Energy Balance and Climate

EES 3310/5310

Global Climate Change

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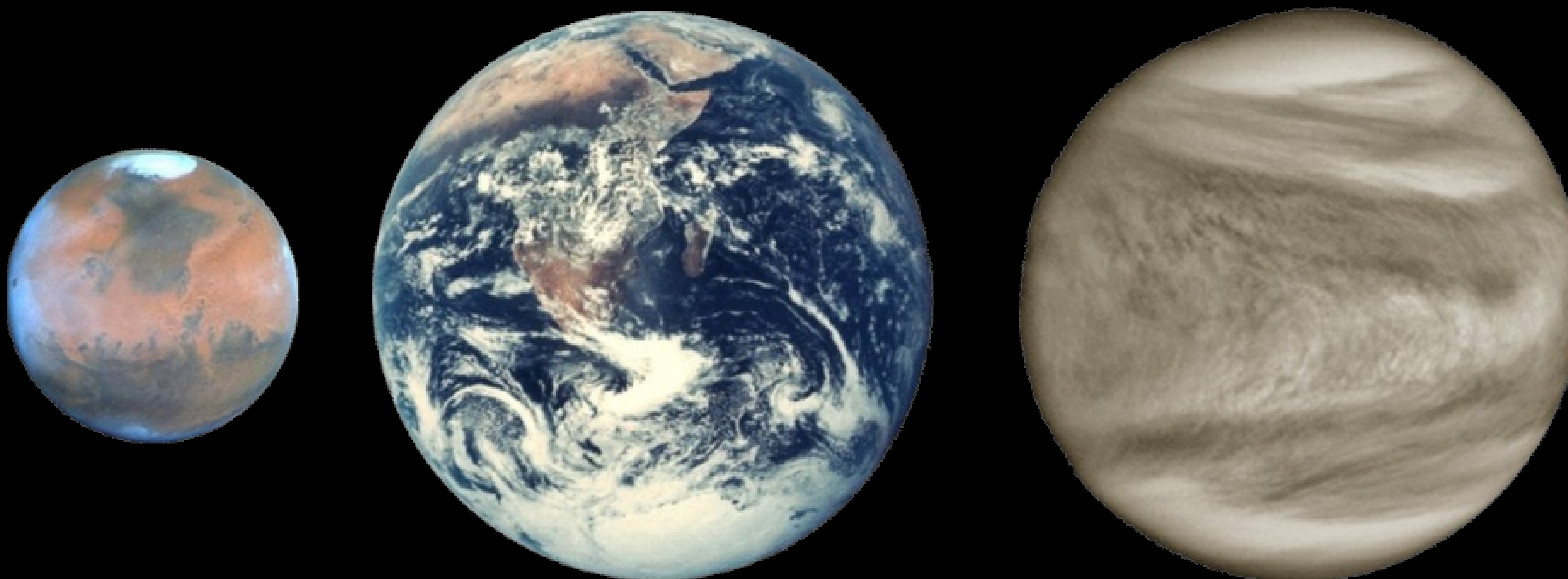
Class #3: Mon. Aug. 27 2018

Looking for a Good Home



Bad — -28°F

Good — 71°F

Worst — 800°F

Basic Concepts

Vocabulary

- **Energy, Heat:**
  - Heat = energy flowing spontaneously from hot to cold
- **Power:** speed at which energy flows or transforms

$$\text{Power, Flux} = \text{Heat flow}/\text{Time}$$

$$\text{Heat, Energy} = \text{Power} \times \text{Time}$$

- **Intensity:** Concentration of power

$$\text{Intensity} = \text{Power}/\text{Area}$$

$$\text{Power} = \text{Intensity} \times \text{Area}$$

Temperature of a planet

- **Basic principle:**

  Steady temperature if and only if

$$\text{Power}_{\text{in}} = \text{Power}_{\text{out}}$$

- **How can heat get in or out?**
  - Electromagnetic radiation

Electromagnetic Waves

- **Color** and **brightness**
- **Color:**
  - Two ways to measure **color**:
  - Wavelength (λ)
  - Wavenumber ($n = 1/\lambda$)
- Archer mostly uses wavenumber
  - Math is simpler that way
- **Brightness:**
  - Intensity (power/area, Watts/square meter)

Colors

Color	wavelengths	wavenumbers
infrared	> 0.70 μm	< 14,000
red	~ 0.70–0.64 μm	~ 14,000-16,000
orange	~ 0.64–0.59 μm	~ 16,000-17,000
yellow	~ 0.59–0.56 μm	~ 17,000-18,000
green	~ 0.56–0.49 μm	~ 18,000-20,000
blue	~ 0.49–0.45 μm	~20,000-22,000
violet	~ 0.45–0.40 μm	~22,000-25,000
ultraviolet	< 0.40 μm	> 25,000

All you need to think about is
shortwave vs. **longwave** radiation.

