

# Planetary Atmospheres

## Structure

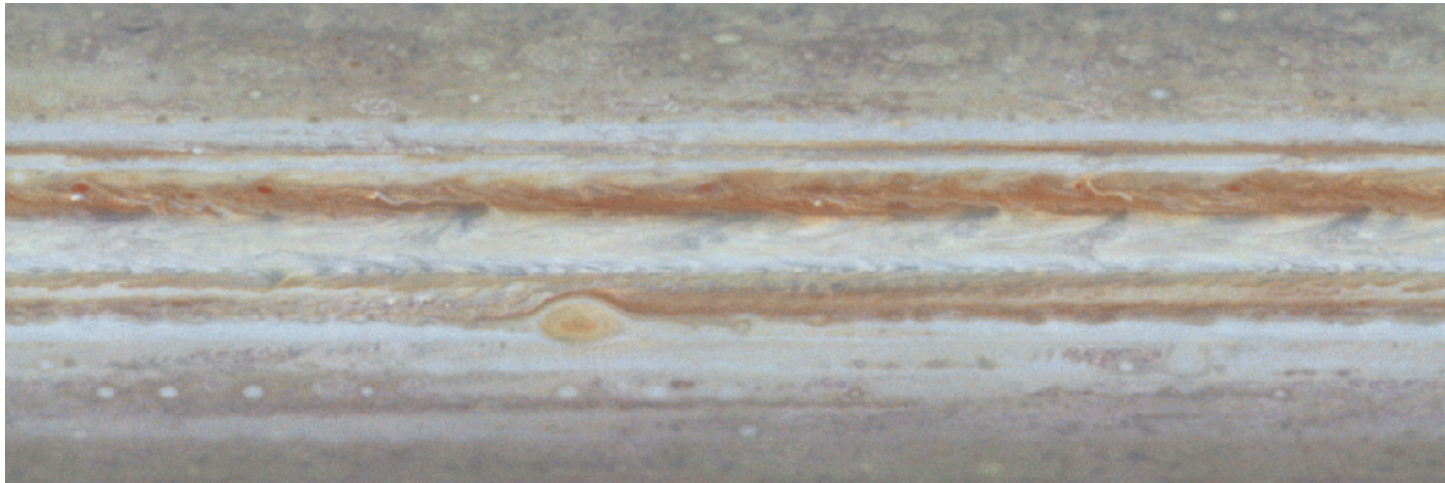
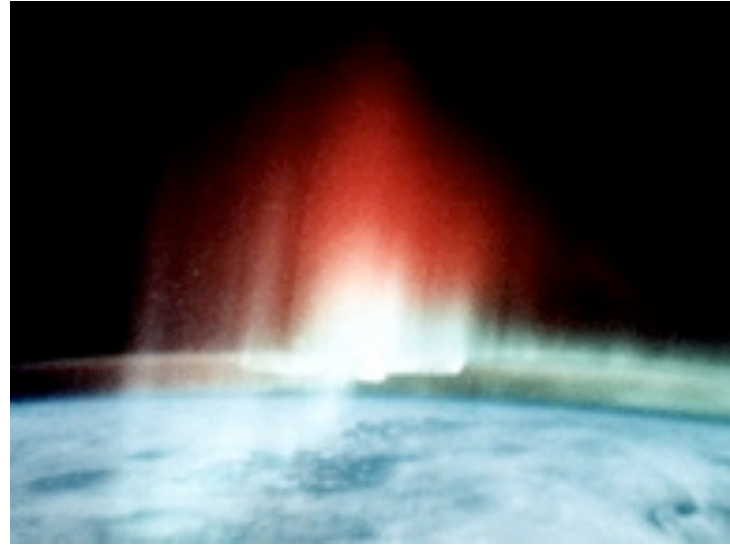
Composition

Clouds

Photochemistry

Meteorology

Atmospheric Escape



# Structure

## Generalized Hydrostatic Equilibrium

$$P(z) = P(0)e^{-\int_0^z dr / H(r)} \quad \rho(z) = \rho(0)e^{-\int_0^z dr / H^*(r)}$$

## Generalized Pressure Scale Height

$$H(z) = \frac{kT(z)}{g_p(z)\mu_a(z)m_{amu}}$$

## Generalized Density Scale Height

$$\frac{1}{H^*(z)} = \frac{1}{T(z)} \frac{dT(z)}{dz} + \frac{g_p(z)\mu_a(z)m_{amu}}{kT(z)}$$

