SPACE WEEK

Our Planet • Our Space • Our Time

Resource Book for Teachers

TOPIC: ExoWorlds in Focus

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Introduction: This series of investigation activities are designed to bring the new field of Exoplanets into context by comparing two known extrasolar systems to our Solar System.

Curricular links

Earth and Space 1 … describe the relationships between various celestial objects including … planets, stars, solar systems…
Earth and Space 3 … interpret data to compare the Earth with other planets … in the solar system, with respect to properties including … size, and composition.

For *Investigation 4*
Physical World 6. … explain energy conservation and analyse processes in terms of energy changes and dissipation.

Investigation 1: *A scale model of OUR planetary system*

Teacher Notes:

Starter questions:

- What is the Sun?
- Why is our planetary system called the "solar" system?
- Do you think the planets are all evenly spaced around the Sun?

What you will need:

A corridor, at least 30 meters long.

Per group of students:

Several blank pieces of poster paper, 2 or 3 per group, 1.7 m length when taped together or 5 pieces of A3 paper, taped together at the short side.

A long tape measure (15m if you have it).

Several sticky notes or wide masking tape.

A 30m length of string.

Some lengths of green, red and blue ribbon, ~1.5 m per colour OR green, red and blue markers

Student Activity:

Solar system fact table:

Definition: An "Astronomical Unit" (AU) equals the average distance between the Earth and Sun, or about 150 million km. We will use a scale of 1 AU = 1 meter. (So this means that 0.01 AU = 1 cm and 0.001 AU = 1 mm!)

Planet	Distance from Sun (km)	Distance from Sun (AU)	Mass of Planet Compared to Earth	Diameter compared to Earth
Mercury	57.9 million	0.39	0.06	0.38
Venus	108.2 million	0.72	0.82	0.95
Earth	150 million	1.00	1	1
Mars	228 million	1.52	0.11	0.53
Jupiter	779 million	5.20	318	11.2
Saturn	1,434 million	9.54	95.2	9.5
Uranus	2,871 million	19.2	14.6	4.0
Neptune	4,500 million	30.1	17.2	3.9

The only objects large enough to model on this scale are the Sun and outer planets. The Sun's diameter is 1.39 million km, so the Sun is roughly one hundredth (0.01) of an AU in diameter.

Since we are using a scale of 1 AU = 1 meter, our model Sun on this scale will be *one hundredth of a meter* or *one centimeter* in diameter.

The largest planet, Jupiter, is about one-tenth as wide as our Sun. So, it would be a dot one millimeter wide! Saturn would be just slightly smaller. Uranus and Neptune would be just about one third of a millimeter wide and the inner planets, just dots on paper.

Procedure:

Break up students into 3 or 4 groups depending on how many tape measures you have and how wide the corridor is.

Each group should have sheets of poster paper / A3 paper taped together end-to-end.

Lay the poster paper at one end of the corridor and draw a small (1 cm wide) circle at the side of the poster paper near the beginning of the hallway to represent the Sun.

From the Sun, measure out distances to the four innermost planets and draw a small dot to represent the planet. (They should fit on the taped together sheets of paper.)

Stretch the string from the Sun to each planet and draw a small arc to represent a segment of the planet's orbit.

Now do the same with the outer planets, but using either a sticky note or piece of wide masking tape to mark out the location of each outer planet. Draw a 1 mm diameter dot to represent Jupiter, a similar dot with a tiny ring around it to represent Saturn, and a 1/3 mm dot to represent Uranus and Neptune. Draw a small segment of each planet's orbit freehand.

What do you notice about the spacing of the planets?

Do you notice any other difference when comparing the 4 innermost planets with the 4 outermost planets?

Do you think this is just a coincidence?

What might be responsible for this difference?

Which planet is the only one which we KNOW has life?

What factors do you think are important to life existing and surviving on a planet?

What do you think will cause the habitable zone to end as you travel closer to the Sun?

What do you think will cause the habitable zone to end as you travel farther from the Sun?