Shortwave and **longwave**:

- **Shortwave**:
  - Near-infrared, visible, ultraviolet
  - $\lambda < 3\mu\text{m}$
  - $n > 3,300\text{cm}^{-1}$ (cycles per centimeter)
- **Longwave**:
  - Mid-infrared, far-infrared
  - $\lambda > 3\mu\text{m}$
  - $n < 3,300\text{cm}^{-1}$

More on this in the next class …

4 Laws of Radiation

1. All objects continually radiate energy
2. Hotter objects are brighter
3. Hotter objects radiate at shorter wavelengths
4. Objects that are good absorbers are also good emitters
    - Black objects emit & absorb the most
    - Transparent and white objects emit & absorb the least

Blackbody Radiation

Blackbody Radiation

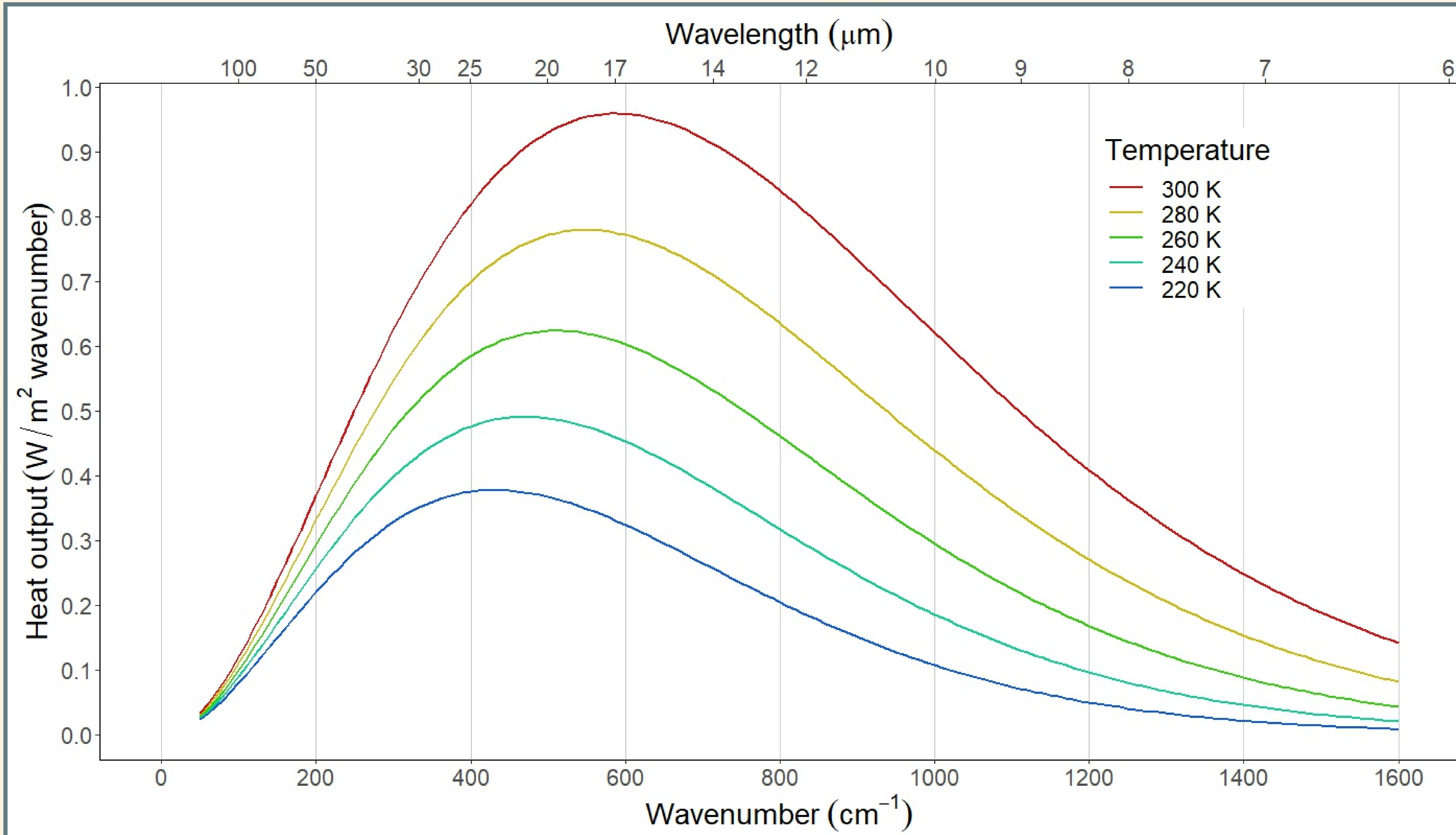
Emissivity (ε) measures how black something is:

- $\varepsilon = 1$ for perfectly black
- $\varepsilon = 0$ for perfectly white or transparent
- In between for gray.
- Black, white, and gray: ε is the same for all wavelengths.
- Colored objects: ε is a function of wavelength.
- **For simplicity:** start by assuming everything is black, white, or gray.

Remember: Good emitters are good absorbers

Fundamental rule: Temperature and emissivity determine radiation.

Heating Up: What Changes??



