EARTH 114: GLOBAL WARMING

Lecture 2: Radiation and planetary temperature

Overview

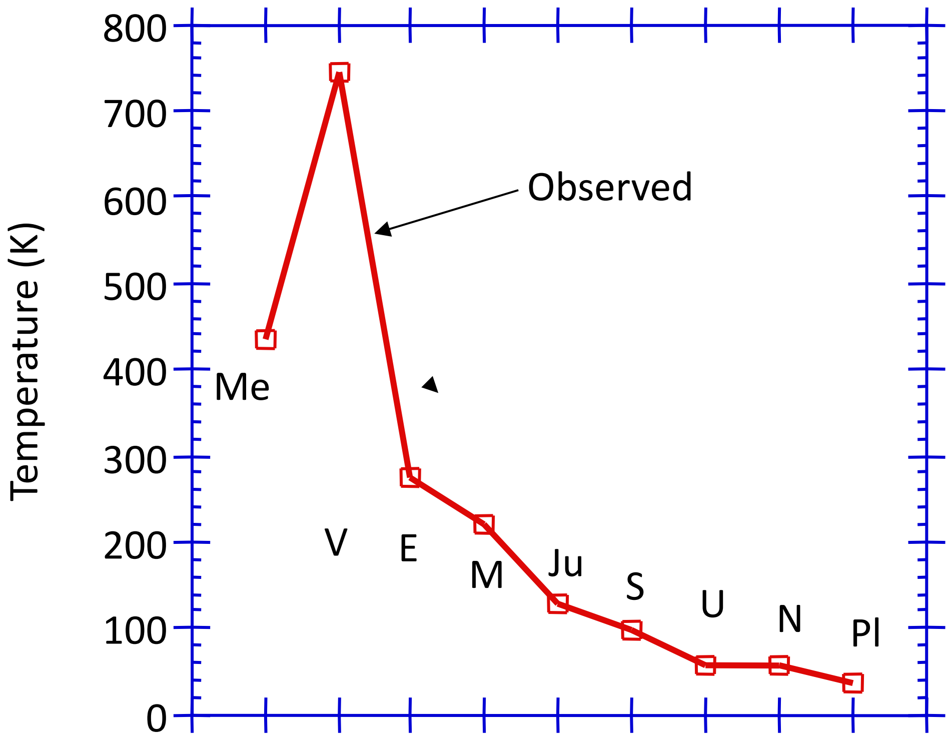
i. Solar energy and electromagnetic radiation– a little about light

ii. Radiation laws– relationship between electromagnetic radiation and temperature

iii. Planetary energy balance & the greenhouse effect– modeling planetary temperature

Planetary temperature

What determines Earth's mean temperature?

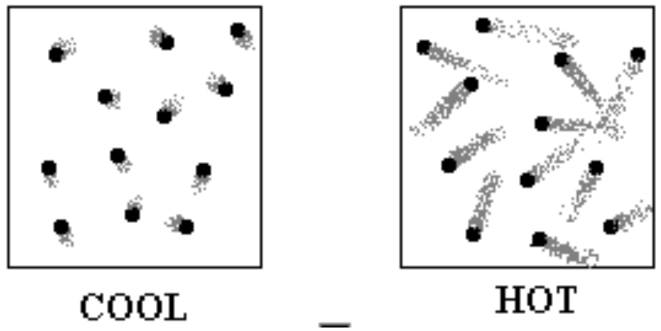


Energy and Heat

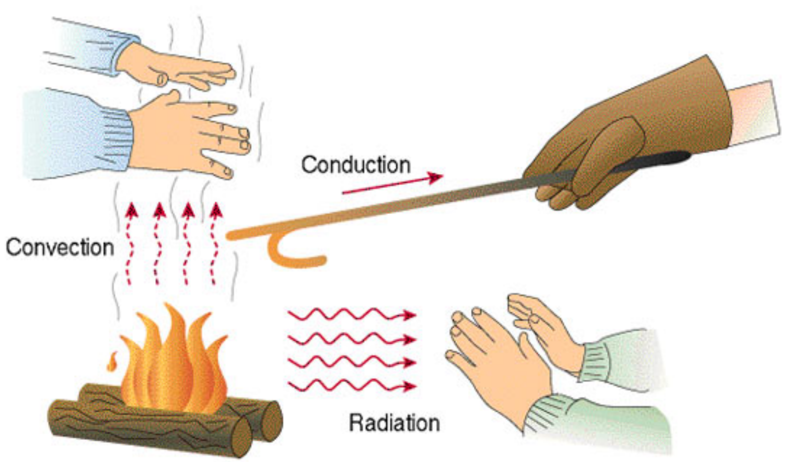
Energy: property responsible for work on or heating of an object.

Heat: Is a measure of the kinetic energy (bouncing-around energy) of atoms.

- Temperature (K, C, F) is a measure of the heat in an object.



- Heat (J) is transferred through convection, conduction, and radiation.



Solar energy

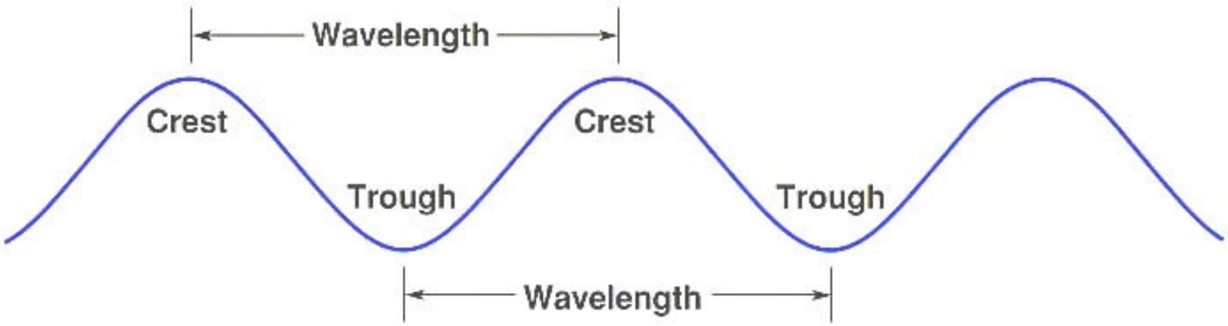
Solar heating: Earth's surface is heated by the Sun

- Earth receives 99.98% of its surface energy from the Sun.
- Solar energy is created in the core of the Sun through nuclear fusion, the welding of H atoms into He atoms.
- Every second our Sun fuses ~600 million tons of H to He, converting >4 million tons of matter into energy.
- And <u>radiates</u> 3.828×10^{26} J/s to space (the Sun's luminosity).
- Some of this energy reaches Earth's surface.

Electromagnetic radiation

Electromagnetic radiation: self-propagating waves that have electric and magnetic fields

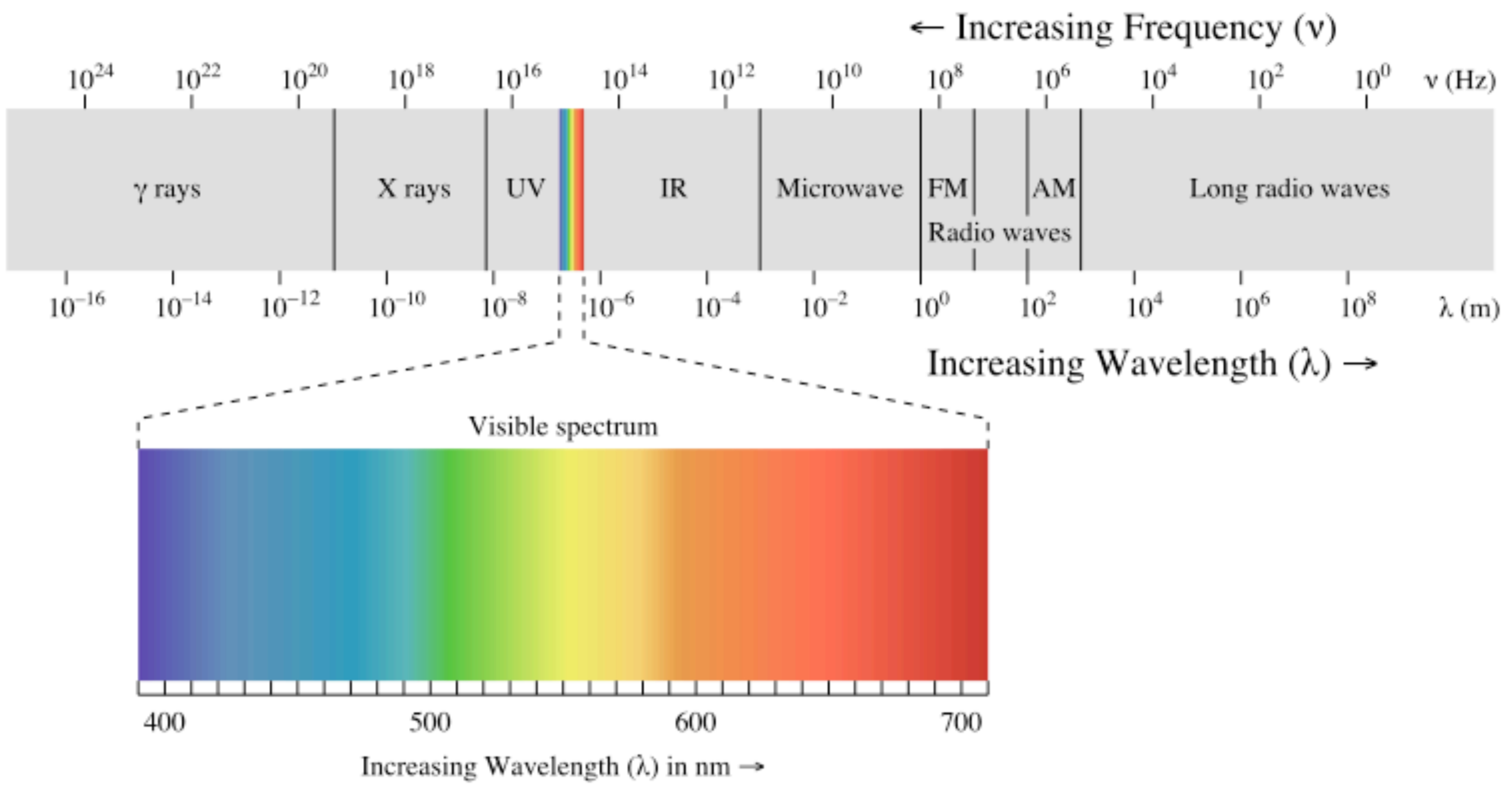
- Induced by acceleration of electrons within atoms
- Moves through vacuum or matter at speed of light ($c = 3x10^8$ m/s)
- Characterized by wavelength (λ) or frequency (ν)



