in troposphere
 - 2% absorbed above troposphere



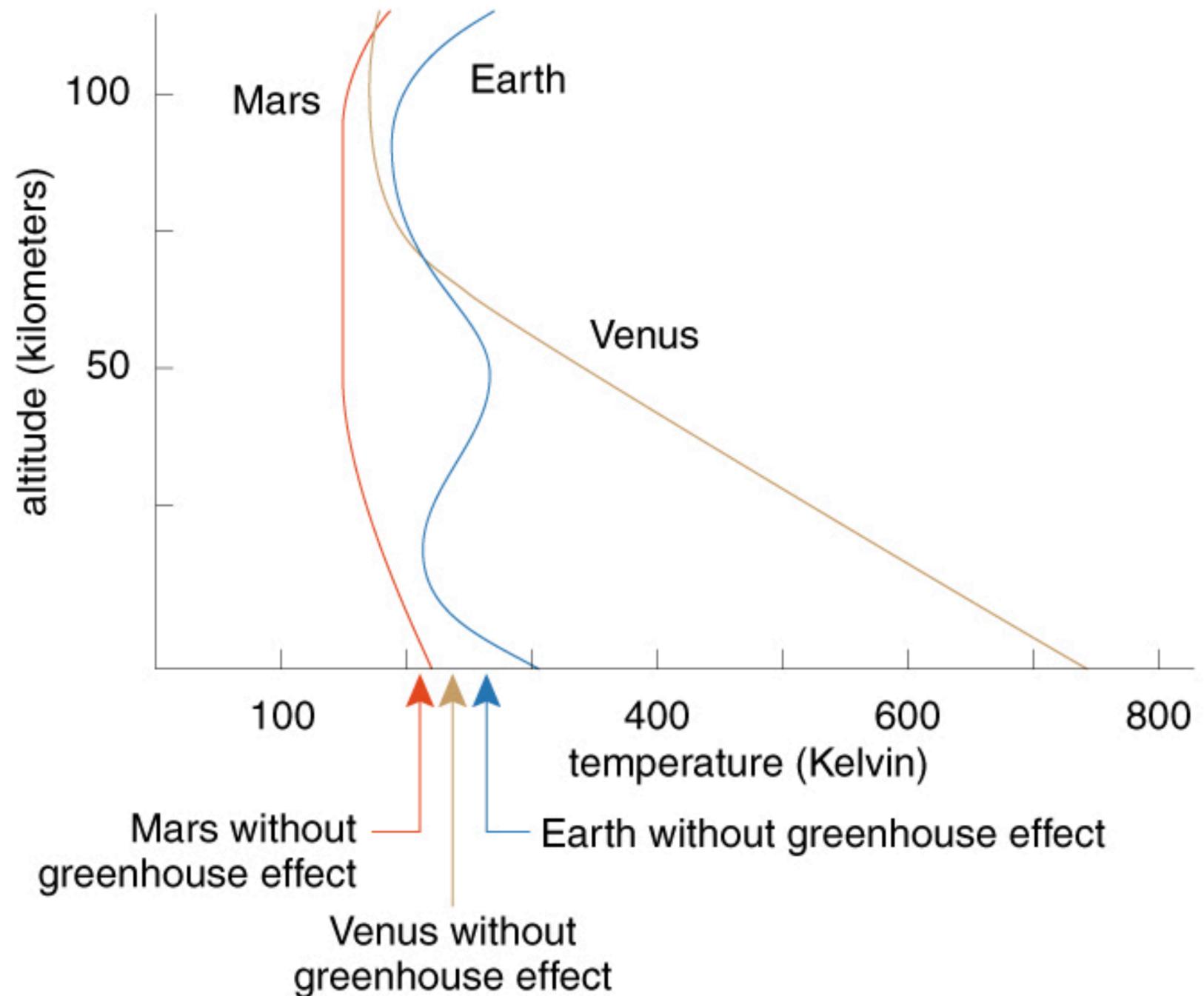
Greenhouse Effect

- Surface temperatures of Venus, Earth, Mars, and Titan are higher than expected from equilibrium according to their albedos and distance from Sun
- Atmosphere is quasi-transparent to solar UV/visible/NIR
- Sunlight heats surface and lower atmosphere, which radiate as blackbodies at the heated temperatures
 - This re-radiation is in the mid-IR (thermal IR, ~10 microns)
- Some atmospheric species (CO_2 , H_2O , CH_4) are semiopaque to this IR radiation)