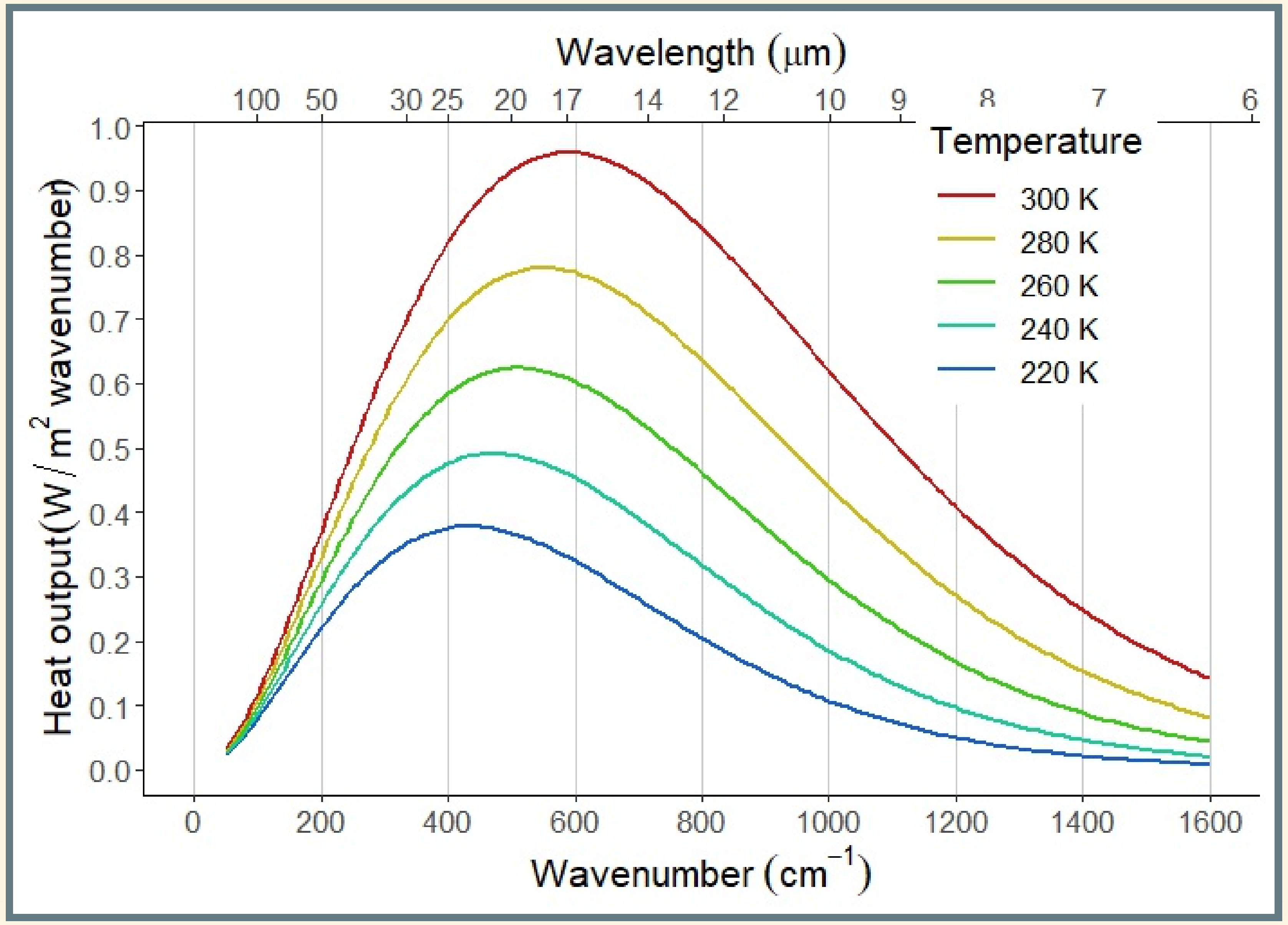
Heating Up: What Changes?

- Hotter temperature:
  - Brighter (greater intensity)
  - Bluer (greater wavenumber, shorter wavelength)

A curious thing:

- A hot black object glows with color!

Total intensity =
area under curve



Mathematical Description

Blackbody Radiation

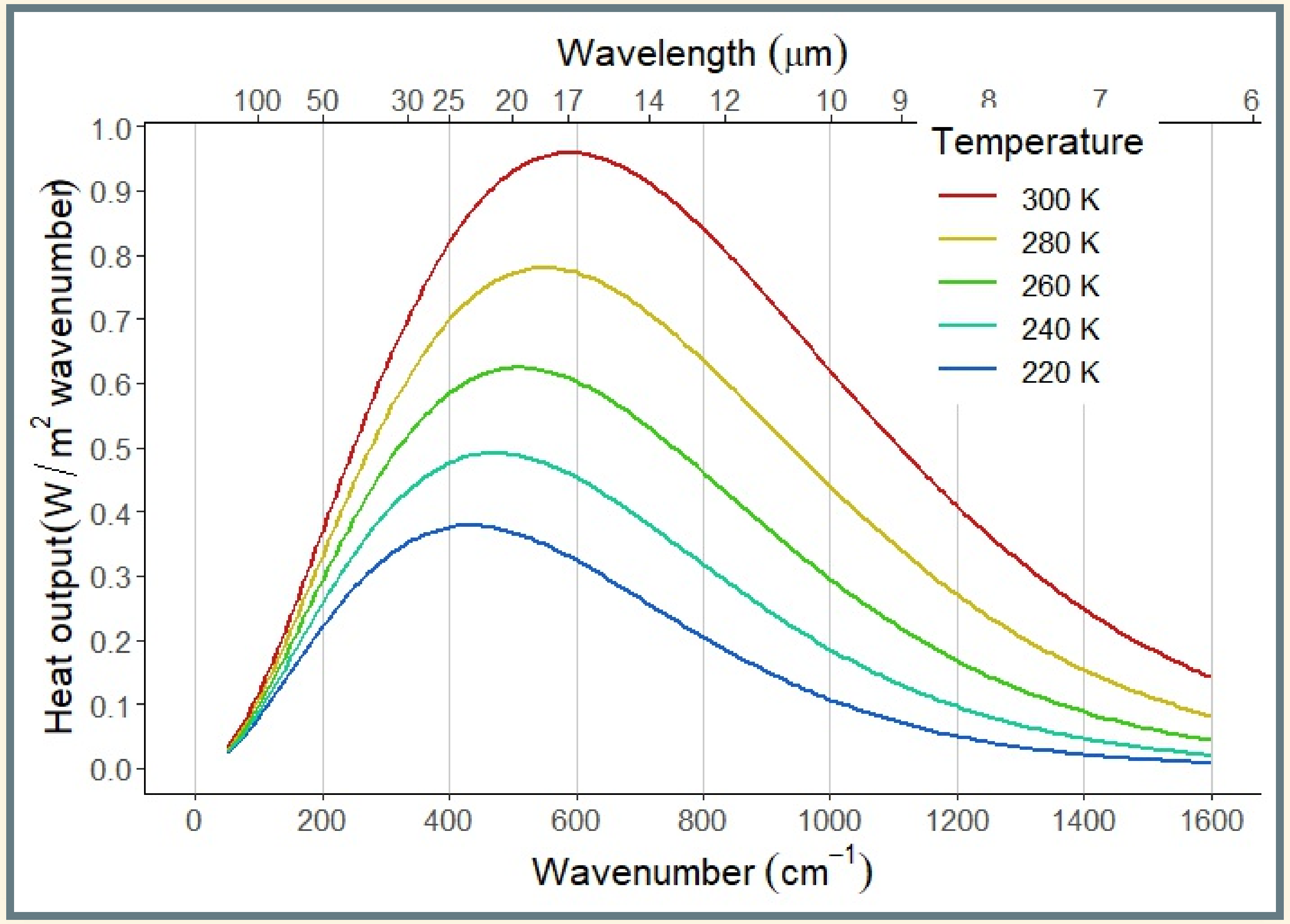
Intensity (brightness):