- Frequency is inversely proportional to wavelength: $\boxed{\nu = \dfrac{c}{\lambda}}$

Electromagnetic spectrum

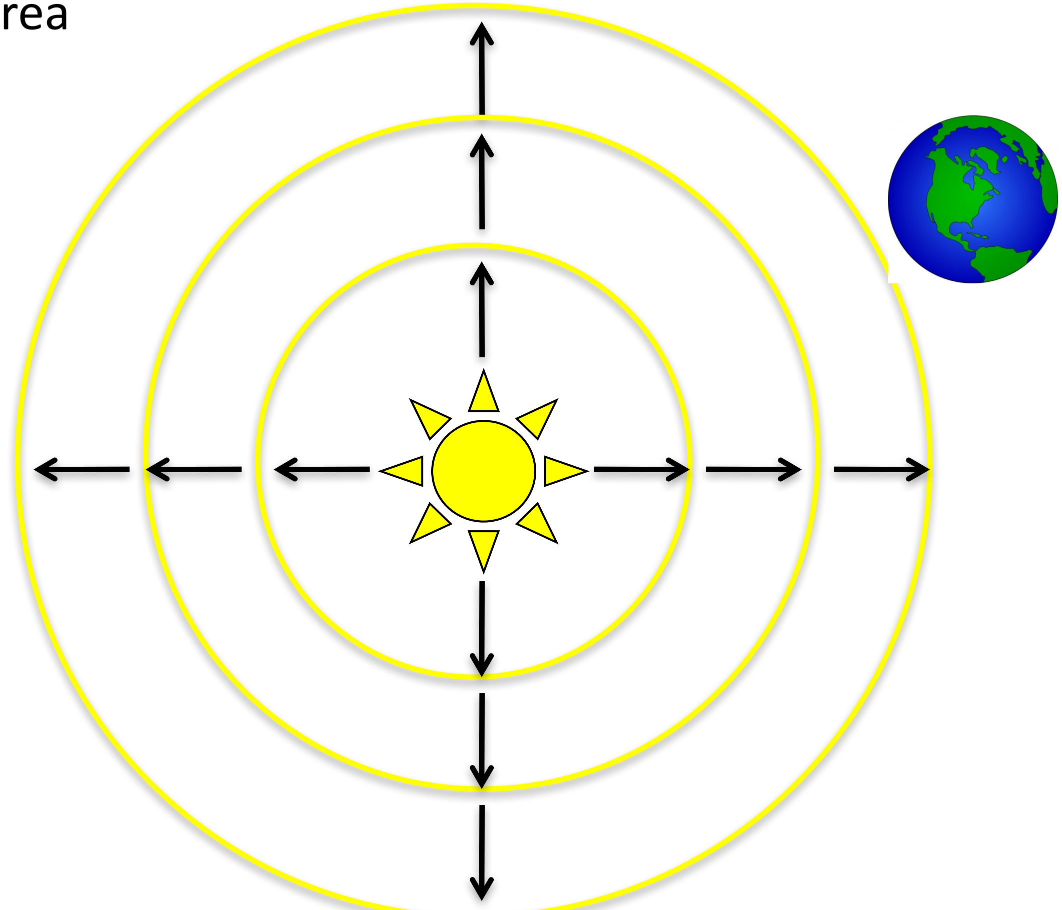
Electromagnetic spectrum: full range of electromagnetic radiation



Inverse square law

Newton's inverse square law: solar flux is inversely proportional to the square of the distance from Sun

- As energy moves away from Sun, it is spread over a greater and greater area



Inverse square law

Newton's inverse square law: solar flux is inversely proportional to the square of the distance from Sun

- As energy moves away from Sun, it is spread over a greater and greater area
- Spread over the area of a sphere, $\boxed{4\pi r^2}$, where r is distance from the Sun
- Solar flux is the luminosity divided by the sphere of incidence:

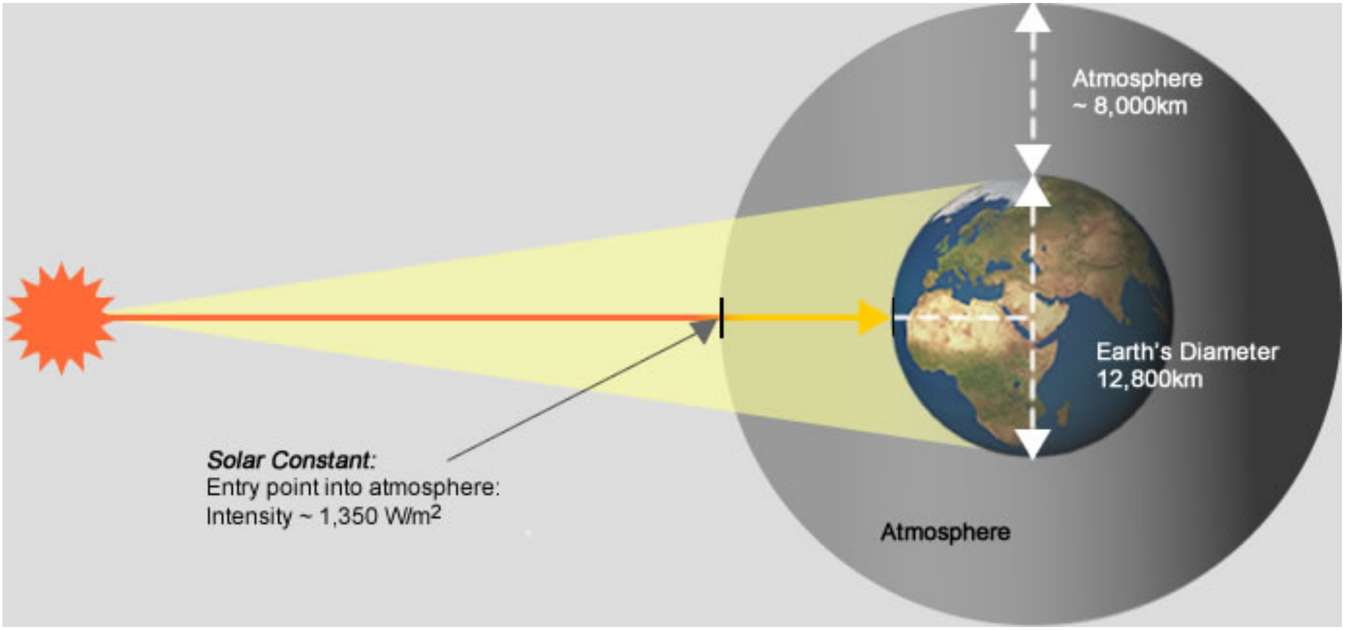
$$\boxed{S = \frac{L}{4\pi r^2}}$$

- What is Earth's solar flux (S_0)?
  - $L = 3.839 \times 10^{26}$ W
  - $r_0 = 1.496 \times 10^{11}$ m