# Structure

Note: For an Isothermal Atmosphere  
(or region of an atmosphere):

$$H(z) = H^*(z)$$

Since  $\frac{dT(z)}{dz} = 0$

Remember that  $g_p(z) = \frac{GM_p}{r^2} = \frac{GM_p}{(R_p + z)^2}$

\* So at small altitudes  $r \Rightarrow R_p$  and  $g_p(z) \cong g_p(R_p)$

# Structure

Most planets have near-surface scale heights ranging between ~10-25 km due to the similar ratios of

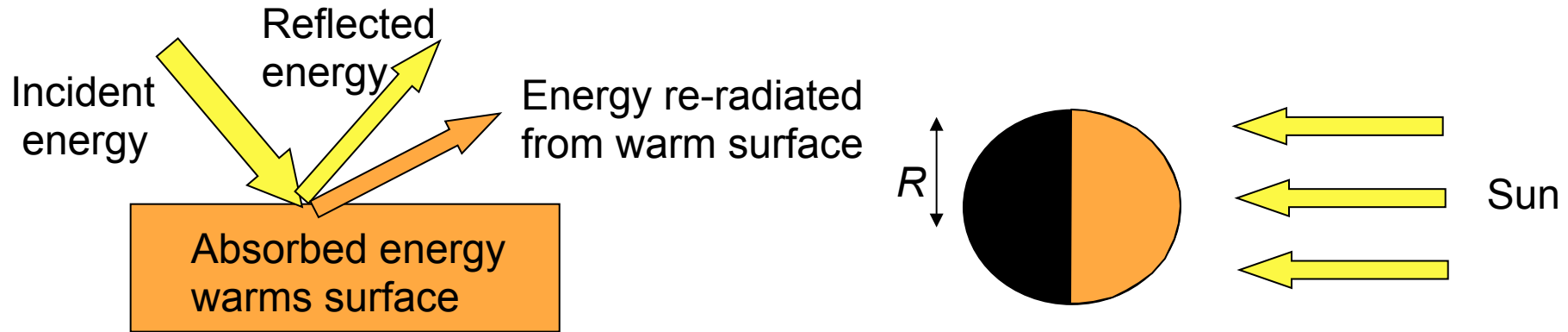
$$T/(g_p \mu_a)$$

	Venus	Earth	Mars	Jupiter	Saturn	Uranus	Neptune
$T_{surf}$ (K)	737	288	215	165*	135*	76*	72*
Bond Albedo	0.75	0.31	0.25	0.34	0.34	0.29	0.31
$H$ (km)	16	8.5	11	24	47	25	23

\* Temperature at 1 bar pressure

# Thermal Structure: Surface

What determines a planet's surface temperature?



$$P_{in} = (1 - A_b) \pi R^2 \frac{F_{\odot}}{r_{\odot AU}^2}$$

$$P_{out} = 4\pi R^2 \epsilon \sigma T^4$$

$A_b$  is Bond albedo,  $F_{\odot}$  is solar flux at Earth's distance,  $r_{\odot}$  is distance of planet to Sun,  $\epsilon$  is emissivity,  $\sigma$  is Stefan's constant ( $5.67 \times 10^{-8} \text{ Wm}^{-2}\text{K}^{-4}$ )

Balancing energy in and energy out yields:

$$T_{eq} = \left( \frac{F_{\odot}}{r_{\odot AU}^2} \frac{(1 - A_b)}{4\epsilon\sigma} \right)^{1/4}$$

# Thermal Structure: Surface

- Solar constant  $F_{\odot} = 1300 \text{ Wm}^{-2}$
- Earth (Bond) albedo  $A_b = 0.3$ ,  $\varepsilon = 0.9$
- Equilibrium temperature = 263 K
- How reasonable is this value?

