The overarching goal of this course is to establish
the main factors controlling global climate

What are we going to do?

By the end of this course, you will be able to…

1. DESCRIBE how Earth's geosphere, atmosphere, hydrosphere, and biosphere comprise an integrated system driven by a continuous supply of energy

On Wednesday, we introduced the overarching goals for this course

This is the first one. On this image of Earth taken from space, you can see all four major components of the Earth system, the continents (part of the geosphere), the clouds (in the atmosphere, but also part of the hydrosphere), the oceans (part of the hydrosphere), and some plants (part of the biosphere).

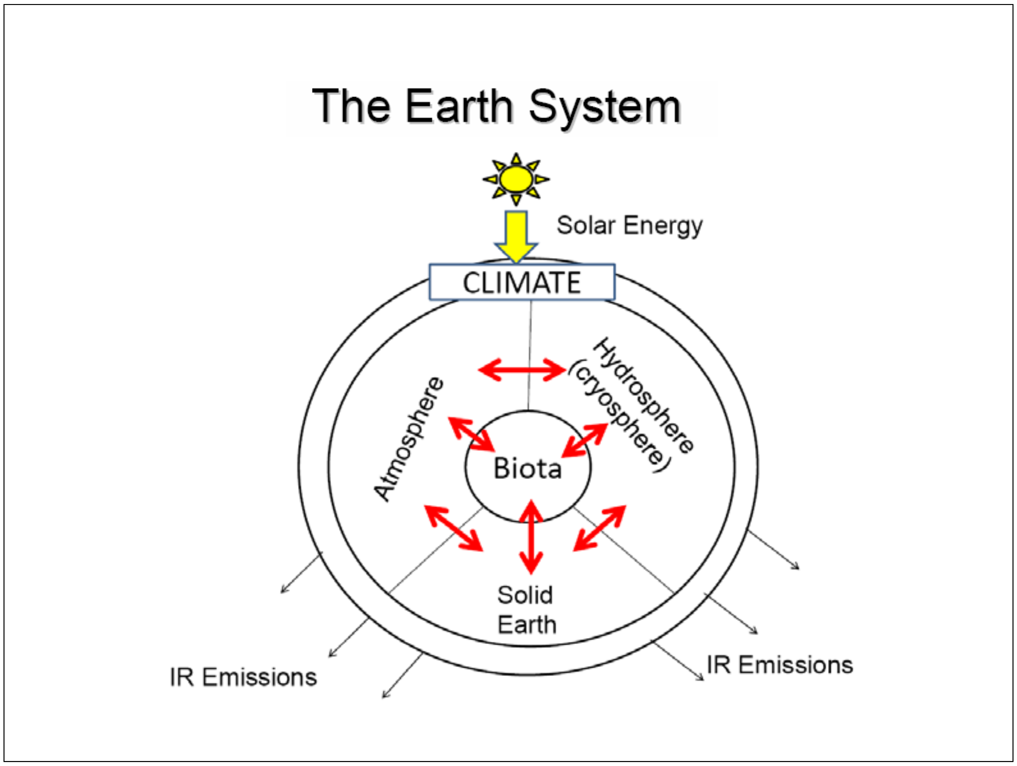
Definitions:

The atmosphere: the thin layer of gases enveloping the Earth

The hydrosphere: all the water found on Earth in liquid form (oceans, rivers, lakes, groundwater, rain), solid form (ice, sometime called the "cryosphere") or gaseous form (water vapor in the atmosphere)

The geosphere, or "solid Earth": all the solid materials that make up the Earth's crust (or outer layer) and the Earth's interior (the mantle and the core)

The biosphere or "biota": which encompasses all living organisms



We can represent the Earth System in a schematic way with:
- four distinct components in separate boxes enclosed into the overall envelop of the Earth System
  - atmosphere → layer of gases enveloping Earth
  - hydrosphere → includes all water on Earth (cryosphere refers to water in the form of solid ice)
  - biota (or biosphere) → includes all living organism on Earth
  - solid earth → Earth's crust and Earth's interior
- arrows indicating exchanges of material or energy between the different components of the system.

the Earth system is driven by the continuous input of solar energy

It is the flux of solar energy (or the Earth's solar constant) that determines the mean temperature and the habitability of the planet

That solar energy also drives Atmospheric and ocean circulation. This in turn redistributes solar heat from the equator to the poles and dictates precipitation patterns, therefore having a clear effect on the Earth's climate.

What about solid earth (i.e. the Earth's crust and interior). How can solid Earth affect the evolution of climate?

Factors controlling the Earth's climate

– Amount of solar radiation received by Earth: controlled by
  - *Intensity of solar radiations*
  - *Earth's orbit*

– Amount of solar radiation absorbed by Earth: controlled by
  - *Earth's albedo*
  - *Atmospheric greenhouse gases*

– Redistribution of solar radiations on Earth's surface: controlled by:
  - *Atmospheric circulation*
  - *Ocean circulation*

We have a lot of information to integrate and digest to understand the climate throughout Earth's history and today..

We must understand the factors that control:

- the amount of incoming solar radiations that reaches and are absorbed by Earth
- the redistribution of solar radiations on the Earth's surface

This slide essentially summarizes what we will be studying in this course..