Stefan-Boltzmann law

$$I = \varepsilon \sigma T^4$$

after Josef Stefan
and Ludwig Boltzmann

- ε = emissivity
  - Different for different objects.
- σ = Stefan-Boltzmann constant.
- T = absolute (Kelvin) temperature.

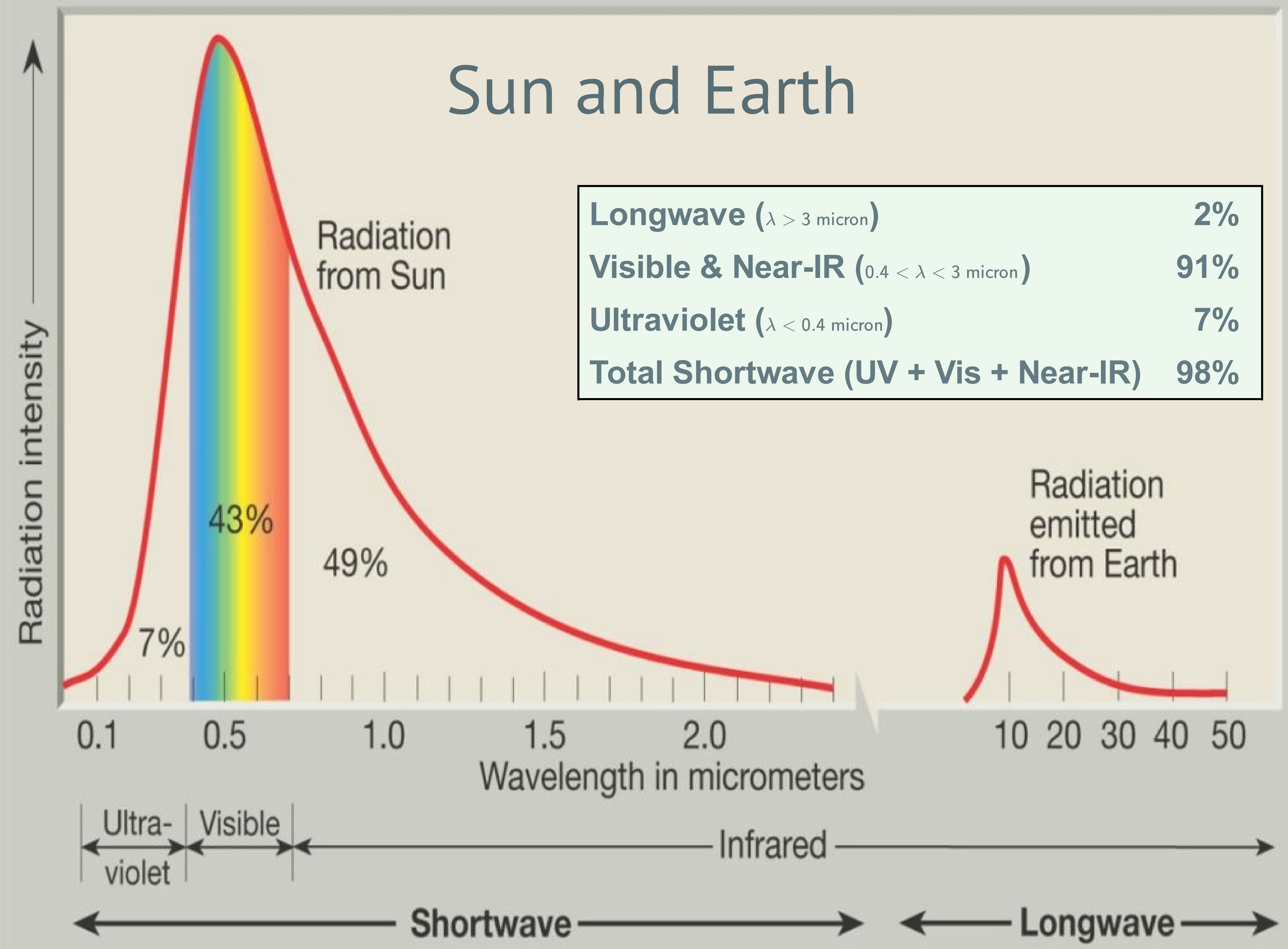


Color: Peak wavenumber proportional to (Kelvin) temperature.