Greenhouse Effect

- To compute effect of greenhouse effect, use the “two-stream” approximation:
 - First stream: visible light going to surface
 - Second stream: infrared light going back up
- Assume radiative equilibrium (flux in = flux out) for every layer in the atmosphere
- Compute radiative transfer through each layer (integrating) and impose boundary conditions at surface and top of atmosphere



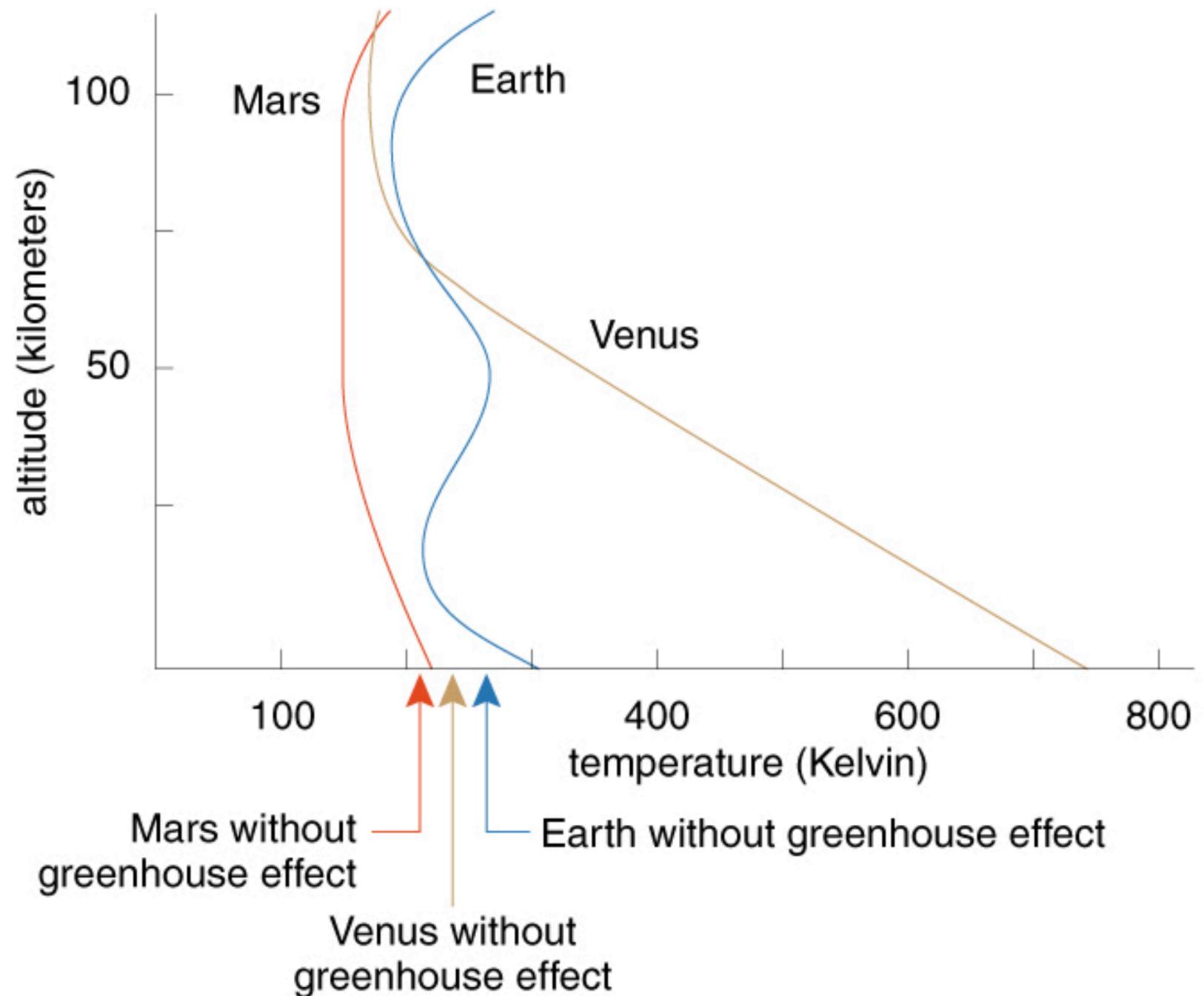
Greenhouse Effect

• Result:

$$T_g^4 = T_{eq}^4 \left(1 + \frac{3}{4} \tau_g \right)$$

• T_g : ground temperature

• τ_g : optical depth (in the infrared) to the ground



Clouds

- Clouds play an important role in atmospheric heat balance and thermal structure
- The formation of clouds involves the fields of microphysics and thermodynamics
- Suspended particles can originate from:
 - condensation
 - chemical/photochemical reactions
 - outgassing
 - lifting from the surface
 - particle bombardment of atoms and molecules in upper atmosphere