During the first two lectures, we will establish the factors that control the amount of incoming solar radiations that reaches and are absorbed by Earth

Radiation Balance I

Goals for Today

1. **DESCRIBE** electromagnetic radiations and **COMPARE** them in terms of **frequency** and **wavelength**
2. **COMPARE** the amount and type of energy emitted by objects at different temperatures
3. **PREDICT** the factors that determine the amount of solar radiation reaching a planet (or its "**solar constant**")
4. **CALCULATE** the flux of solar radiation (W/m^2) reaching the top of the Earth's atmosphere (i.e. Earth's solar constant)

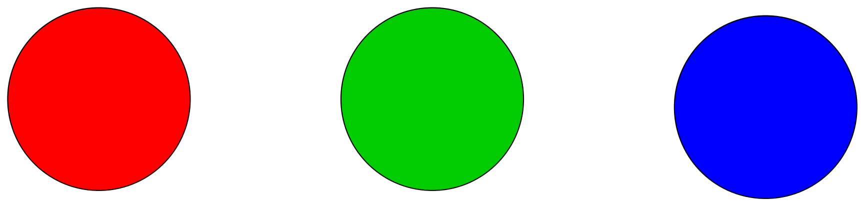
Here are the goals for today's lecture

The sun transfer energy to Earth in the form of ELECTROMAGNETIC RADIATIONS.

We are therefore first going to describe what are electromagnetic radiations

What determines how much solar energy Earth gets? The **solar constant** is the amount of solar radiation or energy (in Joules) reaching Earth per unit time (seconds) and per unit surface area (metres^2). Units of the solar constant are Joules/metre^2*seconds, which is the same as Watts/m^2 (see the extra slide about Key Units). To imagine the solar constant, imagine a piece of cardboard that is one metre square. Imagine the cardboard orbiting Earth at the top of Earth's atmosphere with its flat side DIRECTLY facing the Sun's rays. The solar constant is the amount of solar energy hitting the piece of cardboard every second (Watts/m^2)

RELEVANCE



Venus (too hot) **Earth (just right)** **Mars (too cold)**

The flux of solar radiation reaching Earth is one of the main factors dictating its mean temperature, and therefore its habitability

What is the relevance of knowing how much solar radiation reaches the Earth?

The amount of solar radiation reaching Earth is one of the main factors that dictates its mean temperature.

The mean temperature of a planet is a fundamental variable which dictates its habitability.

To harbor life as we know it, a planet needs liquid water, which only exists within a narrow range of temperature

In our solar system, Venus is too close to the sun and too hot, Mars is too far and too cold. Earth is the “Goldilocks” planet (from the children’s story “Goldilocks and the Three Bears”). It’s not too cold, it’s not too hot, it’s **just right**…, i.e. it just receives just the right amount of solar radiation.

Figuring out the factors that control the mean temperature of our planet is thus central to our fundamental quest for understanding the origin and evolution of life on Earth and to our search for other planets which could possibly support life.

RELEVANCE

Photovoltaics (solar panels)

Artificial photosynthesis

Solar radiation could potentially provide an inexhaustible source of energy

Solar radiation not only controls the Earth's temperature, but also could potentially provide an inexhaustible source of energy if we can devise means of harvesting it effectively.

Photovoltaics (solar panels) have been around for decades now. They generate electricity from solar radiation, which is typically then stored in a battery for later use. Electricity from photovoltaics can also be used directly to operate equipment.

Artificial photosynthesis is an emerging technology that seeks to mimic the process by which plants use solar energy to split water molecules. The primary goal is to use this process to produce hydrogen, which could then be used as liquid hydrogen fuel, or in fuel cells. Major advances in this technology are expected in the next few years.

Key units for Today's Goals (International System; SI)

- **Force (Newton; N) = mass x acceleration**

  A force of 1N accelerates a mass of 1kg at a rate of 1m/sec^2

- **Energy or work (Joule; J) = Force x distance**

  1 J is the energy produced (or work done) by a force of 1N moving an object by 1 m

- **Power (Watt; W) = Energy / time**

  Amount of energy that is emitted, absorbed or reflected per unit time (1J/sec)

- **Energy flux or intensity (Watt per m^2; W/m^2) = Power / area**

  Amount of energy that is emitted, absorbed or reflected per unit area per unit time (J/m^2*sec)

notes

NOTES SLIDE (not shown in class):

In this class, we will come across a range of different units, particularly for energy flux or intensity, which reflects the amount of energy that is emitted, absorbed or reflected by a unit area per unit time [W/m^2 or J/sec*m^2]