Habitable Zones:

A habitable zone in a planetary system is a region where the environment might be right for life-as-we-know-it to survive… given the right kind of planet. So, we make the simple assumption that liquid water must be present on a planet for life to survive!

The most important part of defining a habitable zone is finding where a planet could have a survivable <u>temperature</u> where liquid water can exist.

Teacher Notes:

There are a number of factors that determine a planet's average "equilibrium temperature." You can think of this as a kind of "comfort zone" temperature where a planet will have its average temperature stay pretty much the same. A planet will naturally settle into its equilibrium temperature where it will release (or "radiate") as much energy into space as it absorbs from the Sun. (This will be discussed in more detail in Investigation 4.) So, there is always a balance between energy absorbed by the planet and the energy released. The most obvious factor in determining a planet's equilibrium temperature is distance from Sun. So, if you want a habitable planet, it mustn't be too close or too far.

Other factors include the ratio of how much energy a planet will absorb to how much it will reflect. Another factor, one which is increasingly important for Earth currently, we can call "blanketing." You can think of blanketing as insulating a planet's surface so that it has a harder time releasing the energy into space that it needs to keep itself in equilibrium. If you were to give a planet more atmospheric "blanketing", the planet would naturally warm up and raise its temperature until enough energy is radiated into space to equal the energy it absorbs from the Sun. So, for example, if I were to put an atmosphere on a planet which held back 50% of its radiation, the planet and its atmosphere would heat up and produce more radiation until the amount that leaks out into space is equal to the amount that the planet absorbs.

To calculate the habitable zone for this activity, we will assume that we have a planet with blanketing and reflectivity properties similar to Earth. Then the inner edge (in AU) of the habitable zone is set at 100 °Celsius, where water will be near the boiling point:

$$d_{inner} = 0.87\sqrt{L}$$

L is the luminosity (energy output rate or "total brightness") of the star in multiples or fractions of the Sun's luminosity. For example, if a star has half the brightness of the Sun, it will have L = 0.5. If it is as bright as 3 Suns, L = 3. In *this* case we are dealing with our own solar system and Sun, so L =1!

The outer edge (in AU) of the habitable zone is set at 0 °Celsius, where water will be near the freezing point:

$$d_{outer} = 1.62\sqrt{L}$$

Student Activity:

We can calculate the inner edge of the habitable zone (in AU) as the distance from the star where water will begin to boil and, we assume, life will be impossible. For a planet with similar properties to Earth, that distance is:

$$d_{inner} = 0.87\sqrt{L}$$

L is called "luminosity" and is the energy output rate or "total brightness" of the star in multiples or fractions of the Sun's brightness. For this activity, since we are talking about our own solar system, L=1, because our Sun is exactly as bright as 1 Sun!

We can calculate the outer edge of the habitable zone (in AU) as the distance from the star where water will all be frozen solid:

$$d_{outer} = 1.62\sqrt{L}$$

Again, we are talking about our own Sun, so L=1 in this activity (but will be different in a later activity).

Calculate the distance to the inner and outer edges of the habitable zone for our solar system. Mark the inner and outer edges of the habitable zone for our solar system on the paper scale model. Cut a piece of green ribbon so it will stretch from the inner edge to the outer edge of the habitable zone and paste it on the poster paper. Cut a piece of red ribbon so it will stretch from the Sun to the inner edge of the habitable zone and paste it on the poster paper. Finally, cut a piece of blue ribbon so that it stretches from the outer edge of the habitable zone to the edge of the poster paper and paste it on the paper (maybe even cut the outer end of the ribbon in the shape of an arrow pointing toward the outer planets).

Save the paper for Investigation 2!

What does the red ribbon mean for that part of the solar system?

What does the blue ribbon mean for that part of the solar system?

What planets fall within the "green" part of the solar system?

Do all the planets in the green part of the solar system have life? If not, discuss some reasons why they might not.