Helpful Hint:
Fourth power on a calculator: press the x^2 button twice.

Sun and Earth

Longwave ($\lambda > 3$ micron)	**2%**
Visible & Near-IR ($0.4 < \lambda < 3$ micron)	**91%**
Ultraviolet ($\lambda < 0.4$ micron)	**7%**
Total Shortwave (UV + Vis + Near-IR)	**98%**



Efficiency of Light Bulbs

Type of Bulb	Efficiency
Standard 40W	1.9%
Standard 60W	2.1%
Standard 100W	2.6%
Quartz Halogen	3.5%
Ideal black body @ 7000K	14.0%
Compact Fluorescent	7–10%
LED	8–15%

- 7000K is the optimal temperature for a black body to emit visible light, but it will melt every known substance.
- Standard light bulbs operate at around 2000–3300 K.

Calculating Earth’s Temperature: Bare-Rock Model

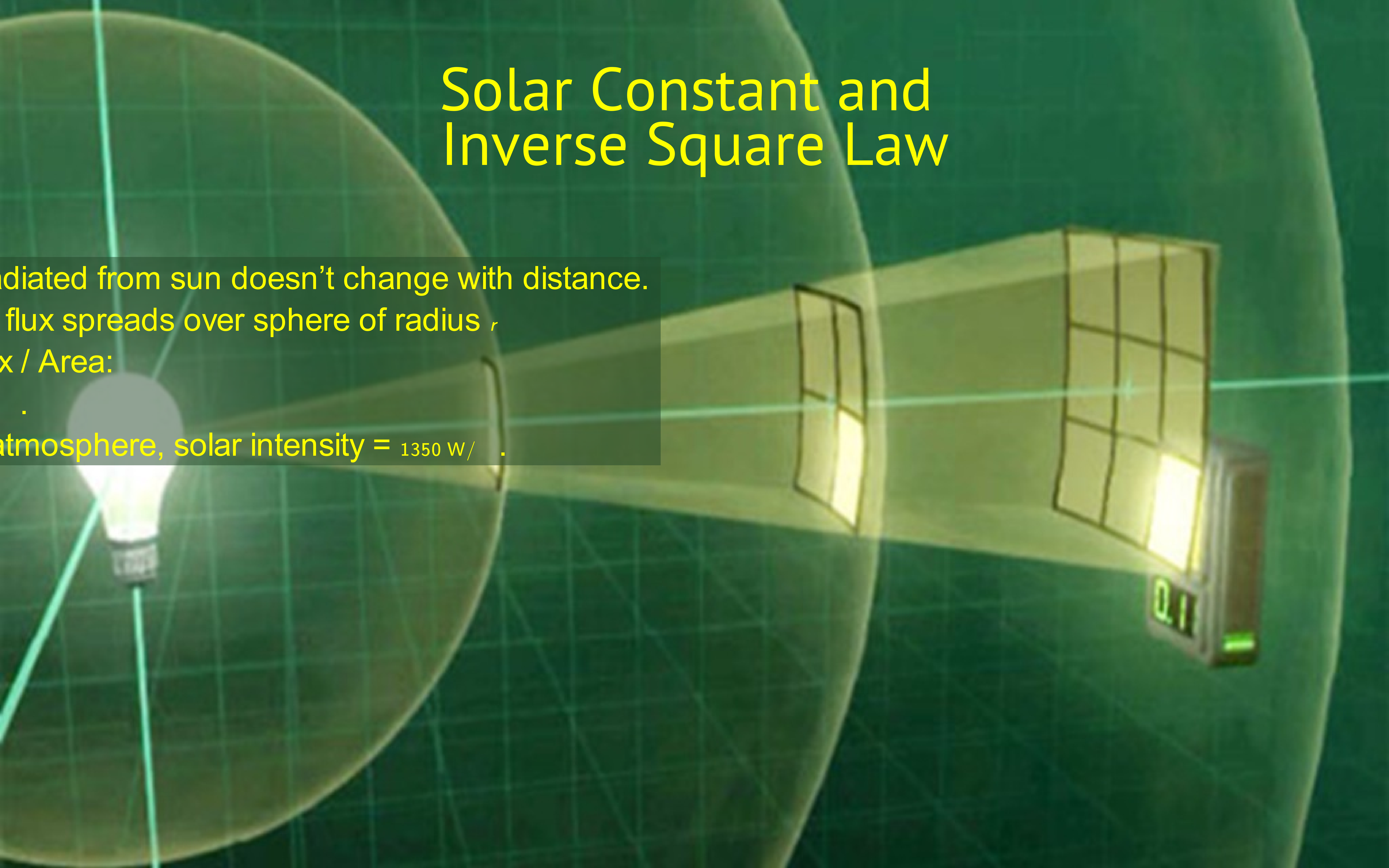
Basics

Steady Temperature

- Heat in must balance heat out
- Total Heat Flux (Power) = Area × Intensity
  - Total heat flux in (F_{in}):
    - Intensity depends on solar constant and albedo
    - Does not depend on earth's temperature
  - Total heat flux out (F_{out}):
    - Intensity depends on earth's temperature and emissivity
- Strategy:

1. Figure out F_{in} .
2. Figure out temperature T that makes $F_{\text{out}} = F_{\text{in}}$.

Solar Constant and Inverse Square Law



diated from sun doesn’t change with distance.

flux spreads over sphere of radius r

x / Area:

.