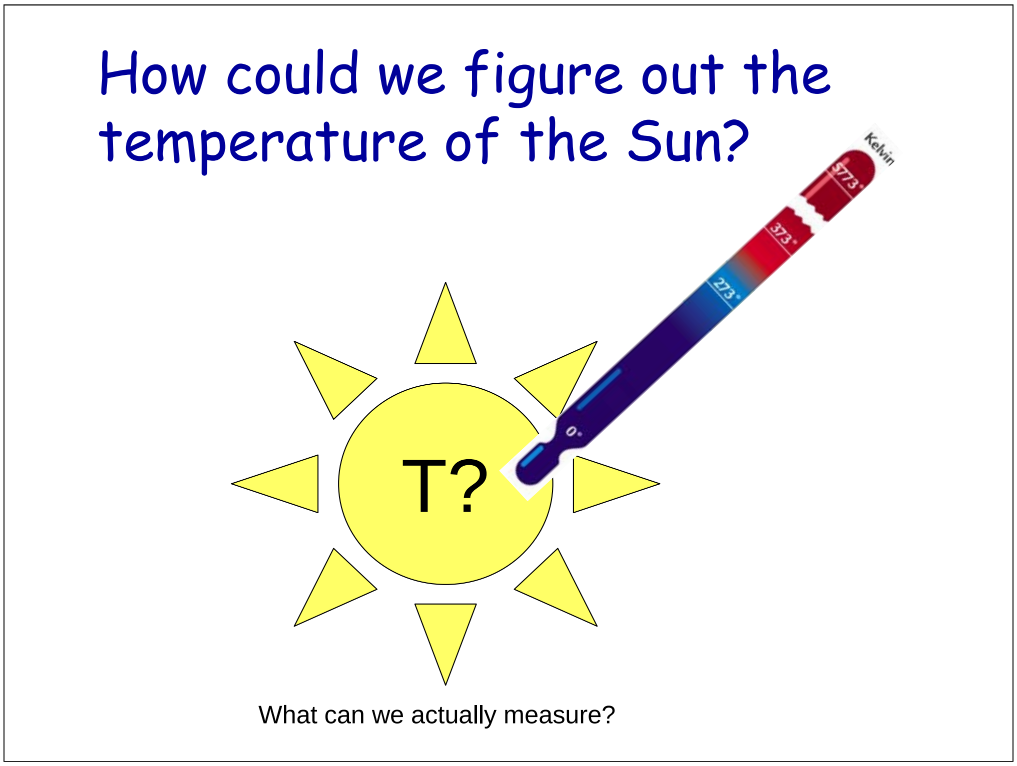
<u>Here are a few analogies for these units:</u>

The **force** of gravity on a medium-sized apple on Earth's surface is about equal to one **Newton**. The **force** of gravity on a 150-pound (68 kg) human on Earth's surface is about 667 **Newtons** (68 kg * 9.81 m/sec^2 (9.81 m/sec^2 is the acceleration at Earth's surface due to gravity)).

One **Joule** is the energy required to lift a medium-sized apple one metre up. One **Joule** is also approximately the energy released as heat by an average-sized person, resting, every 1/00th of a second. The **energy** required for a 150-pound (68 kg) person to climb the stairs from Wreck Beach to the UBC campus (say, about 80 metres up) is about 53360 **Joules** (667N * 80 m).

Different light bulbs use energy at different rates. You can buy light bulbs that use 25 **Watts** (25 J/sec), 60 W (60 J/sec), 100 W (100 J/sec), etc. In walking up those stairs from Wreck Beach, a 150-pound (68 kg) human is emitting about 180 **Watts** (180 J/sec) if it takes about 5 minutes to climb the stairs (53360 J/300 sec).

The surface area of our 150 pound (68 kg) human is about 1.8 m^2. So, in terms of **energy flux** or **intensity**, while climbing those stairs from Wreck Beach, this human is emitting about 100 **W/m^2**.

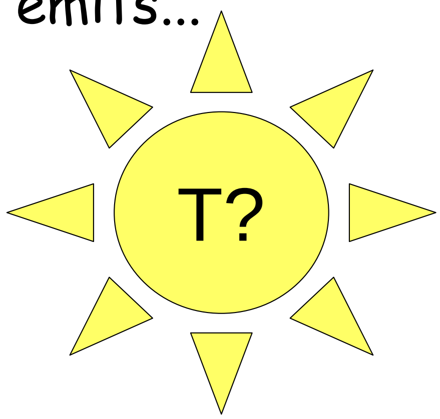


So, if we need to calculate the amount of energy emitted by the sun, we must know its temperature..

Clearly, we cannot use a thermometer…

Then what can we measure to establish the sun’s temperature?

We can figure out the temperature of the Sun from the characteristics of the radiations that it emits...



Solar radiations are electromagnetic radiations..

We can figure out the temperature of the Sun from the characteristics of the radiations that it emits.

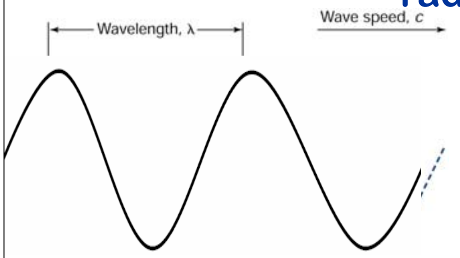
What are solar radiations? Solar radiations are electromagnetic radiations

Any material whose temperature is greater than absolute zero emits electromagnetic radiations

You emit electromagnetic radiations etc…

The sun also emits electromagnetic radiation.

Sun = radiating body that emits electromagnetic radiations..



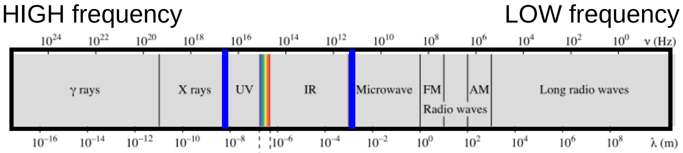
→Waves propagating at the fixed speed ($c = 3\ 10^8\ m.s^{-1}$)

λ = wavelength = distance between adjacent crests

ν = frequency = number of crests that passes a fixed point per second

HIGH frequency

LOW frequency



SHORT wavelength

LONG wavelength

Electromagnetic spectrum

$$c = \lambda * \nu$$

(m/s = m * #/s)

OR

$$\lambda = c / \nu$$

(m = m/s / #/s)

Electromagnetic radiations consist of electromagnetic waves that propagate at a fixed speed (the speed of light in a vacuum $c = 3\ 10^8\ m.s^{-1}$) and are characterized by their wavelength or frequency

The distance between two adjacent crests of the wave is called the wavelength (denoted by the Greek letter lambda)

The frequency is the number of crests that passes a fixed point per second (represented by the Greek lette nu)

The speed (c) of the wave (measured in units of “distance” per “time”, just like a car or bicycle) = the number of crests passing a fixed point (the frequency) x the wavelength

Rearranging this simple equation, we find that as the frequency increases, the wavelength must decrease, and vice versa. Short wavelength corresponds to high frequency (and high energy per photon); long wavelength corresponds to low frequency (and low energy per photon).