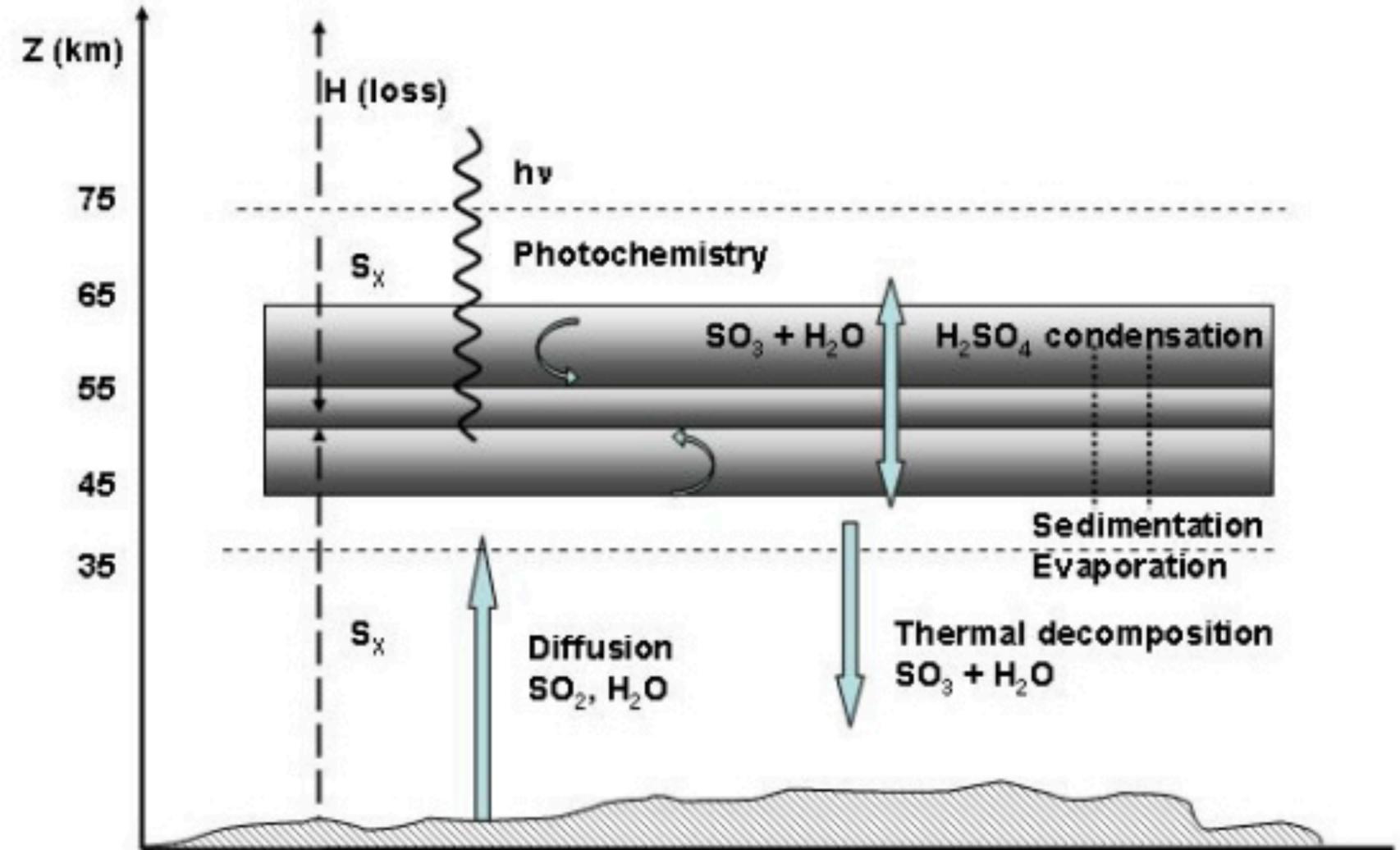
Atmospheric Cycles

- Gases continually being injected into atmosphere:
 - from surface
 - from photochemical reactions in upper atmosphere
- Gases continually being removed from atmosphere:
 - by chemical reactions and deposition (e.g. precipitation/rain)
- mass flows into bulk atmosphere give rise to “cycles” that affect cloud and aerosol formation
- (Aerosols: liquid or solid particles suspended in a gas)