Investigation 2: *A side-by-side scale model of exo-planetary systems compared to the Solar System.*

Teacher Notes:

Starter questions:

- Are other stars like the Sun? (Bigger? Smaller? Brighter? Dimmer?)
- Can other stars have planets?
- What allows us to see the other planets of our own planetary system?
- Why might it be difficult to discover planets around other stars?
- Can you think of any ways to detect the presence of planets around other stars?
- Why do you think planets around stars other than the Sun are called "EXO-planets?"

What you will need:

The paper with the scale model of the inner planets completed in Investigation 1.

A tape measure.

A 2-meter-long string.

Some lengths of green, red and blue ribbon.

Calculator.

Student Activity:

Exoplanet system fact tables:

Remember: An “Astronomical Unit” (AU) equals the average distance between the Earth and Sun, or about 150 million km. As we did in Investigation 1, we will use a scale of **1 AU = 1 meter**. (So that 0.01 AU = 1 cm and 0.001 AU = 1 mm)

We will examine two multi-planet exo-systems. The first system has 5 known planets and is orbiting a star known as **Kepler 62**. Kepler 62 is slightly smaller than our Sun (about 2/3 as wide) and has a cooler surface temperature. So, it is only about one fifth as bright as our Sun. (L = 0.21)

Procedure:

Planets of Kepler 62	Distance from Star (AU)	Mass of Planet Compared to Earth	Period of Orbit (days)
b	0.055	2.1	5.7
c	0.093	0.1	12.4
d	0.120	5.5	18.2
e	0.421	4.5	122
f	0.718	2.8	267

Break up students into the same 3 or 4 groups as in *Investigation 1*. This activity can be done in the classroom if needed.

Each group should have the poster paper from *Investigation 1* with the inner planets marked out on it.

To the left of the Sun, draw a small (6 mm wide) circle to represent the star Kepler 62.

From the star, measure out distances to the five planets of the Kepler 62 system and draw small dots to represent each planet. Stretch the string from the star to each planet and draw a small arc to represent a segment of the planet’s orbit.

What do you notice when you compare the distances of these planets from their star to the distances of our planets around the Sun?

Can you suggest a reason for this?

What is the most obvious difference that you see between the Kepler 62 planetary system and our own?

Does this mean that Kepler 62 doesn’t have any other planets?

Now, using the formulas for the inner and outer edges of the habitable zone…

$d_{inner} = 0.87\sqrt{L}$ and $d_{outer} = 1.62\sqrt{L}$

and plugging in L = 0.21 since Kepler is only about 21% as bright as our Sun, calculate the inner and outer edge of the habitable zone and mark them on the poster at the correct distance from the star.

Using the red, green and blue ribbons, mark out the "too hot," "just right" and "too cold" distances from the star Kepler 62 just like you did in *Investigation 1*.

What are the two main differences that you notice between the habitable zones of the Kepler 62 system and our Solar System?

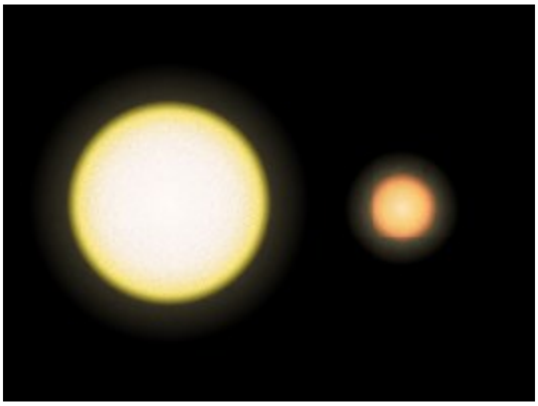
Can you think of any reasons why?

Do any planets orbit Kepler 62 within the habitable zone? If so, which ones?

Do you think a planet or planets in the habitable zone have a chance to be similar to Earth? (Give a reason or reasons for your opinion.)

The second multi-planet exo-systems we will examine has 4* known planets. It is orbiting a star known as **Gliese 581**. (*The existence of Gliese 581g is disputed.)