This produces the electromagnetic spectrum:

The wavelength of electromagnetic radiation ranges from less than 0.01 um [10^{-8} m] (X-rays and gamma rays, which have **short wavelength, high frequency, and high energy per photon**) to more than 1mm [10^{-3} m] (microwaves and radio waves, which have **long wavelength, low frequency, and low energy per photon**). In between these extremes (blue lines on the graph above) we find the **ultraviolet** (UV), **visible light** (from violet to red with increasing wavelength) and the **infrared** (IR) radiation. These are the most important parts of the electromagnetic spectrum concerning climate and life on Earth.

So how does this help with the issue of figuring out the Sun’s temperature?

Scientific Notation

Example: Write a really big number in scientific notation:

63,500,000,000 is more easily written as:

$6.35*10^{10}$

which means 6.35 x 10,000,000,000 (10 zeros)

Example: Write a really small number in scientific notation:

0.000000000635 is more easily written as:

$6.35*10^{-10}$

which means 6.35/10,000,000,000, i.e. $6.35/10^{10}$ (which is the same thing as $6.35*10^{-10}$)

NOTES SLIDE (not shown in class):

For those of you who may not be familiar with the scientific notation, it is a way of writing very large and very small numbers that are awkward to write down in the more familiar decimal notation. We will use scientific notation quite a bit, so work with it until you understand it.

Wien's law

(as temperature increases,
the wavelength (λ) of radiation decreases)

$$\lambda_m = w / T$$

λ_m = wavelength of maximum intensity (μm)
w = Wien's constant (2897 μm K)
T = absolute temperature (K)

What wavelengths of radiation does the Sun emit? (What about Earth? What about you?)

This is what we call Wien's law

Wien's law states that the wavelength of maximum intensity emitted by a radiating body is inversely proportional to the absolute temperature of the radiating body.

That is, as the temperature of an object increases, the wavelength of maximum intensity of radiation decreases. This is an empirically (experimentally) derived relationship.

Wien's law can help us figure out the Sun's temperature, based on the wavelengths of electromagnetic radiation the Sun emits.

How can this help us figure out the Sun's temperature? We could MEASURE the wavelength of maximum intensity of radiation coming from the Sun, then use Wien's law to calculate its temperature.

Absolute temperature and the Kelvin scale

Absolute zero = temperature at which atoms are not vibrating (-273°C)

Absolute temperature (°K)
=
Temperature in °C + 273

As heat is applied:
→ atoms vibrate faster
→ temperature increases

Wien's law gives the ABSOLUTE TEMPERATURE of the Sun

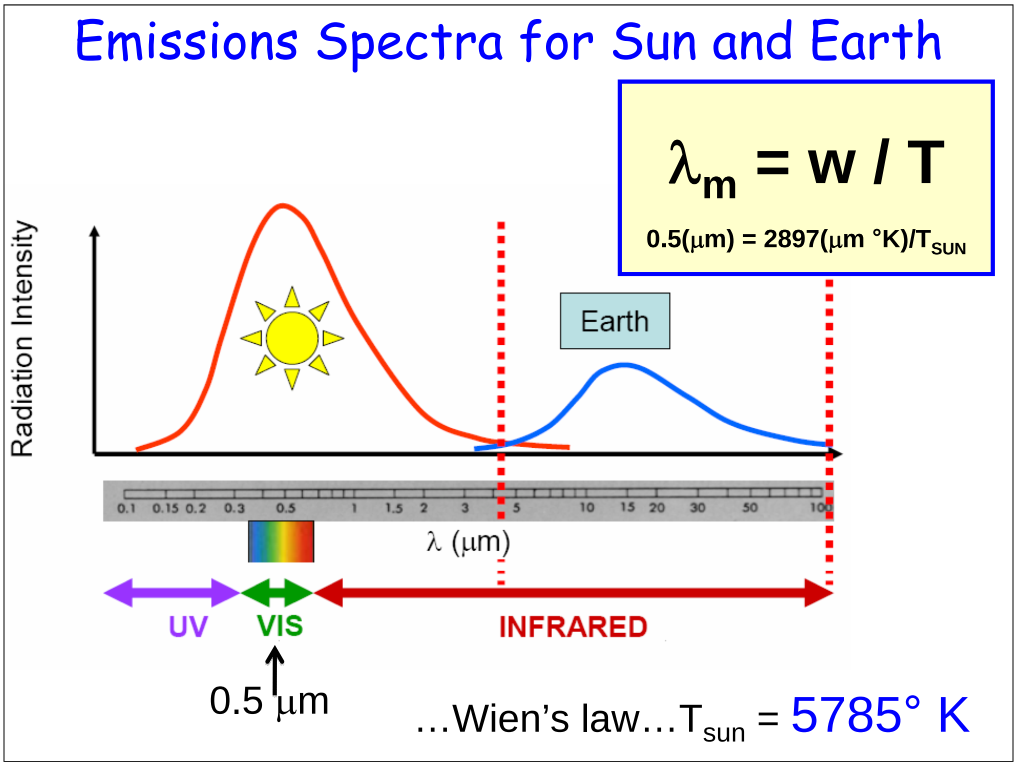
Absolute temperatures refer to temperature measured on the Kelvin scale. On the Kelvin scale, the lowest point is absolute zero (temperature cannot go lower) which is the temperature of a body in which the individual atoms are not vibrating. As heat is applied, atoms start to vibrate faster and temperature increases.