Solar flux

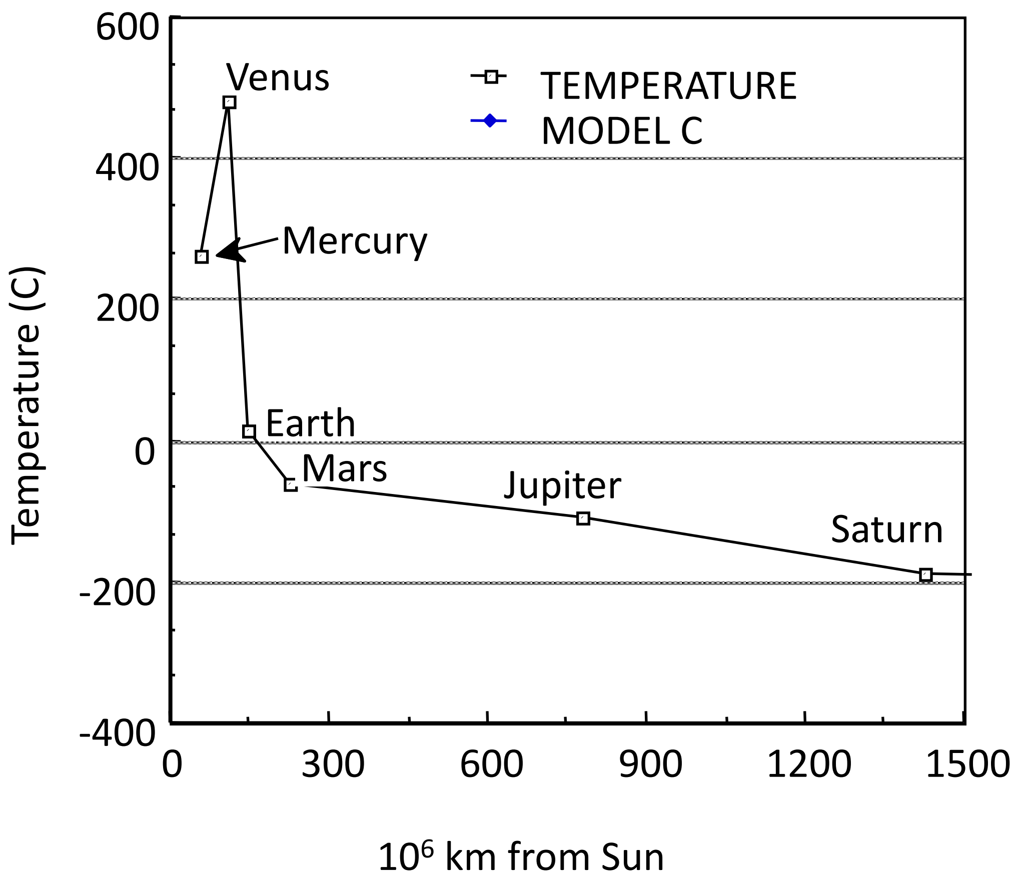
Solar flux: amount of solar energy that reaches a unit area of surface per unit time

- Solar flux is measured in units of $Js^{-1}m^{-2}$ or Wm^{-2}
- S_o = 1367 Wm^{-2} – equivalent to ~13 100 W light bulbs illuminating a square meter



Inverse square law model

Is planetary temperature explained by distance from the Sun?



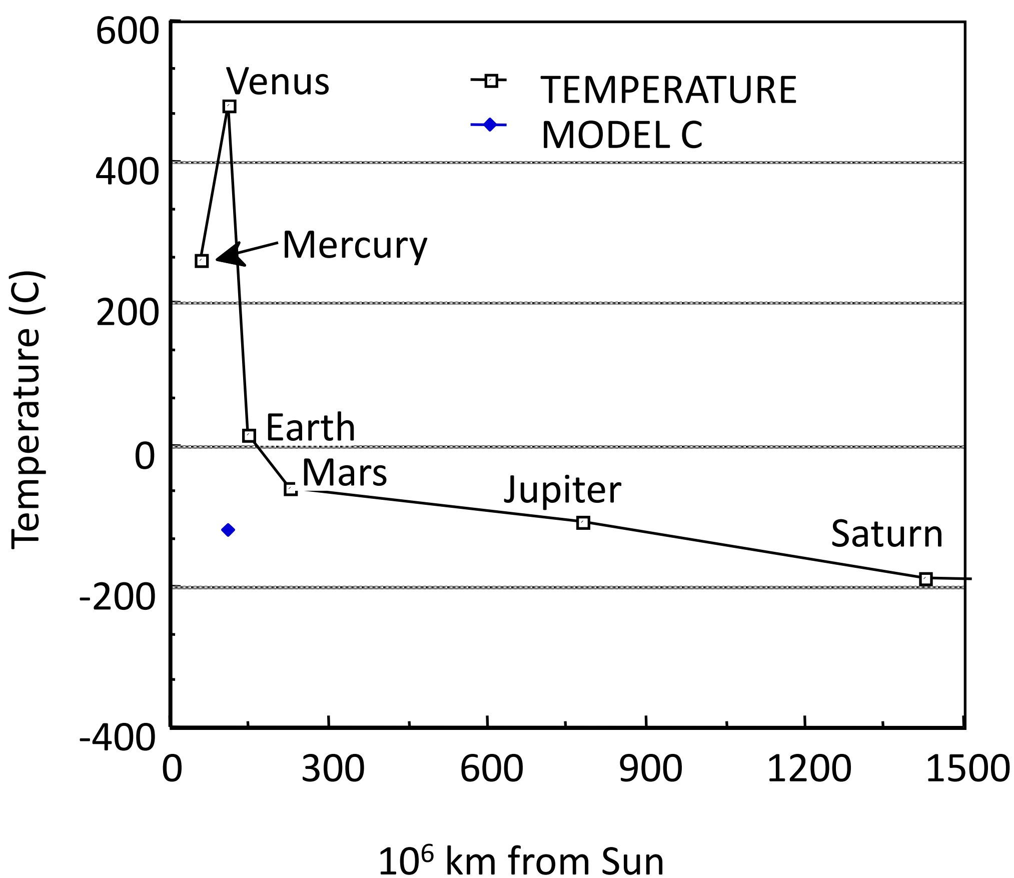
Inverse square law model

Is planetary temperature explained by distance from the Sun?

Mercury's temperature = 539 K, Venus is about 2x as far away from the Sun.

Using the inverse square law, we estimate that Venus should receive ¼ as much solar radiation.

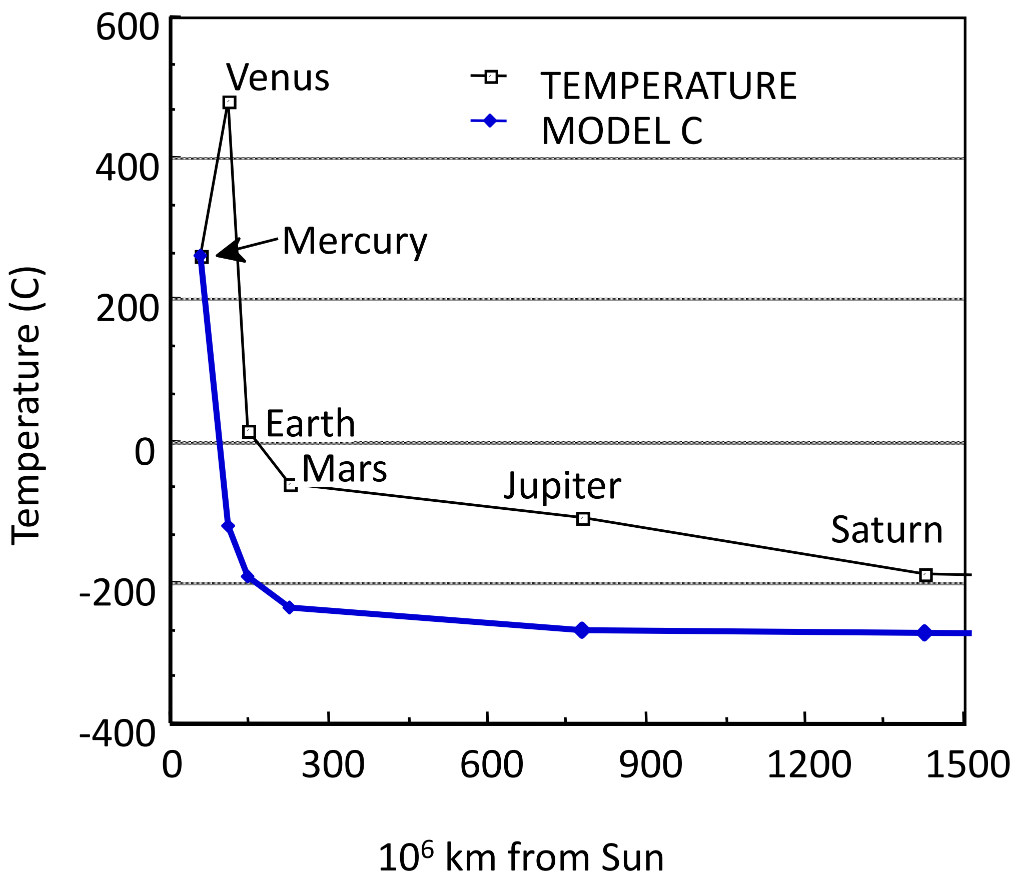
Venus' temperatures would be 539 K (¼) = 135 K or -138 C.



Inverse square law model

Is planetary temperature explained by distance from the Sun?