Gliese 581 is known as a *red dwarf* star. Red dwarf stars are some of the most common stars in the galaxy. They are remarkably dim; Gliese 581 is only about a hundredth as bright as our Sun (L = 0.013). Perhaps the most remarkable thing about red dwarf stars is how long they last. Our Sun has a lifespan of about 10 billion years. A star like Gliese 581 has a life span over a hundred billion years; many times longer than the current age of the Universe!



Comparison of our Sun to Gliese 581

The size of Gliese 581 is about half that of Kepler 62 or roughly 1/3 as wide as our Sun. We can model it as a dot about 3 mm wide!

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Planets of Gliese 581	Distance from Star (AU)	Mass of Planet Compared to Earth	Period of Orbit (days)
e	0.028	1.7	3.1
b	0.041	15.8	5.4
c	0.072	5.5	12.9
g	0.130	2.2	32

To the right of the Sun, draw a small (3 mm wide) circle to represent the star Gliese 581.

From the star, measure out distances to the four planets of the Gliese 581 system and draw a small dot to represent the planet.

Stretch the string from the star to each planet and draw a small arc to represent a segment of the planet's orbit.

Now, using the formulas for the inner and outer edges of the habitable zone…

$d_{inner} = 0.87\sqrt{L}$ and $d_{outer} = 1.62\sqrt{L}$

and plugging in L = 0.013 since Gliese 581 is only about 1% as bright as our Sun, calculate the inner and outer edge of the habitable zone and mark them on the poster at the correct distance from the star.

What do you notice when you compare the distances of these planets from their star to the distances of Kepler 62's planets and our planets around the Sun?

Do you see a trend when you compare the size and positions of the habitable zones for our Sun, Kepler 62 and Gliese 581?

Does Gliese 581 have any planets in the habitable zone?

If so, do the exo-planets in the two systems that we plotted seem to have anything else that might make them similar?

Using the red, green and blue ribbons, mark out the "too hot," "just right" and "too cold" distances from the star Gliese 581 just like you did for our solar system and the Kepler 62 system.

Investigation 3: *How are exo-planets found?*

Teacher Notes:

Other stars are SO far away that it is nearly impossible to detect exoplanets *directly* for two reasons:

1) They are too dim because they only shine by the reflected light from their star.
2) They are too close to their parent star and lost in its glare.

Starter questions:

- How far away are other stars?
- What allows us to see the other planets of our own planetary system?
- Why might it be difficult to discover planets around other stars?

What you will need:

Activity 3-A: The Wobble

A personal headlamp or other object (representing a star) that a student can wear on their head.

A rope (clothesline).

A small laundry sack stuffed with soft things.

A large laundry sack stuffed with heavier soft things.

An electronic alarm, beeper or anything with a specific pitch of sound that can be swung around on a string.

A string to swing the beeper/alarm.

Activity 3-B: Transit Method

A Styrofoam ball about the size of a grapefruit.

A dowel or hexagonal profile pencil.

Several thin wooden BBQ skewers.

Two small spheres (Styrofoam or clay perhaps) much smaller than the Styrofoam ball (about the size of a large blueberry) that could be stuck onto the end of the skewers.

The tube from a roll of paper towels.

Caution:

For Activity 3-A there will need to be enough room so that a student can swing a sack over their head on a rope without hurting anyone. It will have to be heavy enough to make the student wobble a bit, but not so heavy as to injure the student!

Background:

You can watch these short videos from ESA explaining the various ways that exoplanets are discovered, but only show them to students after they have done the activity.
http://sci.esa.int/exoplanets/60655-detection-methods/

Student Activity:

Activity 3-A:

In *Investigations 1 & 2*, we used a scale of 1 AU equals 1 meter to plot the planets of our solar system and two exoplanet systems.

The Wobble

When an exoplanet orbits its star, the two objects are held together by an invisible force called gravity. We can imagine gravity to be like a rope tying two objects together.

> *When one object swings around another, will only one object move? Or will both of them move?*

Have a student put the headlamp/artificial-star on their head and swing the light sack on the rope overhead round-and-round.