Absolute zero (0 Kelvin) corresponds to a temperature of -273°Celsius

To convert Celsius temperature to absolute temperature (Kelvin), add 273.

Absolute temperature (°K) = Temperature in °C + 273

Example: water boils at 100°C, which is (100 + 273) = 373°K



If we measure the spectrum of electromagnetic radiation emitted by the Sun (i.e. intensity of emission as a function of wavelength), we find that the Sun's wavelength of maximum emission is in the visible range, at about 0.5 micrometres wavelength. That's the "peak", or "wavelength of maximum emission" in Wien's Law. Of course, the Sun emits also radiation all across the visible part of the spectrum, and also emits UV and IR radiation.

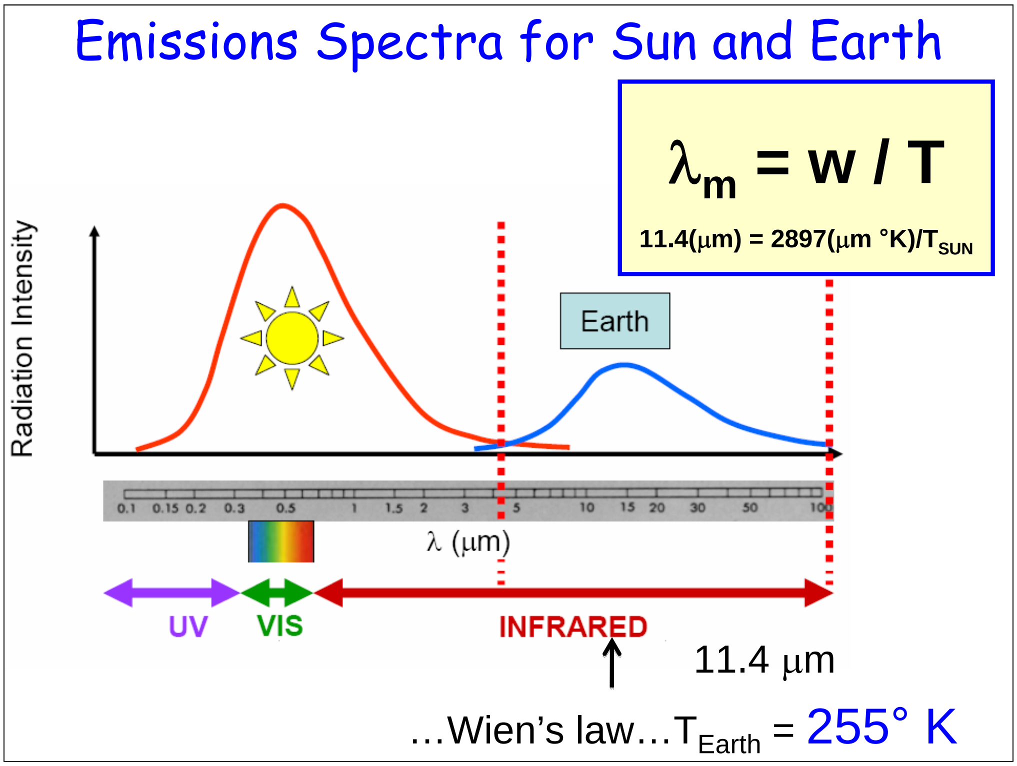
With a peak wavelength of 0.5 micrometres, we can now use Wien's law and figure out the Sun's temperature:

λ_m = w/T

0.501 micrometres = (2897 micrometres K)/Sun's temperature

Rearrange:

Sun's temperature = (2897 micrometres K)/0.501 micrometres = 5785 K (recall, that's "degrees Kelvin").



What about Earth?

Earth emits infrared radiation at a peak wavelength of about 11.4 micrometres.

What temperature does that correspond to? (255-273 = -18°C)

How is ENERGY emitted related to temperature?

If you start with a cold object and add heat…
→ atoms vibrate faster
→ temperature increases
→ some of the kinetic energy is emitted as **electromagnetic waves**
→ electromagnetic waves propagate from the radiating object
→ emitted radiation increases with increasing temperature

So we've established that we can figure out the temperature of an object (the Sun, the Earth, an elephant) using the wavelength of electromagnetic radiation it emits. But HOW MUCH energy does it emit? It turns out that temperature matters for this too. *As a reminder, we're heading toward figuring out how much solar radiation Earth receives per second, per metre^2 (Earth's **solar constant**).*

At absolute zero (= -273°C), the individual atoms of any substance are frozen in place and do not vibrate. At any temperature higher than that, the atoms start vibrating (faster and faster as temperature increases). Some of the kinetic energy associated with these vibrations is emitted from the substance in the form of **electromagnetic waves**, which propagates away from the radiating object. As temperature increases, the amount of radiation emitted also increases, because the atoms are vibrating faster (at absolute zero, atoms do not vibrate and therefore no electromagnetic radiation is emitted)

Any body with a temperature above absolute zero emits electromagnetic radiation. Just like the Sun, we humans emit electromagnetic radiation. The photograph in the slide was taken in the dark with a camera sensitive to infrared radiation. IR radiation cannot be seen by our eyes, which only see visible light.

Stefan-Boltzmann's law (very useful!)