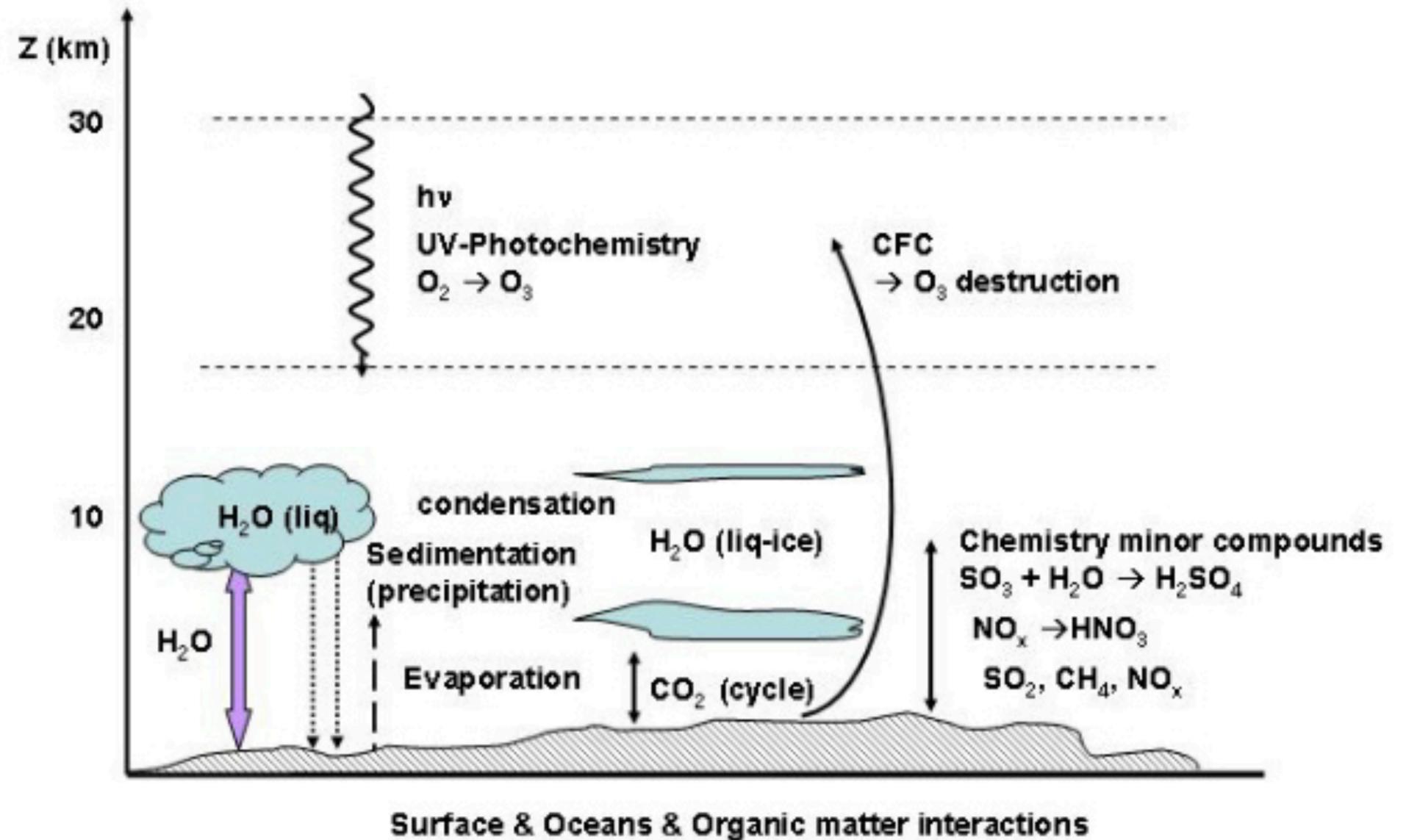
Venus

- Sulfur compounds released from surface interact with photo dissociated oxygen and water in the upper atmosphere to produce sulfuric acid