> *Watch the headlamp/artificial-star carefully. Does it remain still, or does it wob-ble?*

Now have the student swing the heavier sack overhead in a fairly small circle.

> *Does the headlamp wobble more or less than with the lighter sack?*

Now have the student swing the heavy sack in a larger circle.

> *What changes about the wobble? Which wobble was faster? Do you think you could see a wobble like this if it were a star extremely far away? Why or why not?*

It's sometimes, but *rarely* possible to directly detect that kind of wobble. This is called astrometric detection of an exo-planet.

Gliese 581 is 20.5 light years away. Since each light year is equal to 63,000 AU, on our scale 1 light year would be about 63 kilometers. Approximately how far away would Gliese 581 be on a map of the Earth?

Imagine putting your map of planetary orbits for the Gliese 581 system at that distance. Do you think you could see the little dots representing planets at that distance? How about with a powerful telescope?

If you can't detect the actual change in *position* of the star due to its wobble, it still may be possible to detect the change in the star's *motion* due to the wobble!

A star's light has a *frequency* similar to the way a certain sound or musical note has a frequency. We usually call this the "pitch" of the sound. High pitch sounds have a high frequency and low pitch sounds have a low frequency. When an emergency vehicle passes you on a road at high speed the siren seems to change from a high pitch when it's coming at you to a low pitch when it's moving away. This is called the Doppler effect.

Wobbly Beeping Star!

To imitate the changing of starlight because of a star's wobble, we can swing an electronic beeper over our head and others can listen to the change of sound. (CAUTION: When we swing the beeper overhead it is meant to represent the ***star*** wobbling, NOT the orbiting of the planet. It's the change in frequency of the star's light that is detected, not the planet!)

This is how astronomers can indirectly detect the presence of planets they can't see with their telescopes.

Does the frequency (pitch) of the sound get higher or lower when the star (beeper) is coming toward you? (Remember: we're not talking about how loud or soft the sound is, but how high or low the pitch is!)

Does the frequency (pitch) of the sound get higher or lower when the star (beeper) is moving away from you? What if it's going away?

What would cause the greatest change in frequency of a star's light? … a big planet orbiting close to the star and fast, or a small planet orbiting far from the star and slow? Why?

What kind of planets do you think have been most often discovered by this method and why?

Activity 3-B

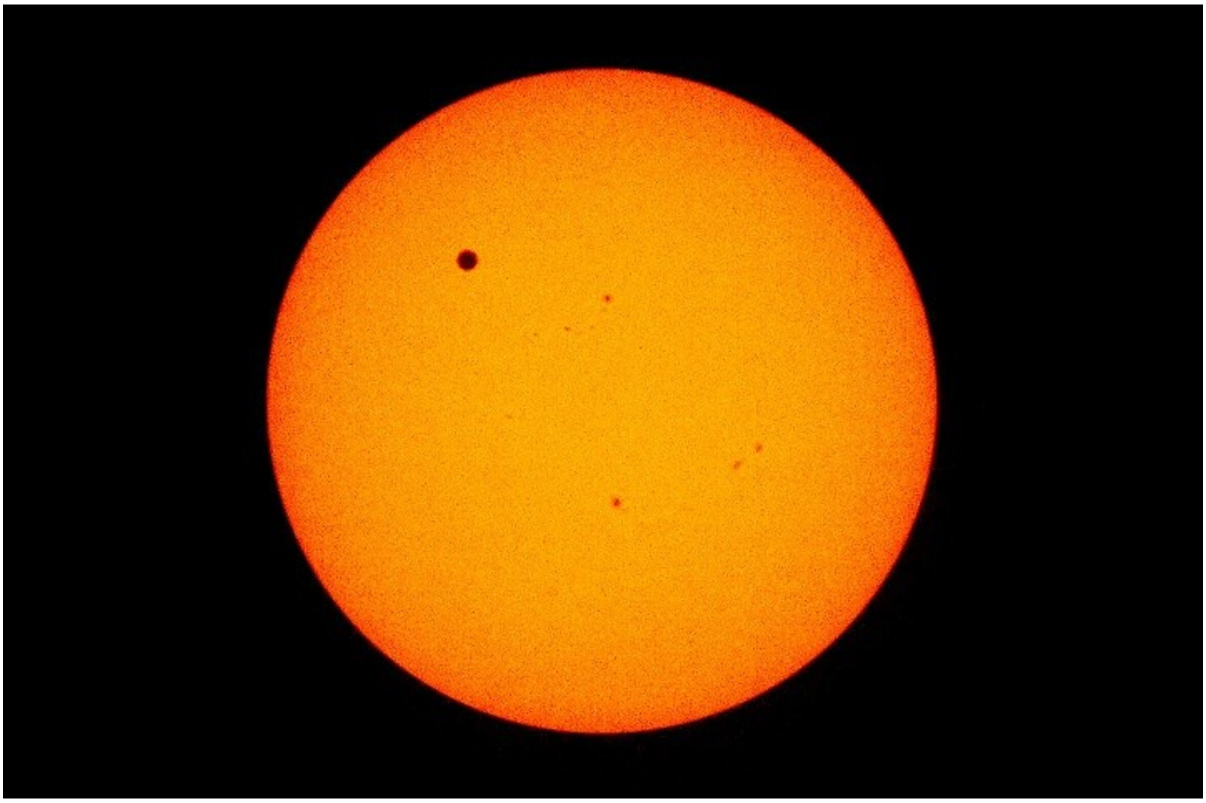
The transit method:

When the Moon passes between the Earth and the Sun, cutting off part or all of the Sun's light, it is called an eclipse.

In our solar system there are two planets that can pass between us and the Sun and cut off a small part of the Sun's light from us.

Which planets are they? Why are they the only ones?

This sort of mini-eclipse is called a transit.



In the photo above, Venus is blocking some sunlight from reaching the Earth. Approximately how much sunlight is cut off?

About 50%   About 20%   About 5%   Less than 1%

How would you calculate how much dimmer the Sun would be because of Venus transiting across its surface? (Explain in words or a maths formula)

Do you think you would notice the dimming of the Sun's light with your eyes? Why or why not?

Do you think modern scientific instruments could detect the dimming of sunlight due to the transit of Venus?

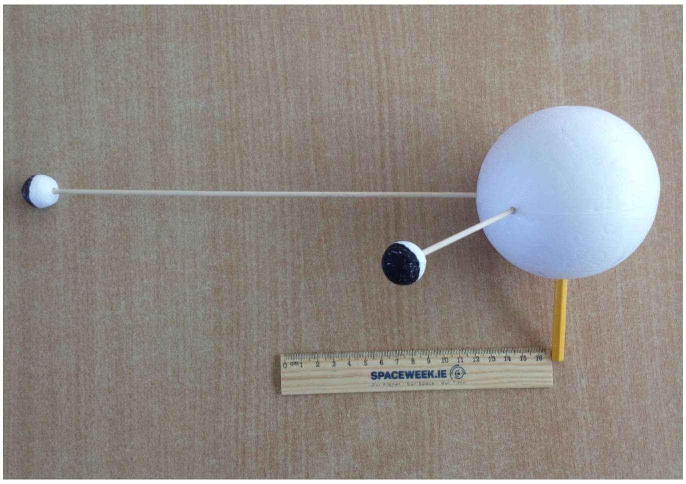
Because stars other than the Sun are so far away, we cannot see them as round disks like the Sun in the photo above, even in our largest telescopes (except for a few exceptionally large stars like Betelgeuse, the red supergiant star in Orion). So, if a star has planets, and a planet in the course of its orbit happens to come between us and that star, we cannot get a picture of the transit like the one above. We can, however, detect the ever-so-slight dimming of that star due to the planet blocking out a tiny portion of the star's light from us. To do this, astronomers use electronic digital cameras to do what is called 'photometry." Photometry is the precise analysis of how much light we receive from a given star and how much that flow of light to our camera changes with time.