(The energy emitted by a star is proportional to its temperature to the 4th power)

$$F = \sigma T^4$$

F is the energy emitted by the Sun, per unit time, per unit area, expressed in W/m^2

σ is a constant [$5.67 * 10^{-8}\ W/m^2K^4$]

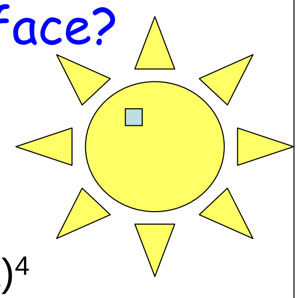
T is the absolute temperature (K)

Stefan-Boltzmann's Law provides us with a means to relate the temperature of a body to the amount of energy it emits. We've figured out the Sun's temperature with Wien's Law; now we can use it in Stefan-Boltzmann's Law to get the energy the Sun emits (F), PER SECOND, PER METRE^2 (the metre^2 is for an area on the Sun's surface).

Try using Stefan-Boltzmann's law for a few examples. Earth? A human? How much energy is emitted?

Recall that the energy per photon is higher for shorter wavelength, higher frequency radiation. Thinking about Wien's law, as something gets hotter, it emits shorter wavelength radiation, which has higher energy per photon. As the temperature goes up, and the wavelength of maximum emission goes down, the energy per photon goes up. Stefan-Boltzmann's law takes into account that increased energy per photon at shorter wavelengths.

How much energy leaves EACH square meter of the Sun's surface?



$F = \sigma T^4$ (Stefan-Boltzmann's law)

F_{Sun} = (5.67×10^{-8} W/m^2K^4)*(5785 K$)^4$

= 6.35×10^7 (W/m^2)

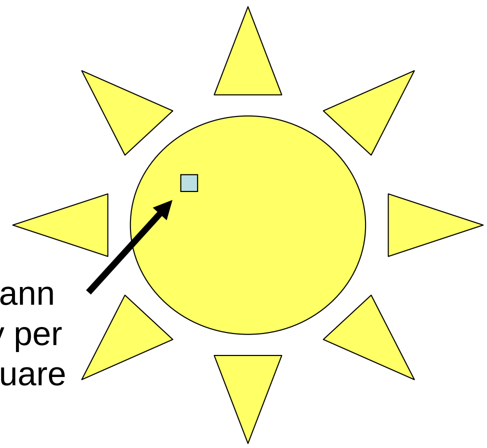
= **63,500,000 W/m^2**

Every single square metre of the Sun's surface emits 63.5 million Joules every second

Using Stefan-Boltzmann equation, we can calculate the energy emitted by the Sun from its temperature

Each square meter of the Sun's surface emits 63.5 10^7 Watts.

How would you figure out the total energy emitted by the Sun?

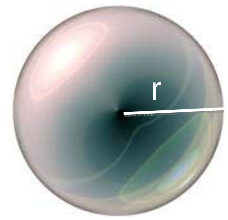


Stefan-Boltzmann tells us energy per second per square metre…

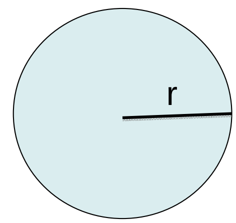
How big is the Sun? How many square metres on its surface?

Useful Geometry

Surface area of a SPHERE = $4\pi*r^2$



Surface area of a CIRCLE = $\pi*r^2$



Surface area of sphere/surface area of circle = 4

NOTES SLIDE (not shown in class):

Useful geometry:

We're going to be doing some math, with geometry. There are ONLY TWO geometric relationships that we're going to use. One of them we use repeatedly. It's the same thing over and over and over again. That's the **SURFACE AREA OF A SPHERE**.

Surface area of a sphere = $4*pi*r^2$ where "r" is the radius of the sphere.

We're going to use the **SURFACE AREA OF A CIRCLE** once.

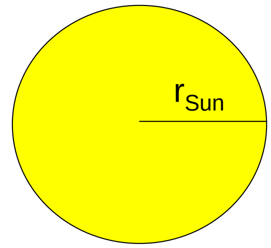
Surface area of a circle = $pi*r^2$ where "r" is the radius of the circle.

NOTICE that the surface area of a sphere happens to be exactly 4 times the surface area of a circle. This will prove useful.

Total energy emitted by the Sun

Sun's radius (r_{sun}) = $7*10^8$ m

(that's 700,000 km)



Sun's total surface area

= $4\pi(r_{sun})^2 = 6.16*10^{18}$ m^2

Total energy emitted by the Sun:

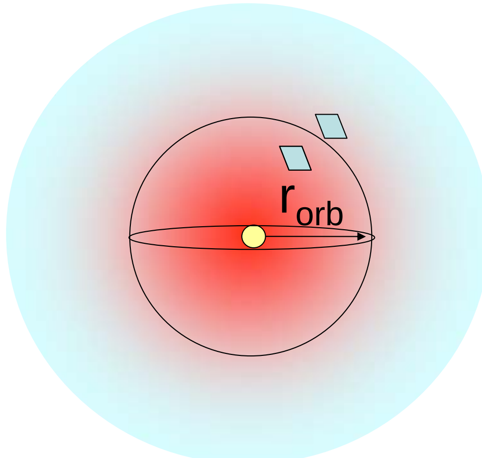
= surface area * energy per m^2

= $6.16*10^{18}$ m^2 * $6.35*10^7$ (W/m^2)

= **$3.91*10^{26}$ W**

The total amount of energy emitted by the Sun per unit time (W; J/s) = energy emitted per surface area (just calculated on previous slides) x surface area of the Sun

What happens to the energy after it leaves the Sun?