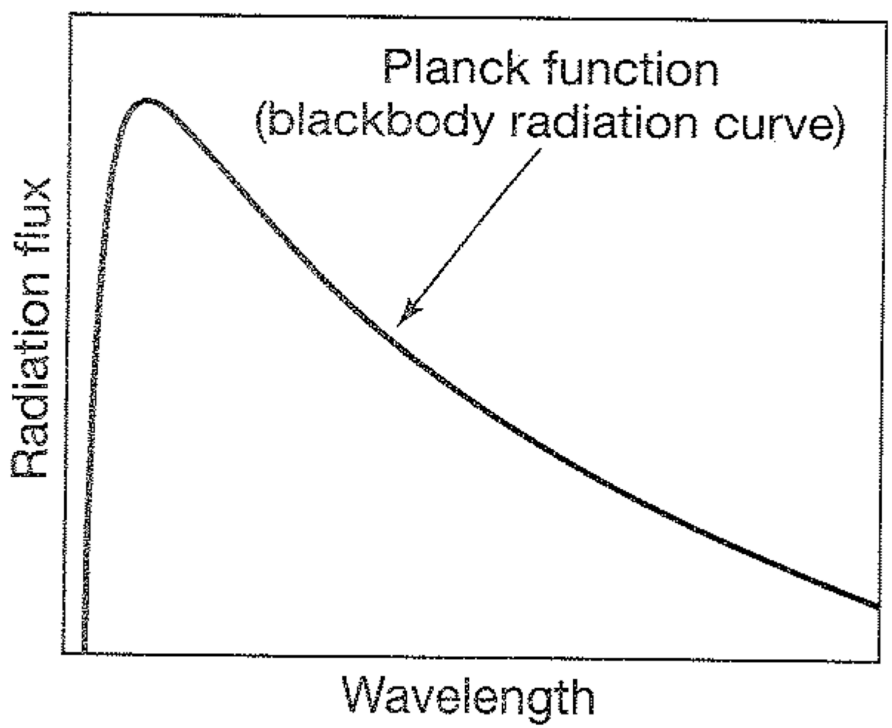
Distance from the Sun does a poor job of estimating planetary temperatures.



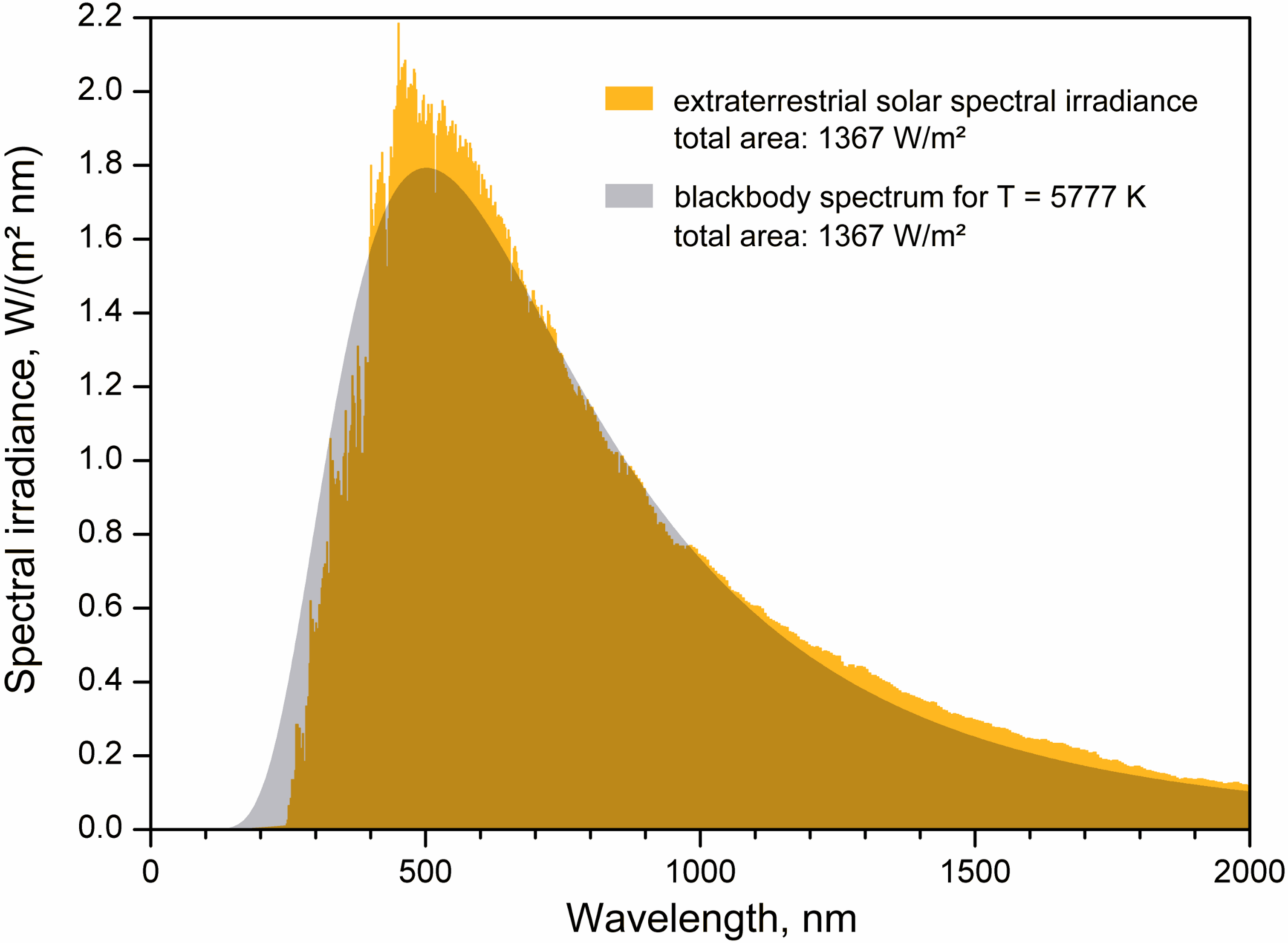
Planck's function

Planck's law of black body radiation: describes the electromagnetic radiation of a black body in thermal equilibrium.

Relates radiation flux to wavelength at equilibrium T



(a)



extraterrestrial solar spectral irradiance
total area: 1367 W/m²
blackbody spectrum for T = 5777 K
total area: 1367 W/m²
Spectral irradiance, W/(m² nm)
Wavelength, nm
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
0
500
1000
1500
2000

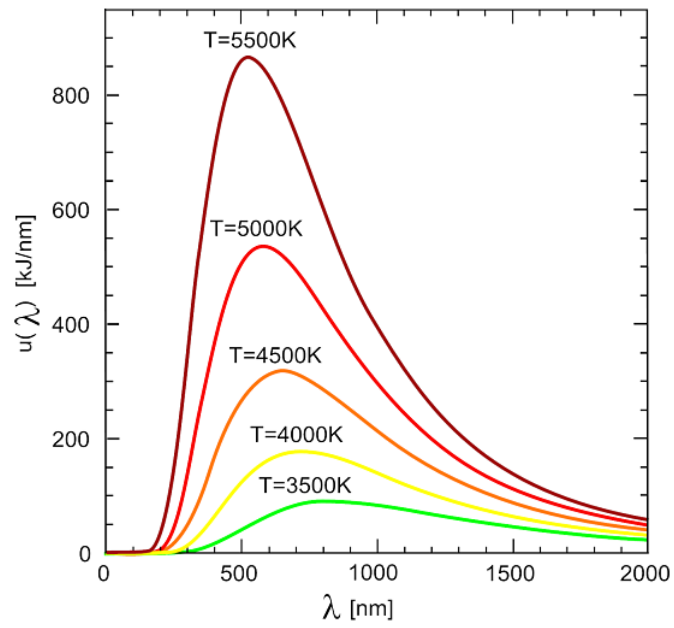
Wien's law

Wien Law: the peak electromagnetic radiation is inversely related to the temperature of a black body

A hot body will radiate at shorter peak wavelengths than a cold one:

$$\lambda_{max} = B/T$$

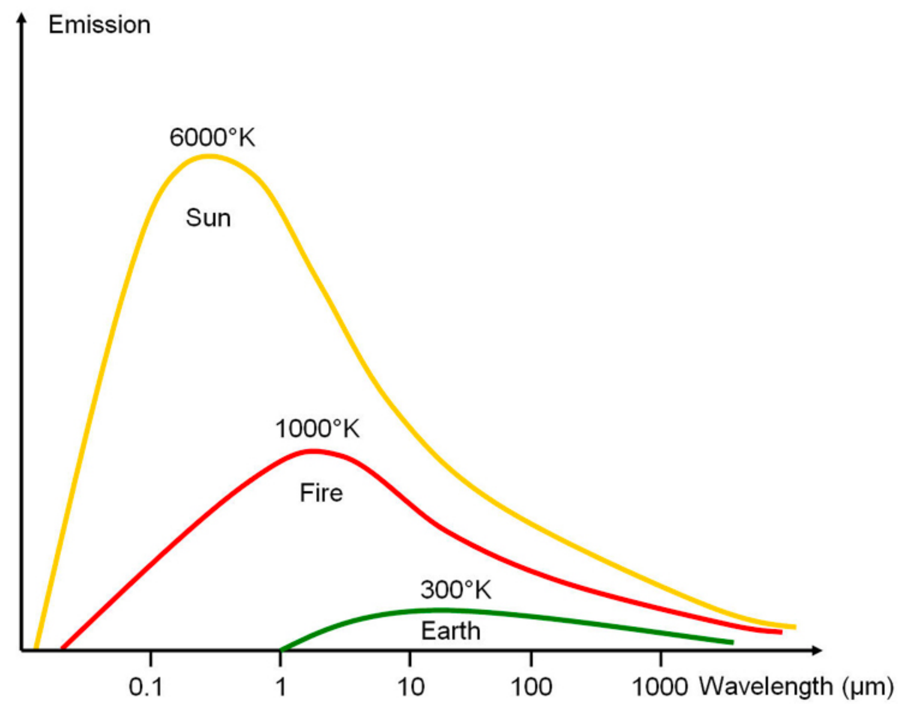
where B=0.0029 K m is Wien's constant



Wien's law

Wien Law: the peak electromagnetic radiation is inversely related to the temperature of a black body