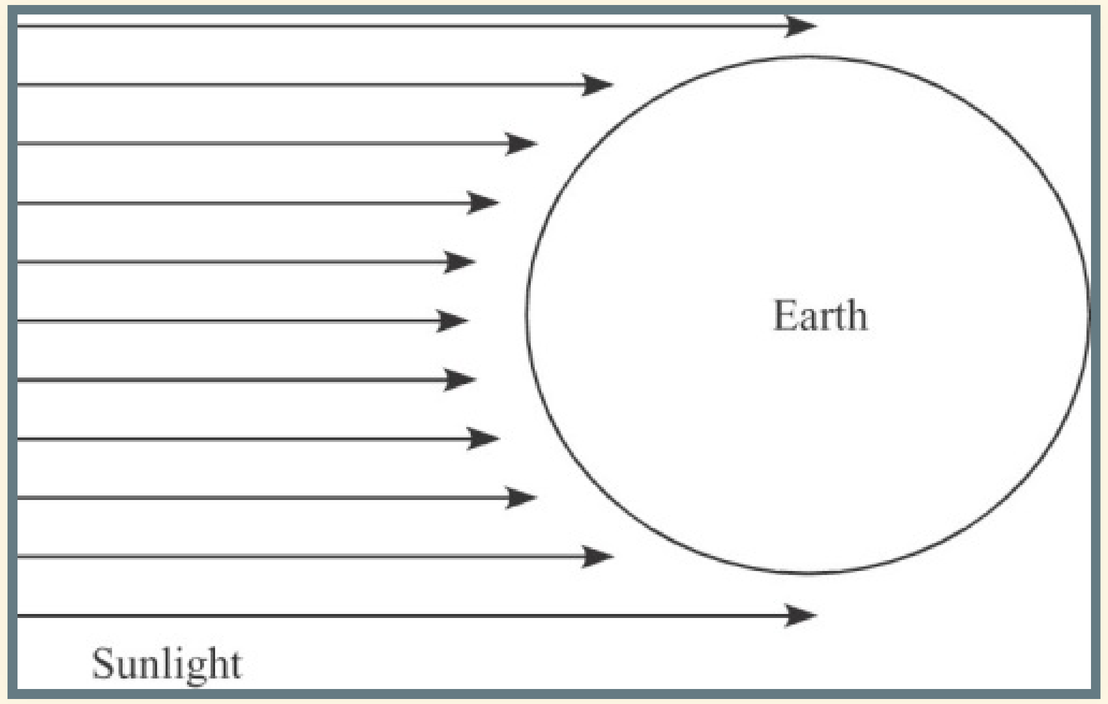
atmosphere, solar intensity = 1350 W/ .

What is F_{in} ?

- $F_{\text{in}} = \text{Area} \times \text{Intensity absorbed}$
  - $\text{Intensity absorbed} = (1-\alpha) \times I_{\text{in}}$
    - $I_{\text{in}} = 1350\ \text{W/m}^2$
    - Average albedo $\alpha = 0.30$ (30% of sunlight is reflected)

What is area?