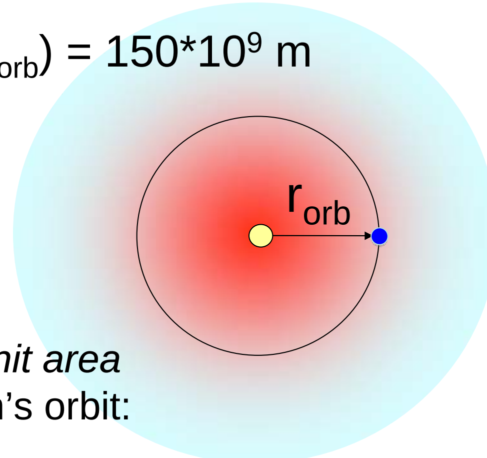


The total amount of energy initially emitted by the Sun's surface is spread over a larger area as it moves away from the Sun

What we want to know is the amount of solar energy (W/m2) that reaches the Earth. As the energy moves away from the Sun, it gets spread over a bigger and bigger area. The amount that reaches Earth (per square metre) depends on the distance between the Earth and the Sun. The farther a planet is from the Sun, the fewer Watts per square metre it receives.

How much solar energy reaches Earth?

Radius of Earth's orbit (r_{orb}) = $150*10^9$ m



Surface area of sphere with radius r_{orb}:

$= 4\pi(150*10^9 \text{ m})^2$

$= 2.83*10^{23} \text{ m}^2$

Solar energy received *per unit area* at the distance of the earth's orbit:

$= F_{orbit} = 3.91*10^{26} \text{ W} / 2.83*10^{23} \text{ m}^2$

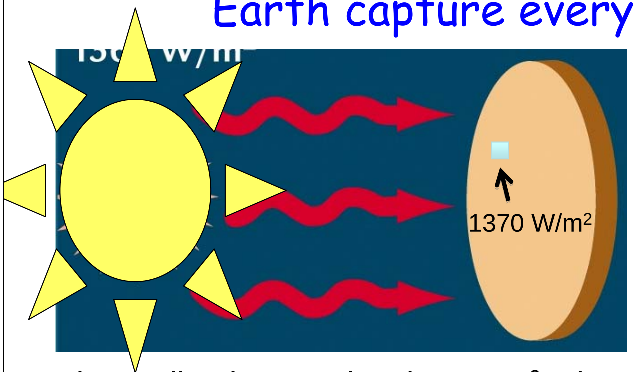
$= 1{,}370 \text{ W/m}^2$ ← This is the SOLAR CONSTANT

To calculate the amount of solar energy reaching Earth, we must take into account that the total amount of energy emitted by the Sun is uniformly spread over the surface area of a sphere whose radius is equal to the Earth's orbit.

We find that at our distance from the Sun, the amount of solar energy per square meter is reduced from 63.5 million W/m^2 to a mere 1,370 W (1370 W/m2), which we call the **solar constant**. This is the amount of energy that would hit that square metre of cardboard in orbit at the top of Earth's atmosphere if its flat side were directly facing the Sun.

As we will see later, the "**solar constant**" is not really constant..

How much TOTAL solar energy does the Earth capture every second?



Earth's radius is 6371 km ($6.37*10^6$ m)

Earth's cross section is $\pi(6.37*10^6 m)^2 = 1.28*10^{14}$ m^2

The total amount of sun energy intercepted by Earth:

$= E_{in} = 1,370 \text{ (W/m}^2) * 1.28*10^{14} \text{ m}^2$

$= 1.75*10^{17}$ W

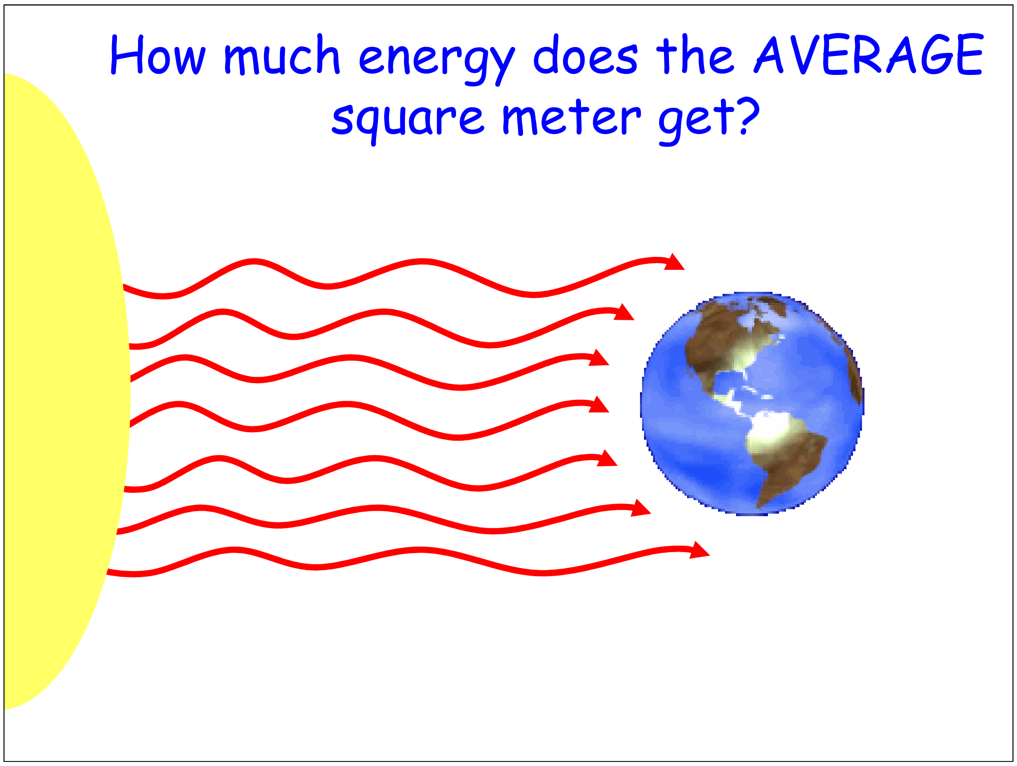
We're getting closer…

To figure out how much TOTAL SOLAR ENERGY the Earth captures every second, we need to think about the Earth as a disk, rather than a sphere. This Earth-disk is blocking the Sun's rays from getting past it (just like you can block the Sun's rays, and you see your resulting shadow).

The area that actually intercepts the Sun's rays is the area of a circle with the same radius as Earth. Earth's radius is 6371 km. We can figure out the area (in square metres) of that circle using area = pi*r^2. From that, we figure out that the disk (cross section of the sphere that is Earth) has an area of $1.28*10^{14}$ m^2. EACH ONE of those square metres is intercepting 1370 W.

So, to get the total amount intercepted, we multiply the solar constant times the area of the disk to get $1.75*10^{17}$ W.

BUT, the Earth is spinning. It's not just a flat disk facing the Sun…



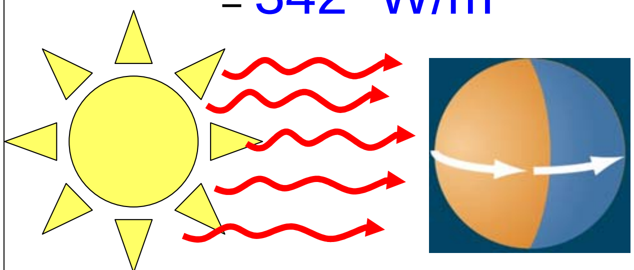
The Earth is spinning. It's not just a flat disk facing the Sun. The total energy received gets spread out over Earth's spherical surface area. What does the AVERAGE square metre get? *(NOTE: this is NOT yet the actual amount we get on the ground. We haven't dealt with the atmosphere yet)*

Energy received by the AVERAGE square metre

E_{in} = 1.75*10^{17} W (this is the total intercepted)

Spread this over the entire surface area of the Earth to get the AVERAGE W/m^2 (F_{in})

$$F_{in} = 1.75*10^{17} / 4\pi(6.37*10^6 \text{ m})^2$$
$$= 342 \text{ W/m}^2$$

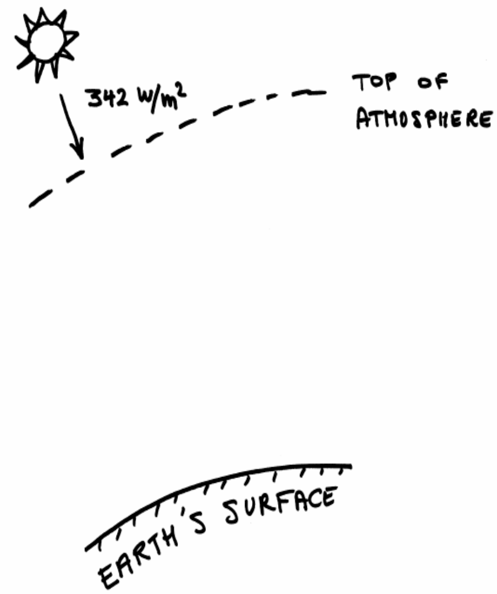


Since the Earth is a rotating sphere, this intercepted solar energy is spread over its entire surface.

Knowing the surface area of the Earth (4*pi*(earth's radius)^2), we can calculate the average amount of solar energy received per m^2 by dividing the total amount of solar energy intercepted by Earth (calculated on the previous slides) by the Earth's surface area.

Notice that 342 W/m^2 is equal to the solar constant (1370 W/m^2) divided by 4. That's because the surface area of the spherical Earth (4*pi*r^2) is 4 times larger than the surface area of the "disk" that intercepted the solar radiation (pi*r^2). See the Notes slide about useful geometry.

Amount of solar radiation that reaches the top of the Earth's atmosphere



342 W/m^2

Next…how do we use this information to figure out the **mean temperature** of Earth?

So, we just did what we set out to do, which was to calculate the average solar radiation (W/m^2) reaching the Earth

This is the amount of solar energy that reaches the top of the Earth's atmosphere and our first constraint on the radiation budget of the planet and its control on the mean temperature of the Earth.

Note that 342W/m^2 is simply the solar constant (1370W/m^2) divided by 4.

Knowing this number, we can now undertake the calculation of the mean temperature of the planet, one of the key variables which determines its climate.

Summary: Radiation Balance I

- Objects with temperatures above absolute zero emit electromagnetic radiation
- Hotter objects emit radiation with shorter wavelengths (higher frequencies & greater energy per photon) than cooler objects
- The energy an object radiates is proportional to its temperature raised to the 4^{th} power
- The Earth's SOLAR CONSTANT (1370 W/m^2) depends on the energy output by the Sun, and the Earth-Sun distance
- Because Earth is a spinning sphere, on average, Earth receives 342 W/m^2 at the top of the atmosphere
- The amount of solar energy coming in is crucial to determining Earth's temperature