## Extraterrestrial Life: Lecture #6

What are the requirements for the Earth (or another planet) to be habitable?

- liquid water on surface
- atmosphere
- plate tectonics / volcanism
- magnetic field
- …



Liquid water is important because:

- solvent for organic molecules
- allows transport of chemicals within cells
- involved in many biologically important chemical reactions

Other solvents (ammonia, methane etc) exist in liquid form on planets but are much less promising for life

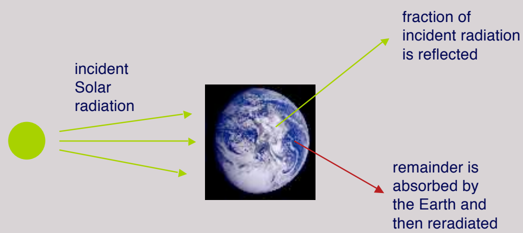
Normal atmospheric pressure: liquid water requires:

$$0^\circ \text{ C (273K)} < T < 100^\circ \text{ C (373K)}$$

…require planets with surface temperatures in this range



What determines the Earth's surface temperature?




If the Earth is not heating up or cooling down, the total of incoming and outgoing radiation must balance

Are there other sources of energy for a planet?

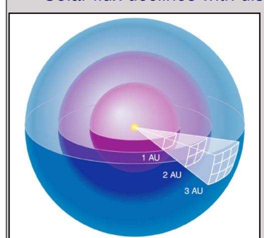


Solar constant

The **flux** of energy is the amount of energy that passes through unit area (1 $m^2$) in one second

Measured in units of watts / $m^2$

Solar flux declines with distance as 1 / $d^2$:




$$\text{flux} = \frac{L}{4\pi d^2}$$

…where d is the Sun - planet distance and L is the total luminosity of the Sun (watts)



Solar constant

Solar luminosity is 3.9 x $10^{26}$ watts

Earth-Sun distance is d = 1.5 x $10^{11}$ m (1 AU)

$$\text{Solar flux } = \frac{3.9 \times 10^{26} \text{ watts}}{4\pi \times \left(1.5 \times 10^{11} \text{ m}\right)^2}$$

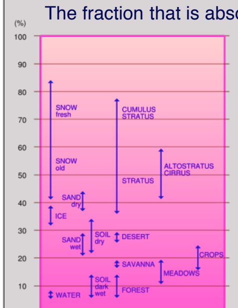
$$= 1380 \text{ watts / m}^2$$

This is the Solar flux that would be measured above the Earth's atmosphere



The fraction of the incident flux that is *reflected* is called the **albedo** of the planet: 0 < A < 1

The fraction that is absorbed is (1-A)

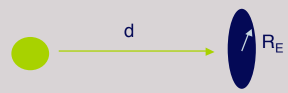



The albedo varies greatly depending on the surface terrain

For the Earth, a global average value is about A ~ 0.3

How does A change as the Earth rotates?

First consider the reflected component of sunlight




Fraction of total Solar luminosity that is reflected is:

$$f = \frac{\text{flux} \times \text{area of Earth as seen from Sun} \times A}{\text{solar luminosity}}$$

$$= \frac{1380 \text{ watts / m}^2 \times \pi R_E^2 \times A}{3.9 \times 10^{26} \text{ watts}}$$

Earth radius is $R_E$ = 6.4 x $10^6$ m

$f = 1.4 \times 10^{-10}$

Seen from another star, Earth is ~10 billion times dimmer than the Sun



How much energy is absorbed?

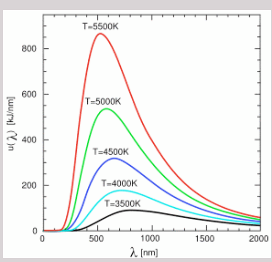
$$P = \text{flux} \times \pi R_E^2 \times (1 - A)$$
$$= 1380 \times \pi \times \left(6.4 \times 10^6\right)^2 \times (1 - 0.3) \text{ watts}$$
$$= 1.24 \times 10^{17} \text{ watts}$$

c.f. total world electricity consumption ~ 5 x $10^{12}$ watts

Note: total forcing due to greenhouse gases is about 2 watts / m$^2$ - i.e. a few tenths of a percent of the total Solar flux… this is why climate change is a complex scientific problem



The absorbed radiation is reradiated as **thermal** radiation, mostly in the infra-red part of the spectrum


As T increases, the peak of thermal radiation moves to shorter wavelengths, and the total emission increases rapidly as ~$T^4$

Sun: 6000K (visible)
Earth: 300K (IR)



Thermal radiation emitted by the Earth is:

$$P_{thermal} = 4\pi R_E^2 \times \sigma T^4$$

area of the Earth's surface in m$^2$

power (watts / m$^2$) emitted by thermal radiation at a temperature T

$\sigma$ is a constant called the Stefan-Boltzmann constant, it equals 5.67 x $10^{-8}$ watts per m$^2$ per K$^4$

Setting the emission equal to the energy absorbed from sunlight determines the equilibrium temperature of the Earth



Find that predict T ~ 260K - a bit too cold! But we have ignored the influence of the atmosphere in blocking some of the outgoing radiation…

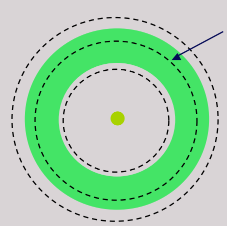
What does the surface temperature depend on:

$$T^4 \propto \frac{L(1-A)}{d^2}$$

- distance to the star
- luminosity of the star
- properties of the atmosphere and surface



Habitable Zone



Earth orbit

Define the *habitable zone* as the range of distances from the Sun for which a planet can have liquid water on its surface

Empirically: Venus is inside the habitable zone and Mars outside for the Solar System

But… calculating the exact boundaries is hard - depends upon the nature of the planet and its atmosphere

Additional complication: Solar luminosity changes with time (slowly)… Sun was less luminous in the past and is slowly getting more luminous

Faint Sun problem: initial Solar luminosity is predicted to be ~70% of the current luminosity… but no evidence that temperature on the early Earth was much colder

Thought to be an atmospheric effect



The *continuously habitable zone* is the range of radii for which liquid water is possible *throughout* a planet's lifetime

Obviously narrower than the instantaneous habitable zone - possibly much narrower…

Means that stars whose luminosity changes relatively quickly are unpromising hosts for life-bearing planets



What about planets on elliptical orbits that dip in and out of the habitable zone?

- surface temperature adjusts to the Solar forcing on a timescale << 1 year (e.g. seasons!)
- temperature underground, or in the oceans, adjusts much more slowly
- planets with non-circular orbits can't be ruled out immediately