- Sun – radiates in the shortwave (visible) spectra
- Earth – radiates in the longwave (ir) spectra



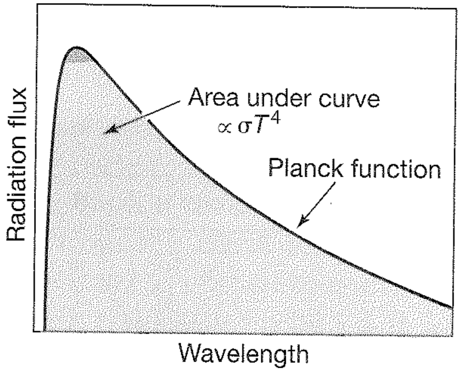
Stefan-Boltzmann law

Stefan-Boltmann law: the total energy emitted by an object is proportional to its temperature:

$$\mathbf{I = \sigma T^4}$$

where $\boldsymbol{\sigma}$ = 5.67e-8 $Wm^{-2}K^{-4}$. Note that I is an energy flux (energy per time per area)! Units = Wm^{-2} = $Jm^{-2}s^{-1.}$

Stefan-Boltzmann Law is derived by integrating Planck's Function.



(c)

Radiation characteristics

	T (K)	**λ_{max} (μm)**	**region in spectrum**	**F (W/m^2)**
Sun	6000			
Earth	300			

Radiation characteristics

	T (K)	λ_{max} (μm)	region in spectrum	F (W/m^2)
Sun	6000	0.5		
Earth	300	10		

Radiation characteristics

	T (K)	λ_{max} (μm)	region in spectrum	F (W/m^2)
Sun	6000	0.5	visible	
Earth	300	10	infrared	

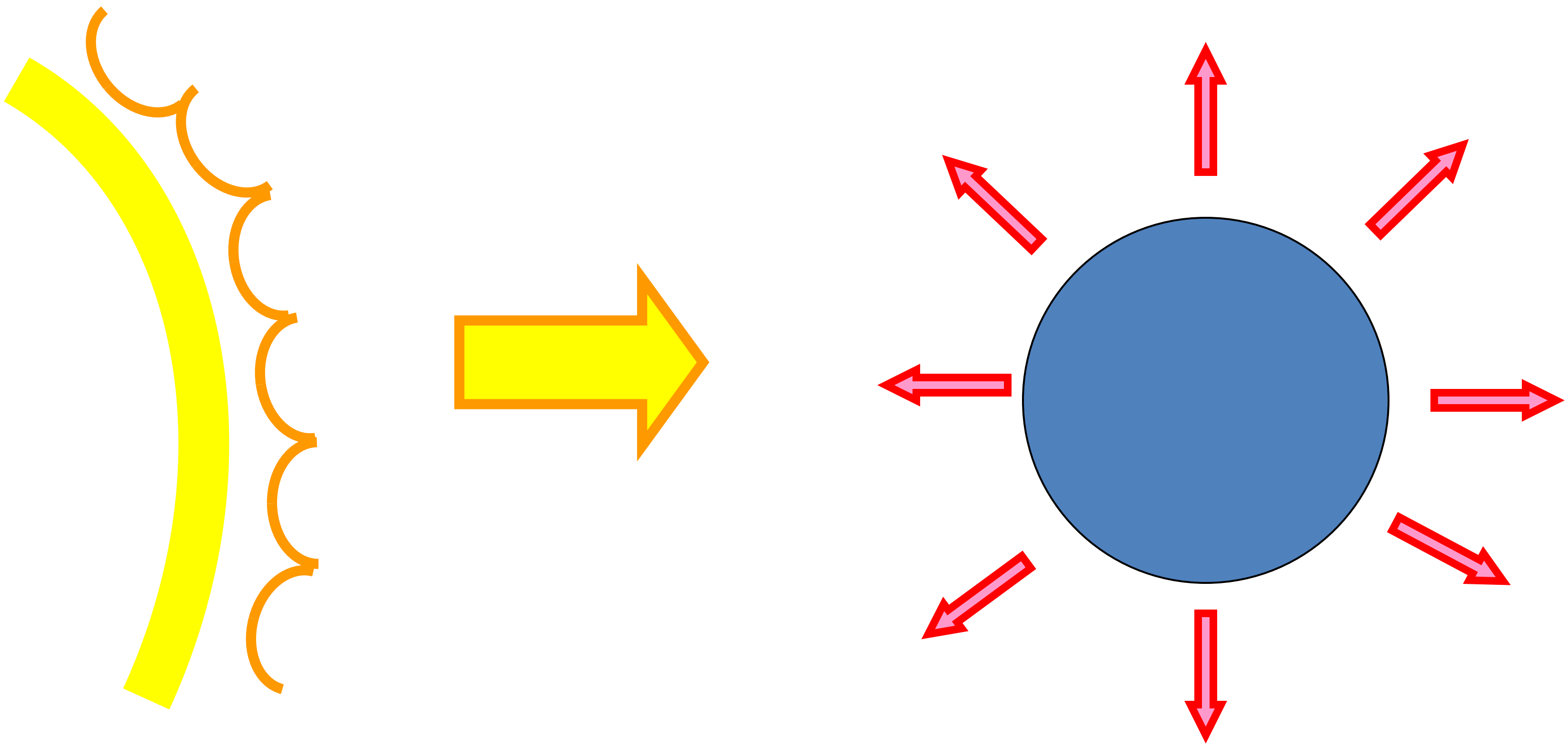
Radiation characteristics

	T (K)	λ_{max} (μm)	region in spectrum	F (W/m^2)
Sun	6000	0.5	visible	$7x10^7$
Earth	300	10	infrared	460

Planetary energy balance

Radiative equilibrium: assumes energy balance, incoming radiation equals outgoing radiation

- If incoming and outgoing radiation are not in balance, Earth's temperature will rise or fall.



Earth's radiative temperature

Let's calculate the radiative equilibrium temperature for Earth!

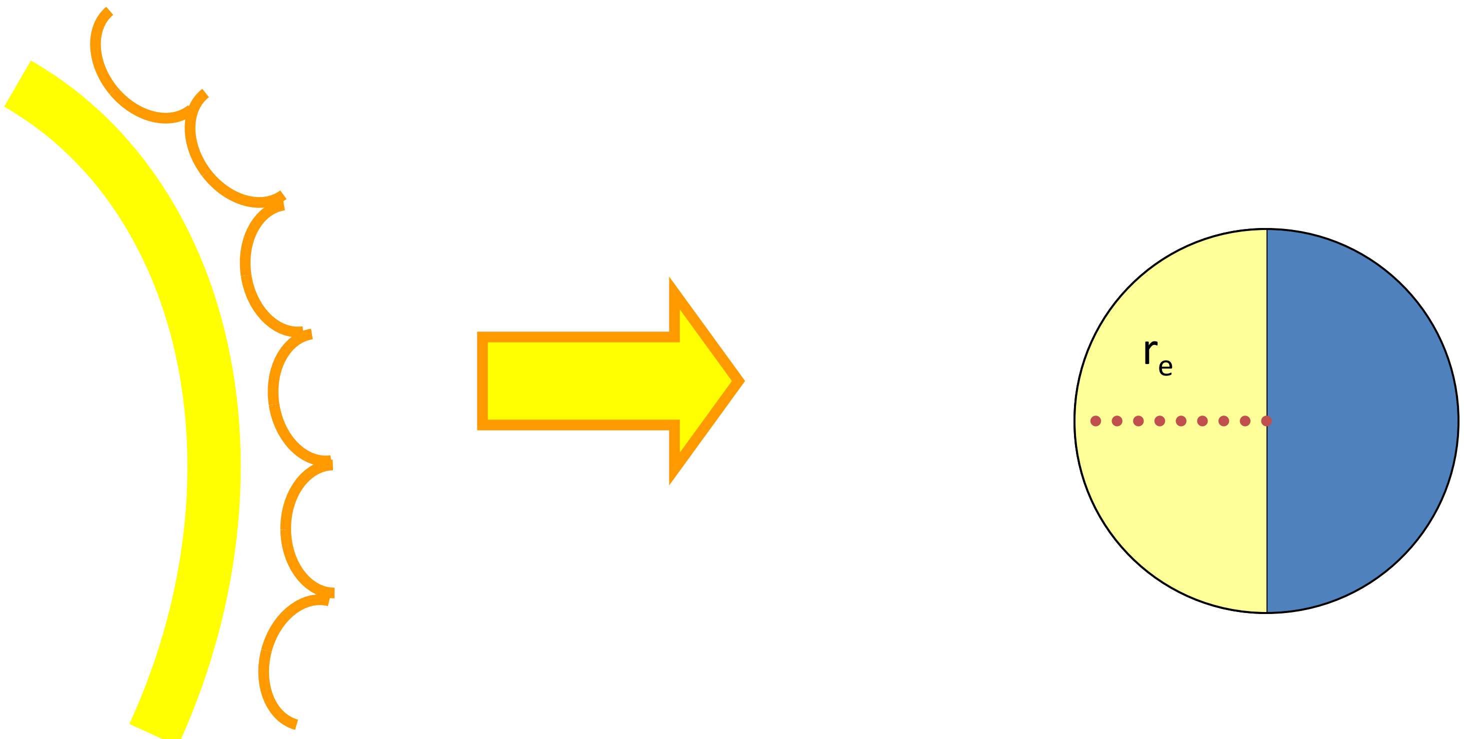
- Start from our equation for radiative equilibrium:

Incoming Radiation = Outgoing Radiation

- Write equation for Incoming Radiation
- Write equation for Outgoing Radiation
- Solve

Earth's radiative temperature

Incoming radiation: energy received from the Sun



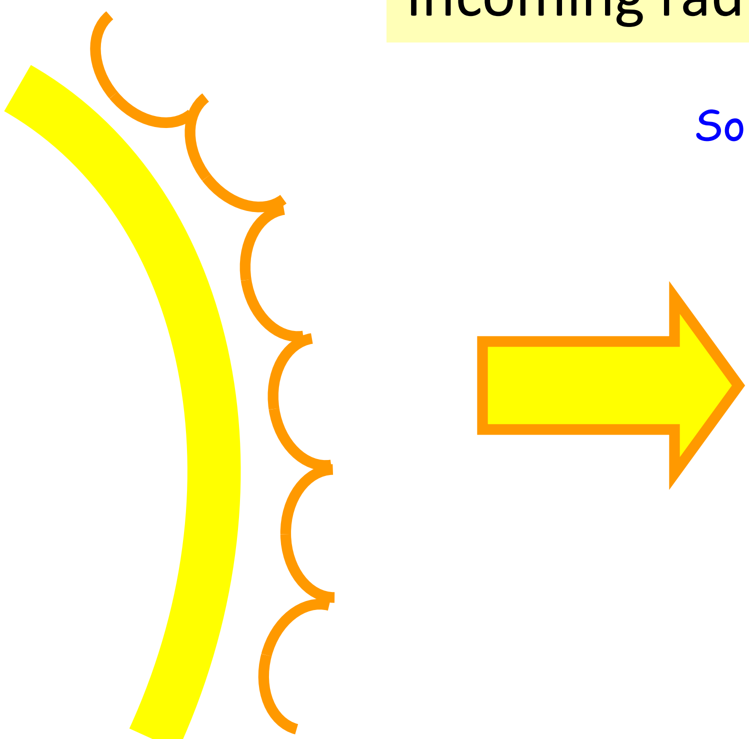
Earth's radiative temperature

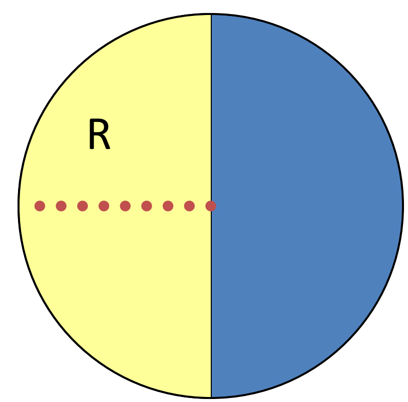
Incoming radiation: energy received from the Sun (S) covers the area of a circle defined by the radius of the Earth (R)

Incoming radiation = $S\pi R^2$

Solar flux

Area

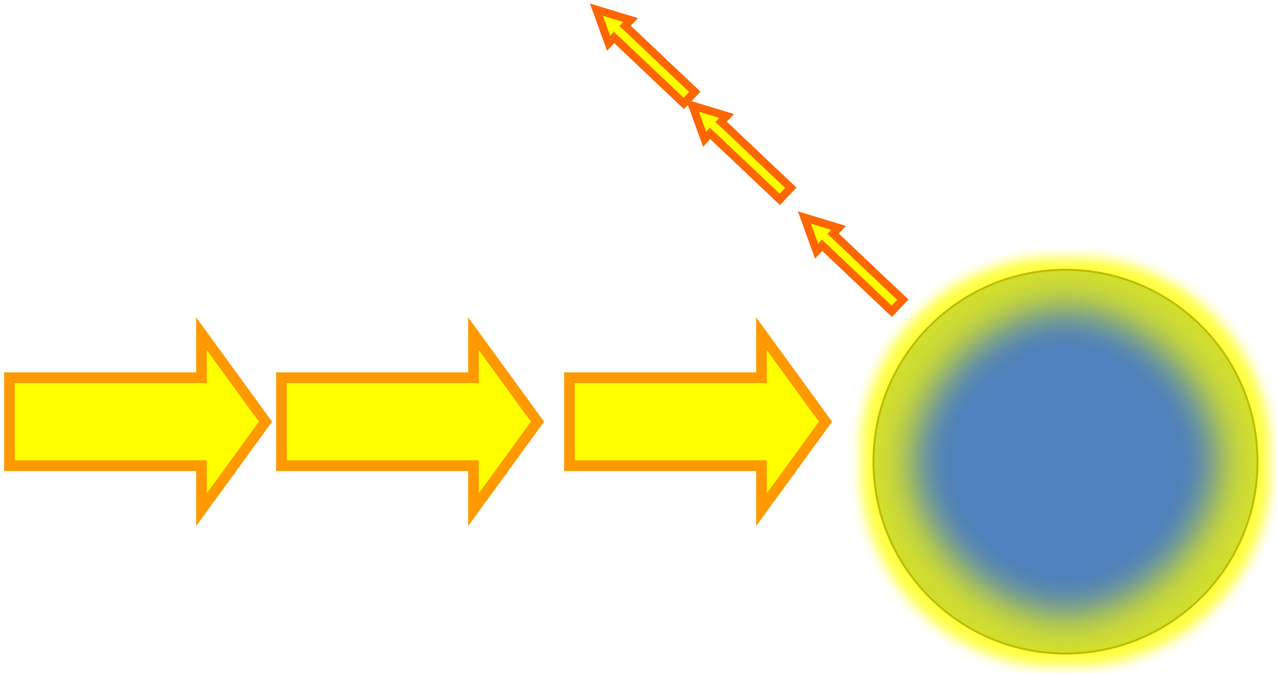




Albedo

Albedo: measure of visible light reflection

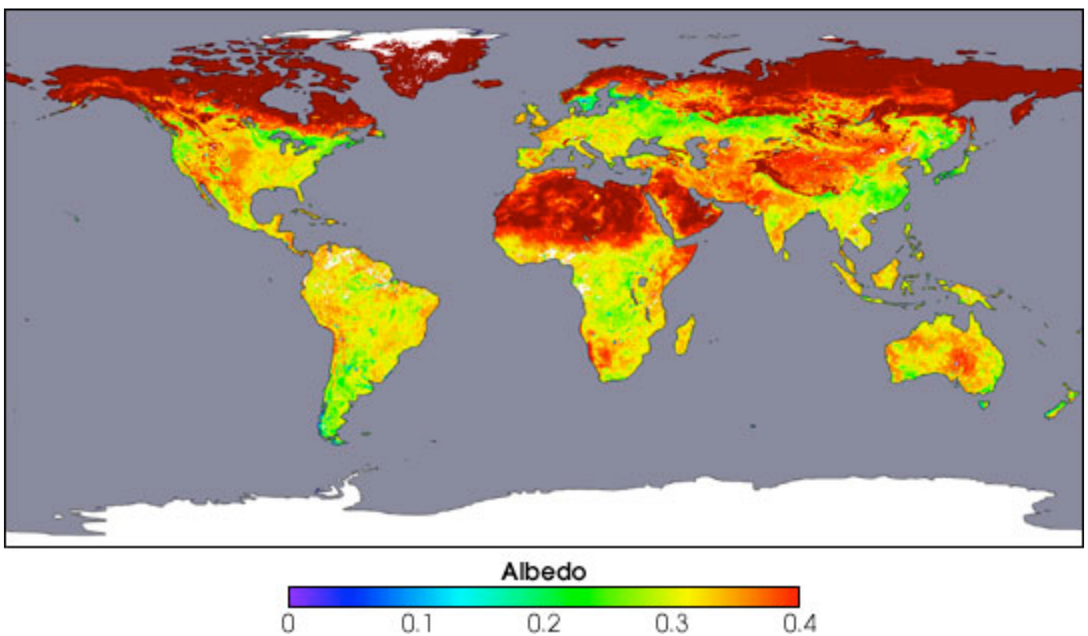
- Some of the incoming visible radiation is not absorbed, it is reflected