- Area = silhouette or shadow
- Circle: πr^2

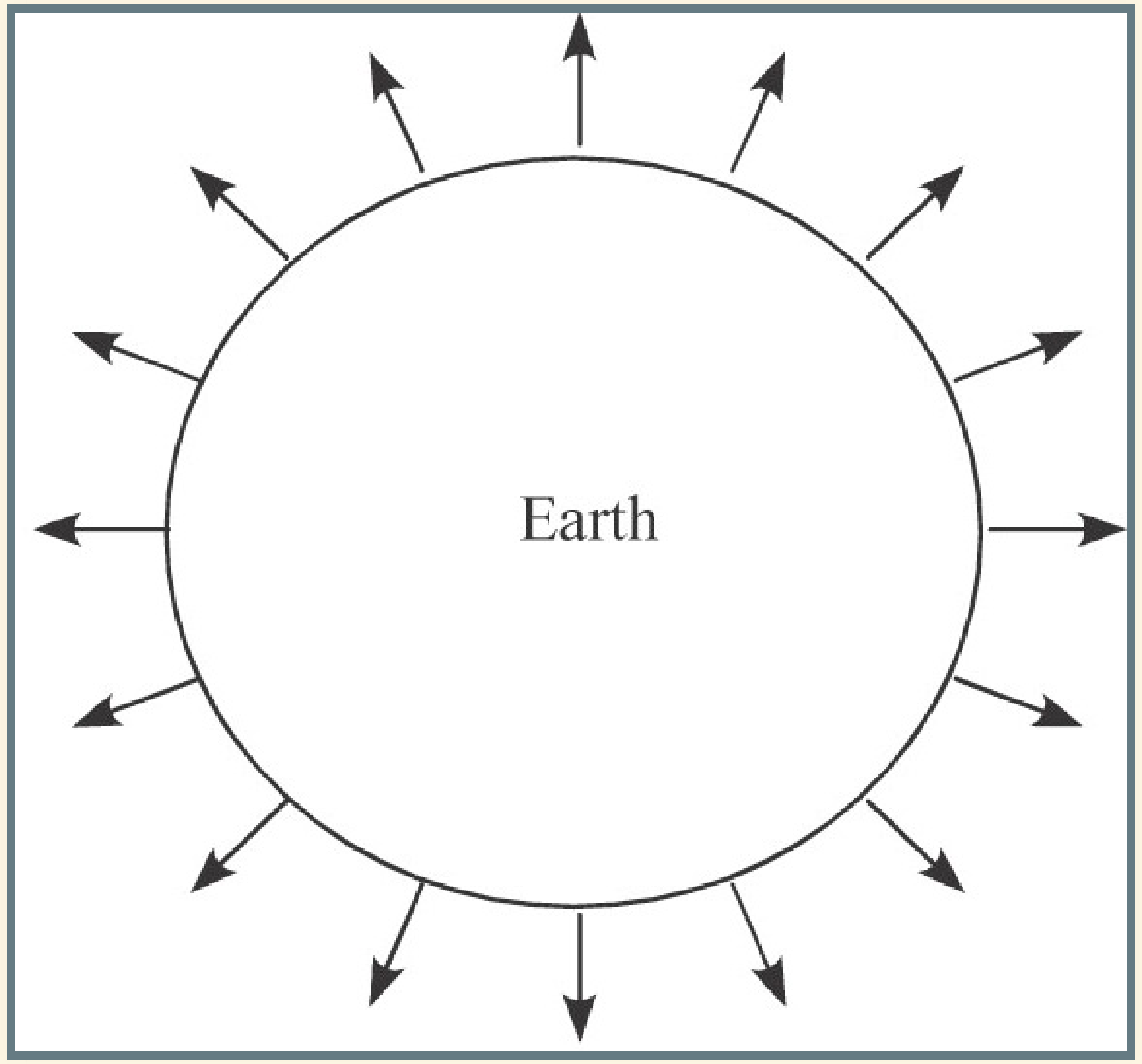


What is F_{in} ?

- $F_{\text{in}} = \pi r_{\text{Earth}}^2 \times (1-\alpha) I_{\text{in}}$
  - $\pi r^2 = 1.3 \times 10^{14}\,\text{m}^2$
  - $\alpha = 0.30 \Rightarrow (1-\alpha) = 0.70$
  - $I_{\text{in}} = 1350\ \text{W}/\text{m}^2$
- $F_{\text{in}} = 1.2 \times 10^{17}$ Watt
  - 11,000 times total human energy production.

What is F_{out}?

- $F_{\text{out}} = \text{Area} \times I_{\text{out}}$
  - $I_{\text{out}} = \varepsilon \sigma T^4$
    - $\varepsilon = 1$ (blackbody)
    - $\sigma = 5.67 \times 10^{-8}\ \text{W}/\text{m}^2/\text{K}^4$
  - What is area?
    - Sphere: $4\pi r^2$
- $F_{\text{out}} = 4\pi r_{\text{earth}}^2 \times \varepsilon \sigma T^4$



Putting it all together

$$F_{\text{out}} = F_{\text{in}}$$

$$4\pi r^2 \times \varepsilon\sigma T^4 = \pi r^2 (1-\alpha) I_{\text{in}}$$

$$4\pi r^2 \times \varepsilon\sigma T^4 = \pi r^2 (1-\alpha) I_{\text{in}}$$

$$4\varepsilon\sigma T^4 = (1-\alpha) I_{\text{in}}$$

$$T^4 = \frac{(1-\alpha) I_{\text{in}}}{4\varepsilon\sigma}$$

$$T = \sqrt[4]{\frac{(1-\alpha) I_{\text{in}}}{4\varepsilon\sigma}}$$

Temperature of Earth

- Steady Temperature:
  - Heat flux in must balance heat flux out ($F_{\text{out}} = F_{\text{in}}$).
  - F_{in} :
    - Does not depend on earth's temperature.
    - Depends on solar constant and earth's albedo.
  - F_{out} :
    - Depends on earth's temperature.
  - T adjusts until heat out = heat in.

$$T = \sqrt[4]{\frac{(1-\alpha)I_{\text{in}}}{4\varepsilon\sigma}}$$

Temperature of Earth

$$T = \sqrt[4]{\frac{(1-\alpha)I_{\text{in}}}{4\varepsilon\sigma}}$$

Earth:

(Note: My numbers are slightly different from Archer's textbook)

- $I_{\text{in}} = 1350\ \text{W/m}^2$
- $\alpha = 0.30$
- $\varepsilon = 1$
- $\sigma = 5.67 \times 10^{-8}\ \text{W/(m}^2\,\text{K}^4)$
- Calculate T:
- $T = 254\ \text{K} = -19^\circ\text{C} = -2^\circ\text{F}$.

If the sun got 5% brighter, how much warmer would the earth become?

$$T = \sqrt[4]{\frac{(1-\alpha)I_{\text{in}}}{4\varepsilon\sigma}}$$

- Normal: $I_{\text{in}} = 1350\ \text{W}/\text{m}^2$:
  - $T = 254\ \text{K}$
- 5% Brighter: $I_{\text{in}} = 1.05 \times 1350\ \text{W}/\text{m}^2 = 1418\ \text{W}/\text{m}^2$:
  - $T = 257\ \text{K}$
- $\Delta T = 3\ \text{K} = 6^\circ\text{F}$

Temperature of Earth

$$T = \sqrt[4]{\frac{(1-\alpha)I_{\text{in}}}{4\varepsilon\sigma}}$$

Earth:

(Note: My numbers are slightly different from Archer's textbook)

- $I_{\text{in}} = 1350\ \text{W/m}^2$
- $\alpha = 0.30$
- $\varepsilon = 1$
- $\sigma = 5.67 \times 10^{-8}\ \text{W/(m}^2\text{K}^4\text{)}$
- $T = 254\ \text{K} = -19^\circ\text{C} = -2^\circ\text{F}$.