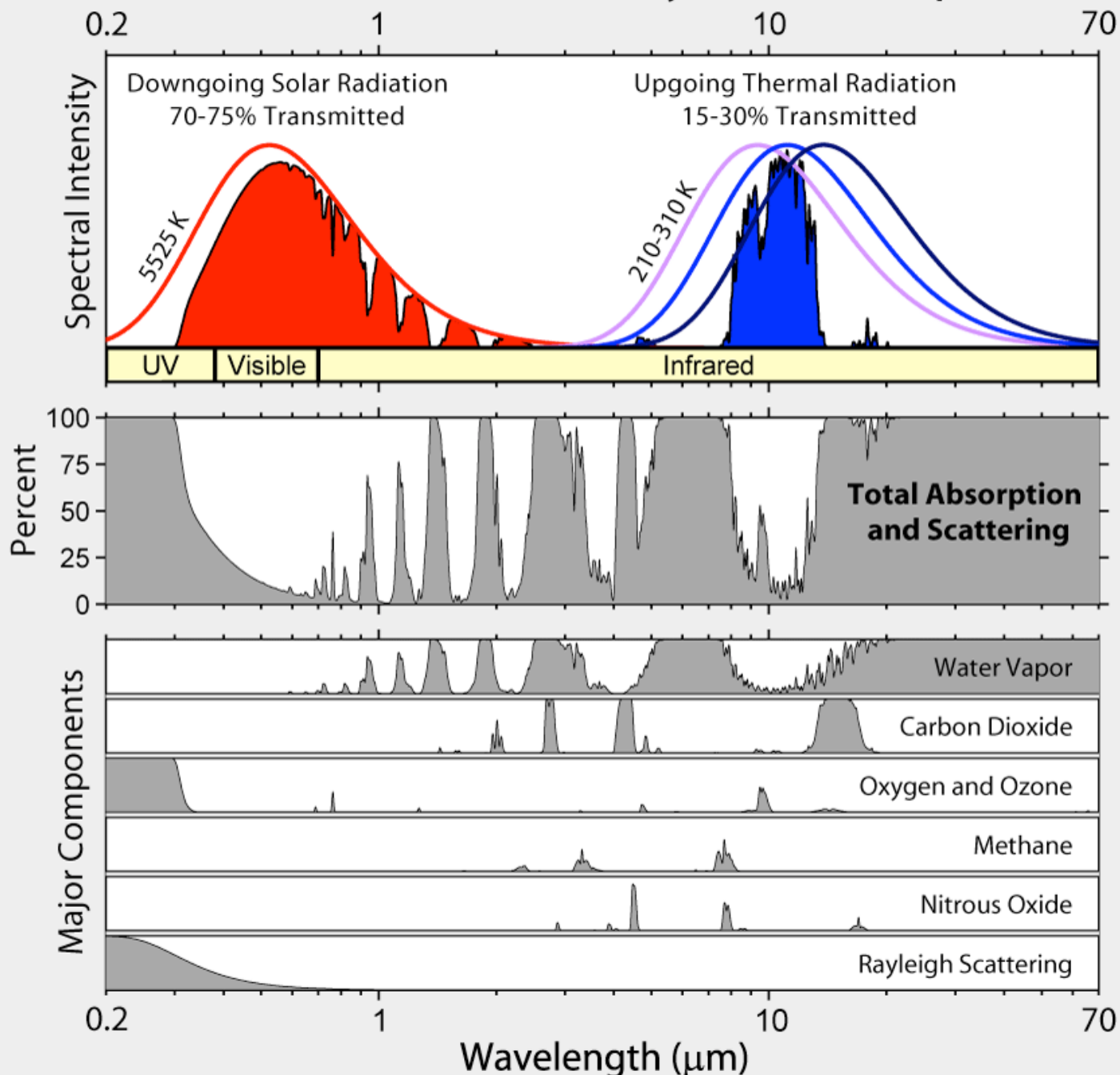
Body	Mercury	Venus	Earth	Mars
$A_b$	0.12	0.75	0.3	0.25
$T_{eq}$	446	238	263	216
Actual $T$	100-725	737	288	215

- How to explain the discrepancies?
- Has the Sun's energy stayed constant with time?