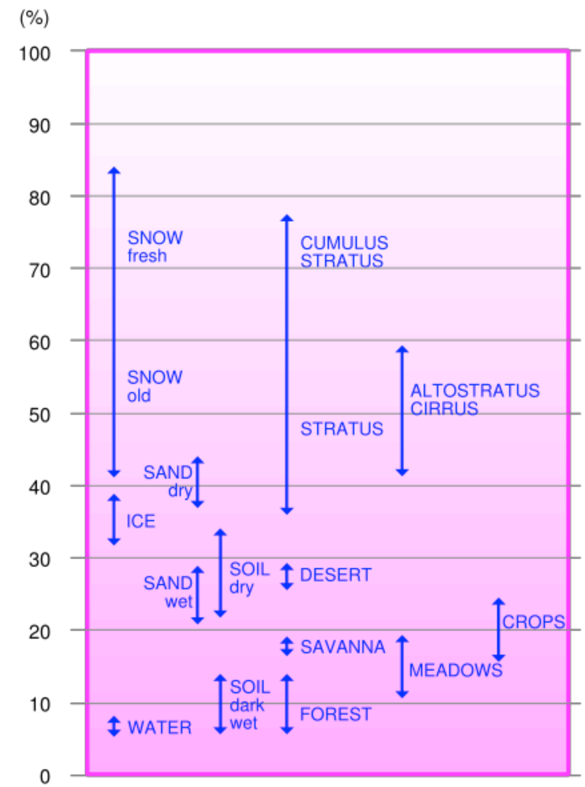


Albedo

Albedo: measure of visible light reflection

- Some of the incoming radiation is not absorbed, it is reflected
- Expressed as a fraction of the total incident radiation
- Varies from 0 (no reflection) to 1 (complete reflection)





Earth's radiative temperature

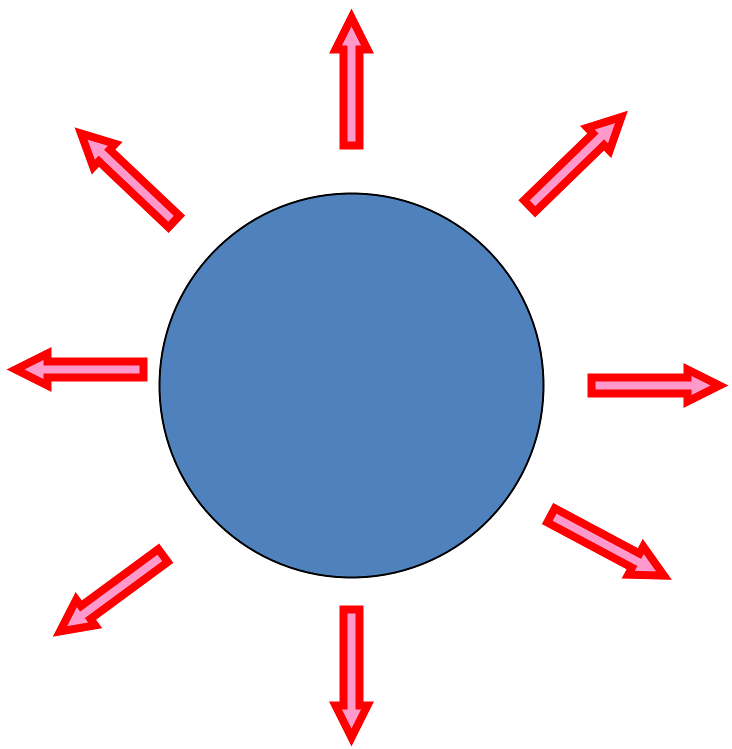
Incoming radiation: energy received from the Sun

- Fraction of incoming radiation that is absorbed is $(1 - \alpha)$

$$\text{Incoming radiation} = \underbrace{S}_{\text{Solar flux}}\underbrace{(1-\alpha)}_{\text{Fraction absorbed}}\underbrace{\pi R^2}_{\text{Area}}$$

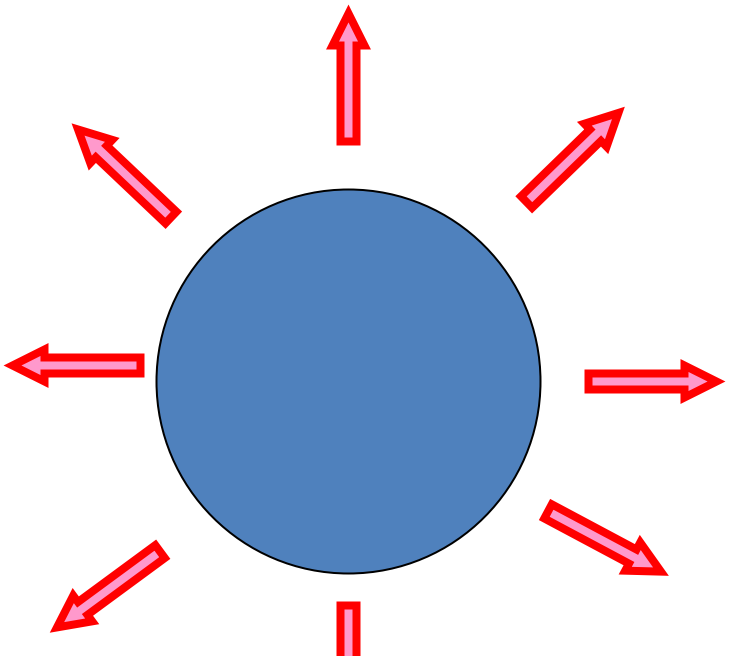
Earth's radiative temperature

Outgoing radiation: energy emitted by planet



Earth's radiative temperature

Outgoing radiation: energy emitted by planet is equal to its black body radiation over its surface area



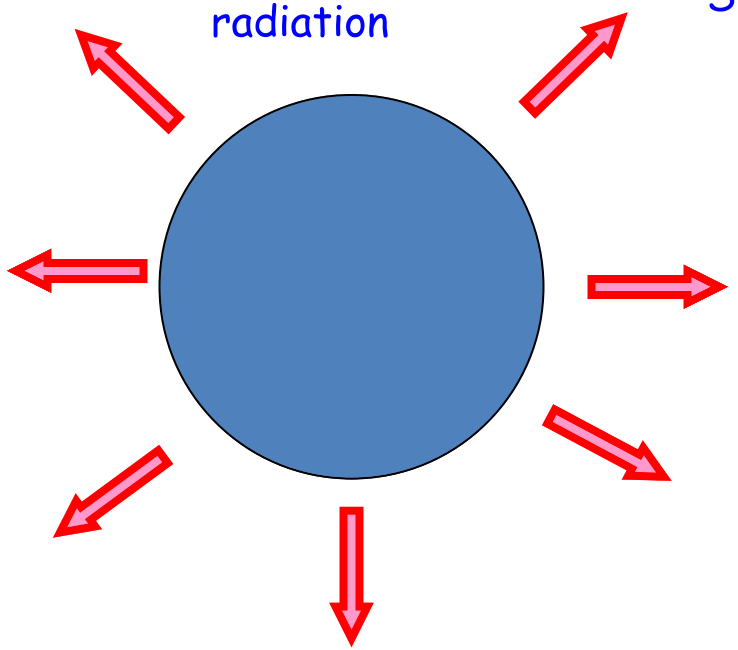
Earth's radiative temperature

Outgoing radiation: energy emitted by planet is equal to its black body radiation over its surface area

Outgoing radiation = $\sigma T^4 4\pi R^2$

Black body radiation

Surface area



Earth's radiative temperature

- Radiative equilibrium model for planet:

Incoming solar radiation

$$S(1-\alpha)\pi R^2 = \sigma T^4 4\pi R^2$$

Outgoing black-body radiation

- Solve for T to estimate planetary temperature

Earth's radiative temperature

- Radiative equilibrium model for planet:

$$S(1-\alpha)\pi R^2 = \sigma T^4 4\pi R^2$$

- Solve for T to estimate planetary temperature

$$S(1-\alpha)\cancel{\pi R^2} = \sigma T^4 4\cancel{\pi R^2}$$

$$\sigma T^4 4 = S(1-\alpha)$$

$$T^4 = S(1-\alpha) / 4\sigma$$

$$T = (S(1-\alpha) / 4\sigma)^{1/4}$$

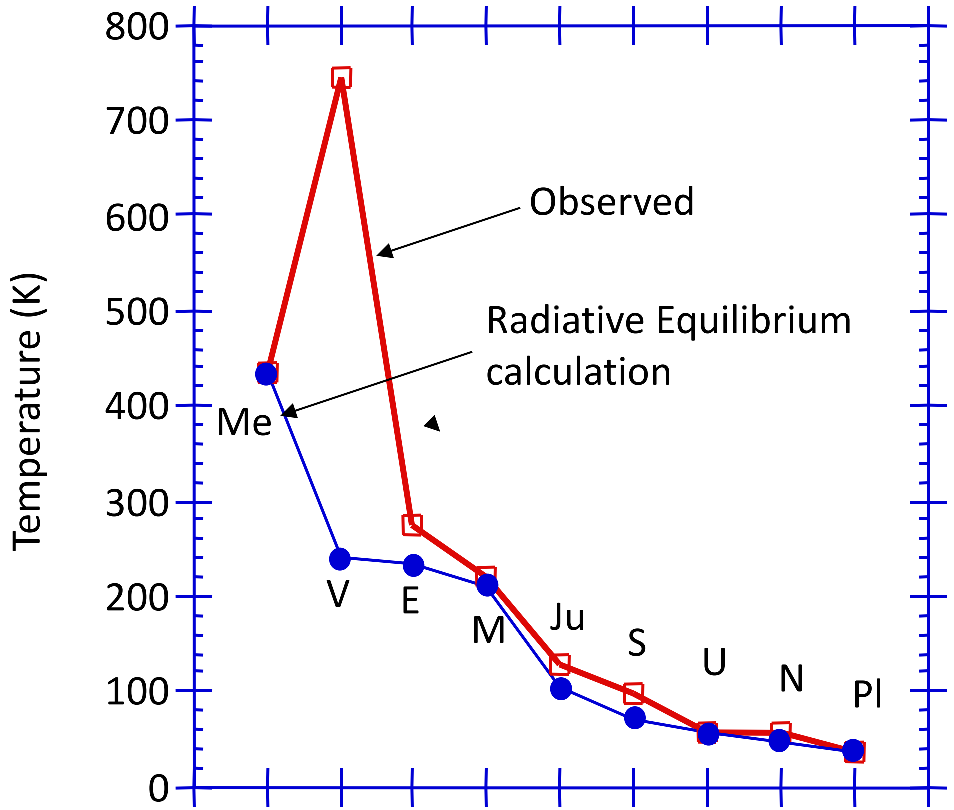
where $S = 1367\ Wm^{-2}$, $\sigma = 5.67 x 10^{-8}\ W\ m^{-2}K^{-4}$, and $\alpha = 0.3$.

Earth's radiative temperature

255 K

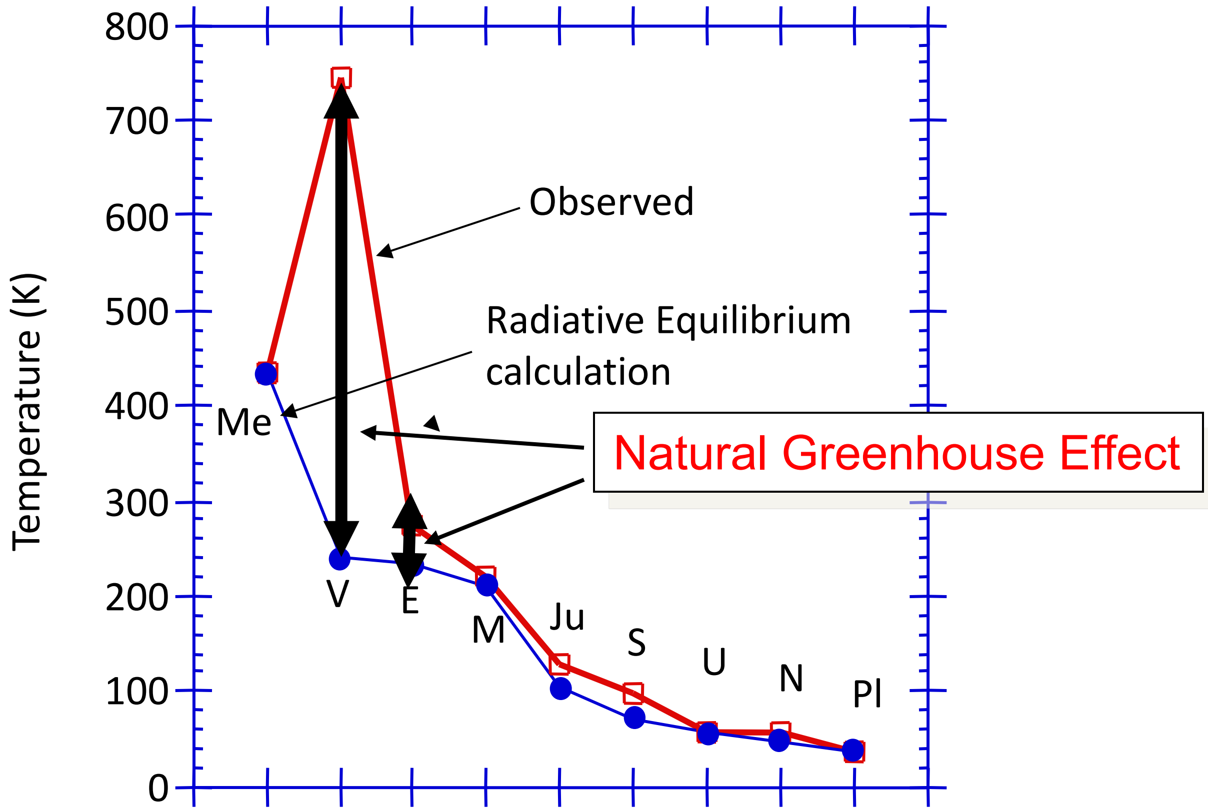
Planetary radiative temperature

Can we use the radiative equilibrium model to predict planetary temperature?



Where did we go wrong?

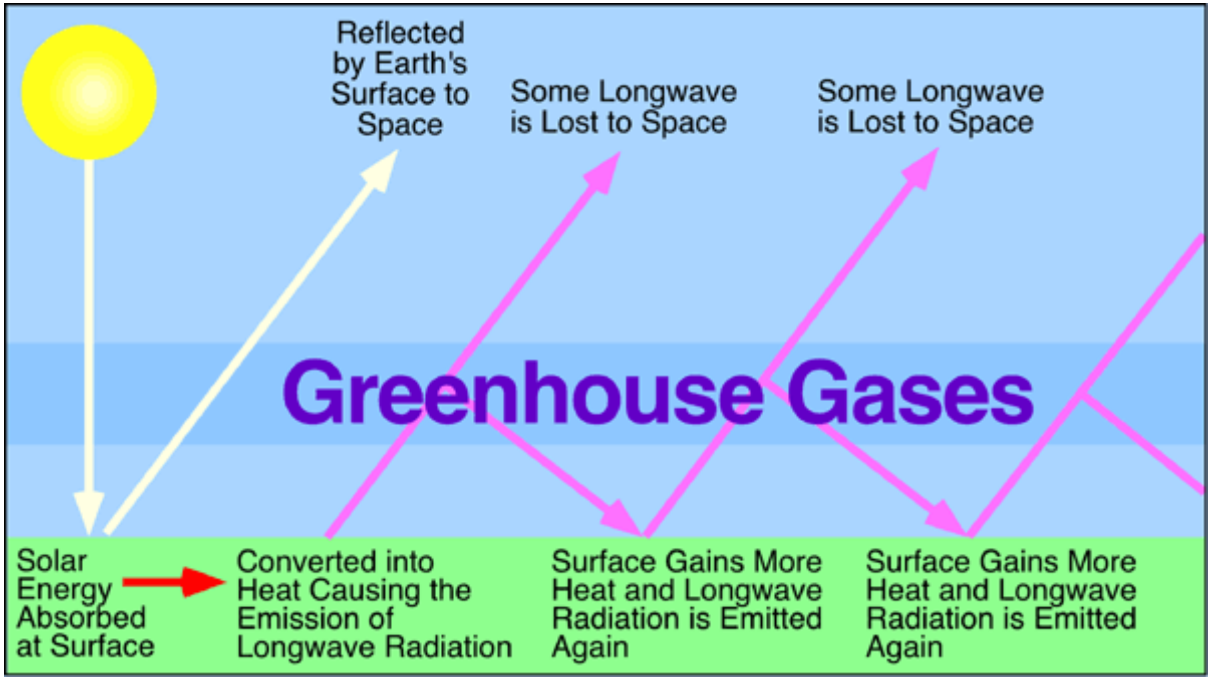
Greenhouse effect: not all radiation emitted by the surface escapes to space. Some is absorbed by gases in the atmosphere (greenhouse gases) and re-emitted back to the surface



Greenhouse effect

Greenhouse effect: traps heat in the lower atmosphere causing warming.

- Atmosphere is almost **transparent** to solar (shortwave) radiation!
- Greenhouse gases absorb infrared (longwave radiation) and re-emit radiation in all directions



Summary

i. Earth receives its energy from the Sun in the form of electromagnetic radiation. Electromagnetic radiation varies by wavelength with warmer objects emitting more energy at shorter wavelengths.

ii. Earth’s global temperature is determined by its energy budget, the difference between the incoming and outgoing energy.

iii. The greenhouse effect exists because gases in our atmosphere are transparent to shortwave radiation, but absorb longwave radiation. The greenhouse effect reduces the amount of outgoing energy, increasing Earth’s temperature.