How does this compare to Earth's actual temperature?

Radiative Temperature

- Satellites orbiting in space can measure longwave radiation from earth
- To the satellites, the earth looks very much like a blackbody at the bare-rock temperature (254 K).
- Thus, scientists generally call the bare-rock temperature the **radiative temperature** because it describes the radiation coming off the earth.
- However, the surface temperature of the earth is around $295\text{ K} = 71^{\circ}\text{F}$, which is significantly different from the radiative, or bare-rock, temperature.

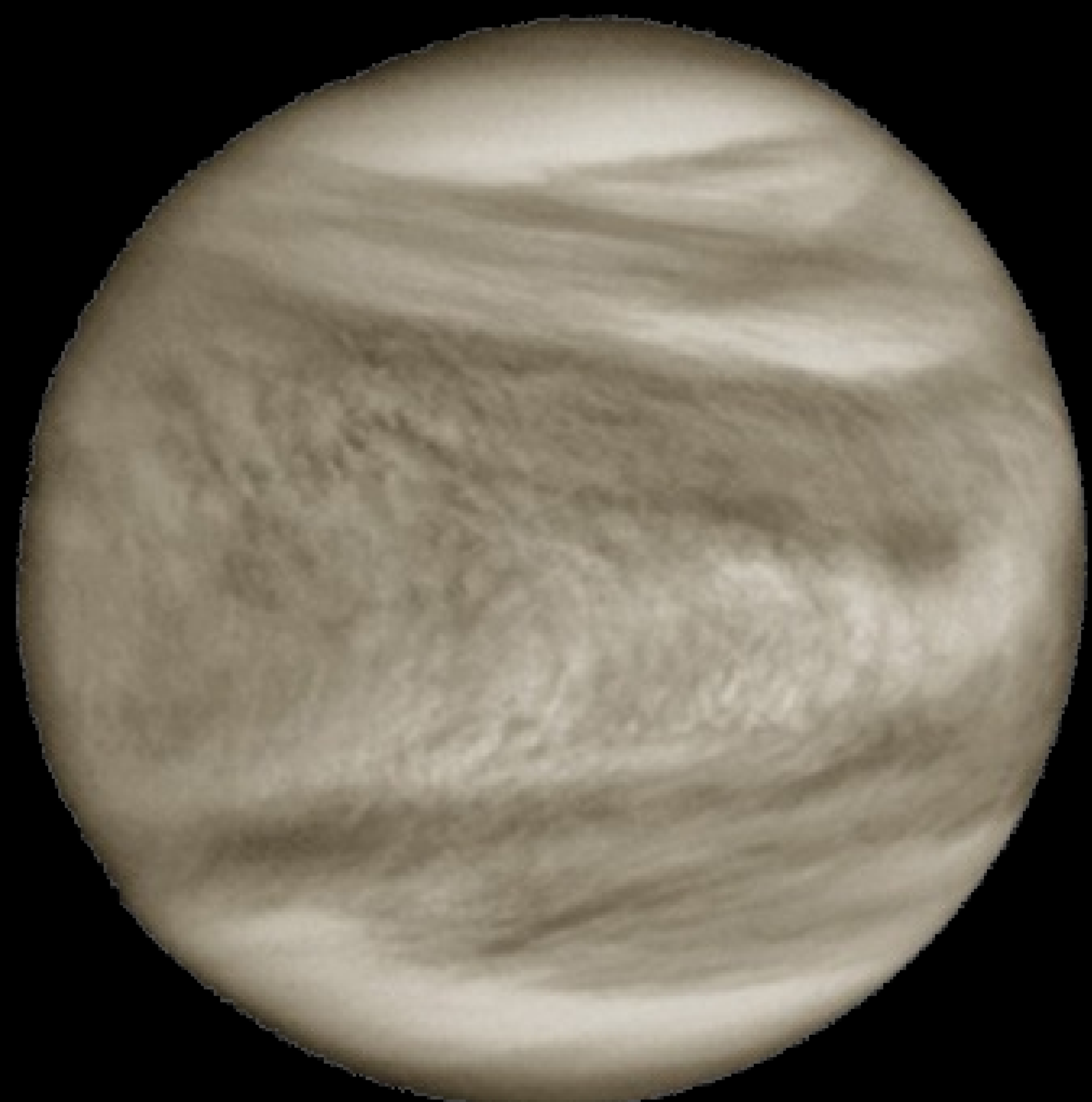
The Terrestrial Planets

Mars

240 K

Earth

295 K



Venus

700 K

Terrestrial Planets

	Earth	Mars	Venus
Distance from sun	1 AU	1.5 AU	0.72 AU
$1/\text{Distance}^2$	1.00	0.44	1.9
Solar constant	$1350\ \text{W}/\text{m}^2$	$600\ \text{W}/\text{m}^2$	$2604\ \text{W}/\text{m}^2$
Albedo	0.30	0.17	0.71
$T_{\text{bare rock}}$	254 K (-2°F)	216 K (-70° F)	240 K (-27° F)
T_{surface}	295 K (71° F)	240 K (-28° F)	700 K (800° F)
Δ_T	41 K (74° F)	24 K (42° F)	460 K (828° F)