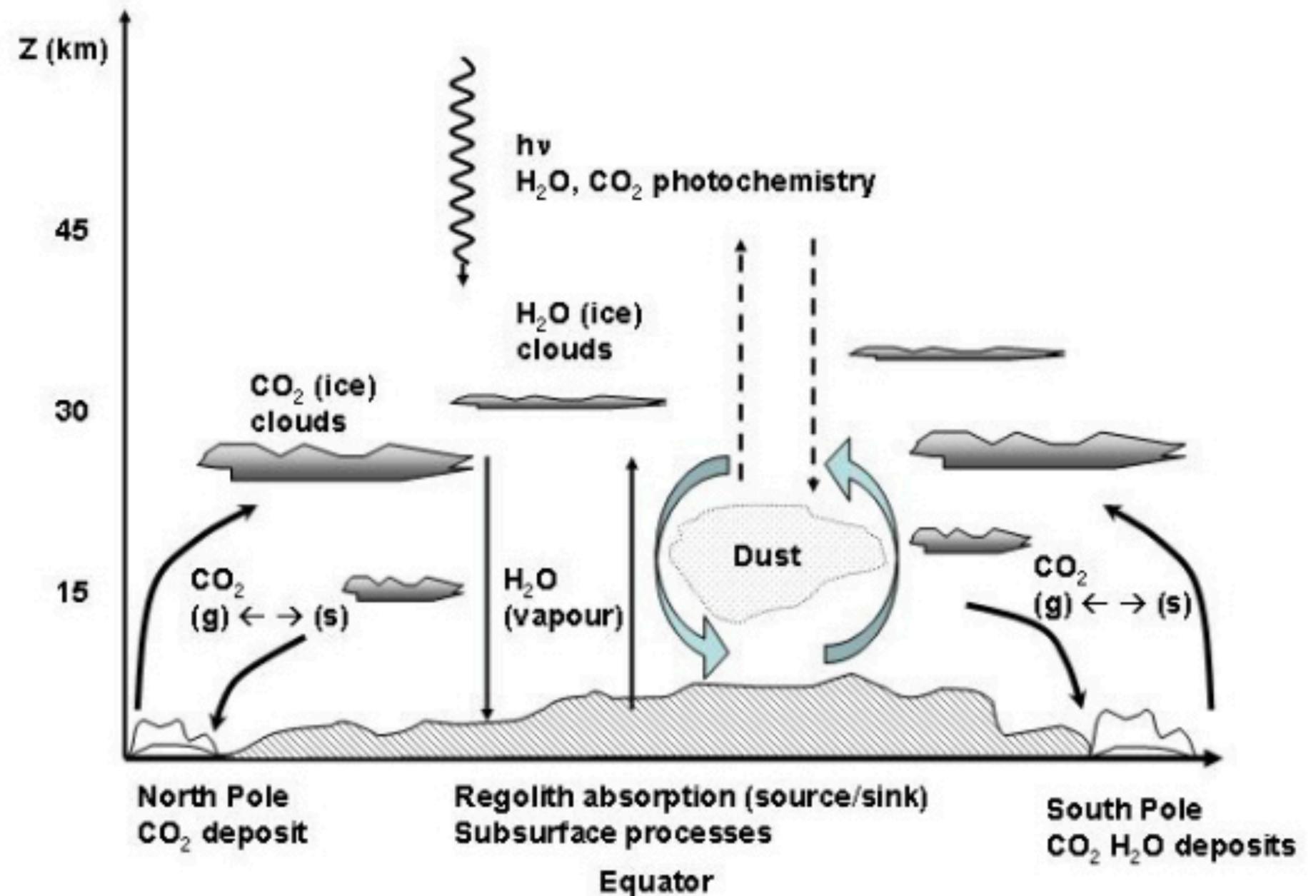
Earth

- Water vapor abundance is highly variable because of variations in surface temperature (liquid, gas, solid) over diurnal and annual timescales
- Other cycles:
 - Carbon dioxide
 - nitrogen
 - sulfur