# Thermal Structure: Greenhouse Effect

- Atmosphere is more or less transparent to radiation (photons) depending on wavelength – **opacity**
- Opacity is low at visible wavelengths, high at infrared wavelengths due to absorbers like water vapor, CO<sub>2</sub>
- Incoming light (visible) passes through atmosphere with little absorption
- Outgoing light is infrared (since the surface temperature is lower) and is absorbed by atmosphere
- So atmosphere heats up
- Venus suffered from a *runaway* greenhouse effect – surface temperature got so high that water was unstable, so no CO<sub>2</sub> could dissolve and form carbonates as on Earth

# Radiation Transmitted by the Atmosphere



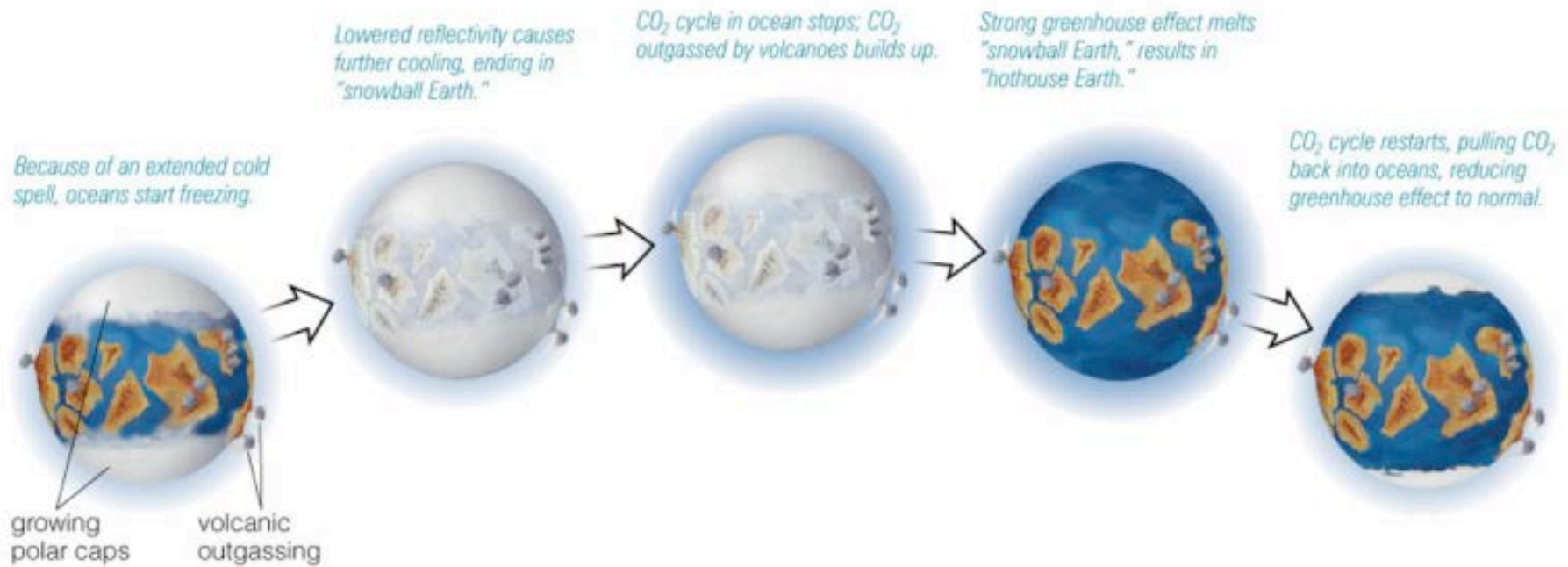


# Thermal Structure: Albedo Effects

- Fraction of energy reflected (not absorbed) by surface is given by the albedo  $A$  ( $0 < A < 1$ )
- Coal dust has a low albedo, ice a high one
- The albedo can have an important effect on surface temperature
- E.g. ice caps grow, albedo increases, more heat is reflected, surface temperature drops, ice caps grow further . . . runaway effect!
- This mechanism is thought to have led to the Proterozoic **Snowball Earth**
- **Aside: how might clouds affect planetary albedo?**

# Recurring Snowball Earth?

## Five Stages of "Snowball" Earth



# Atmospheric Thermal Structure

The atmospheric temperature profile is governed by the efficiency of energy transport, which largely depends on optical depth,  $\tau_v$ . Remember that heating by solar radiation is a 'top-down' process.

Optical depth (or transparency) is determined by physical and chemical processes in the atmosphere and can change in time and in altitude.

# Atmospheric Thermal Structure

Other factors to consider:

Clouds can change the albedo, the optical depth, and the local temperature (via release/absorption of latent heat).

Surface variations/composition can affect albedo and surface temperatures depend on the thermal properties of materials and their chemical interactions with the atmosphere

Geologic processes such as volcanism can greatly impact the composition, as well as chemistry and albedo (via dust grains and aerosols) of the atmosphere.