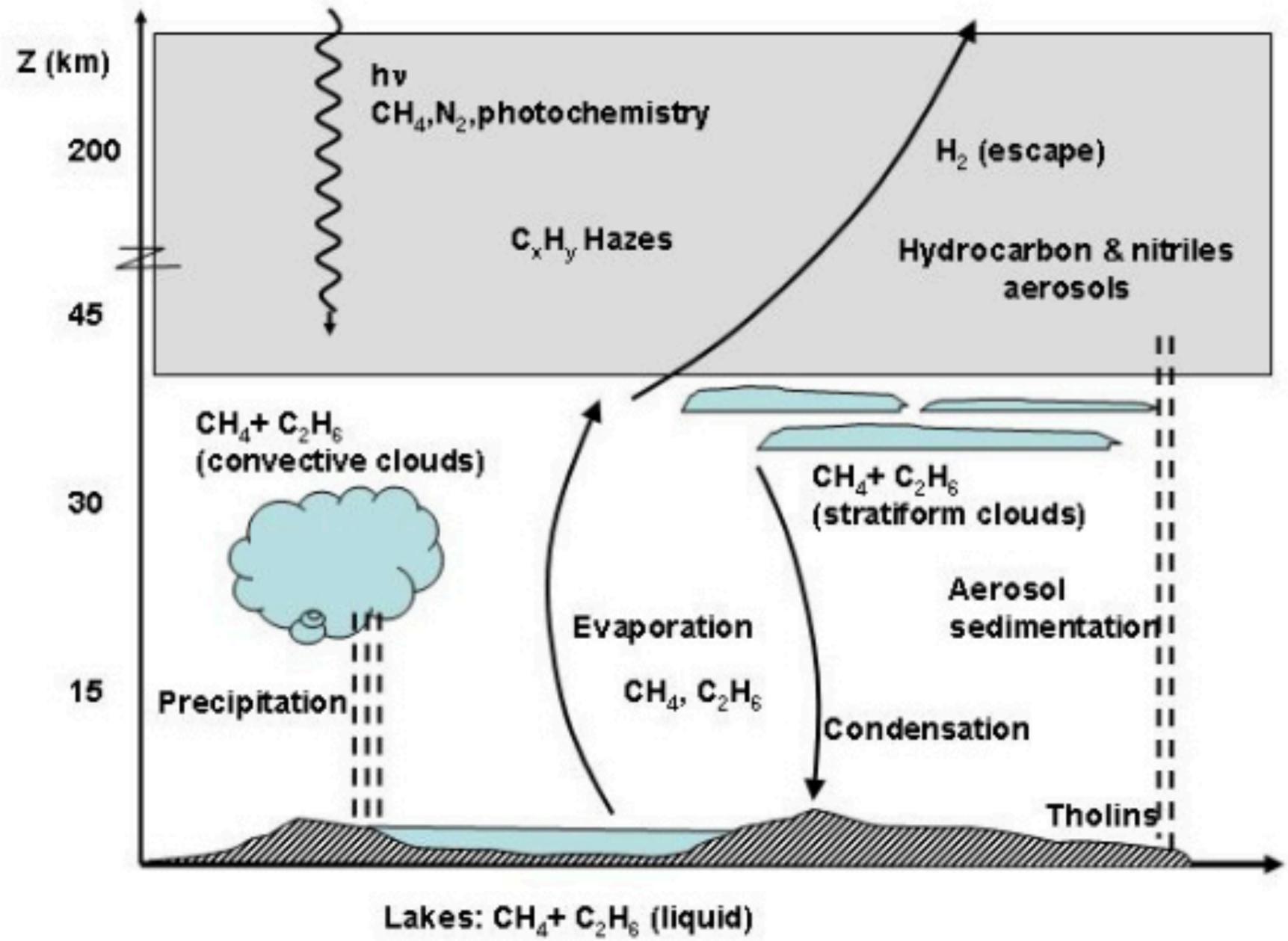
Mars

- 3 main cycles: carbon dioxide, water, dust
- Injection of airborne dust represents a source of opacity for solar radiation
- Also serves as condensation nuclei for cloud formation
- Alters radiative balance and affects atmospheric dynamics



Titan

- Hazes are a result of photochemical reactions in upper atmosphere
- Methane subject to cycle of condensation and sublimation (methological cycle)
- Possible additional source of methane: outgassing from cryovolcanism



For next time

- Homework 4 due on Wednesday, October 19 at 11:59pm
- Reading: Planetary Science, 3.3.2