The video clip below shows an artist's conception of an exo-planet transit, and the "light curve" that the photometric camera would record as the eclipse happens.

http://sci.esa.int/gaia/58789-detecting-exoplanets-with-the-transit-method/

Activity 3-B: The Selection Effect:

Teacher Notes and Preparation:



This activity will explore why it is easier to detect planets close to their star rather than planets far from their star!
See: https://youtu.be/qV2igZMvMxc

Get a large Styrofoam ball, about the size of a grapefruit, to represent the central star of an exoplanet system. If the ball has a seam running around the middle, you can conveniently use that as the star's "equator." You can push a long wooden skewer or a long pencil through the ball perpendicular to the "equator" and directly through the centre. Do this carefully; it's more difficult than it sounds. The dowel represents the star's rotation axis. Get two small objects to represent planets. If they are tiny Styrofoam balls, you can use a black marker to make the hemisphere of the planet facing away from the star black. Place one of the small "planet" balls at the end of a shortened skewer (which should be about 1/3 or slightly less than 1/2 the length of a normal skewer). The dark side of the planet should be pointed away from the star. Then stick the skewer into the star at the equator so that the planet is at least 2/3 of the star's diameter away from the surface. Do the same with the longer skewer and second "planet" ball, placing the skewer in a slightly different location on the equator of the star.

We will now try to simulate the planets transiting the star's disk as they orbit. Note: the orbiting motion is NOT astronomically accurate because the planets will orbit at the same rate as the star rotates and the same rate as each other. This is NOT the way a real planetary system works, where the inner planet will orbit faster than the outer one and at a different rate than the star spins! But what we are trying to demonstrate here is just the *geometry* of the transits for planets close to and far from the star.

Student Activity:

Take a cardboard paper towel roll representing a telescope and have a student look through it to observe the star from well across the room; about 3 – 4 meters away. Slowly rotate the star on the dowel, with the dowel held straight up and down.

What does it look like through the paper towel roll when each "planet" passes in front of the star?

Now have the person rotating the star *tilt the star very slightly toward or away from the student observer* and slowly rotate it.

Continue observing the rotating star as it is tilted slightly more each time.

If the star were actually giving off light, would the star dim more for the closer or farther planet, or would it be about the same?

How do the transits of the planets, as seen through the imitation telescope, change as the star is tilted?

Which planet stops performing a transit first and why?

How can you use this result to try to explain the differences between the two exoplanet systems we plotted in Investigation 2 and our solar system?

There are a number of other excellent activities online from which the teacher can choose to demonstrate how the transit method of finding stars works.

https://www.jct.ie/perch/resources/science/activitybasedonkeplerdatawebinarscience.pdf

or:

https://nai.nasa.gov/media/medialibrary/2013/10/TransitTracks-Activity-2010.pdf

or:

https://www.iop.org/education/teacher/resources/exoplanet_physics/page_65137.html

Investigation 4 (Advanced): *Radiation balance and habitable zones*

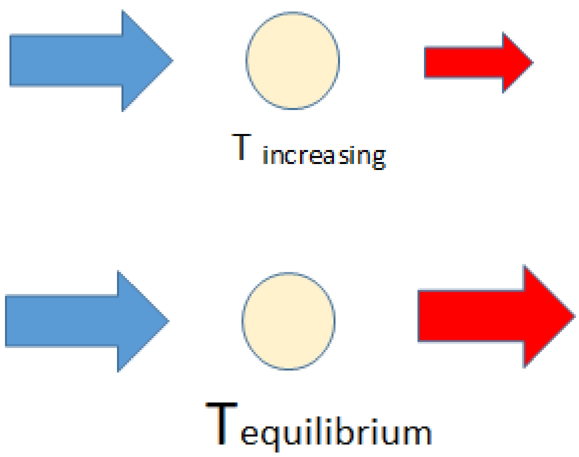
There are a number of properties of an exoplanet that determine the planet's average equilibrium temperature which, in turn, determines if it is suitable for life as we know it.

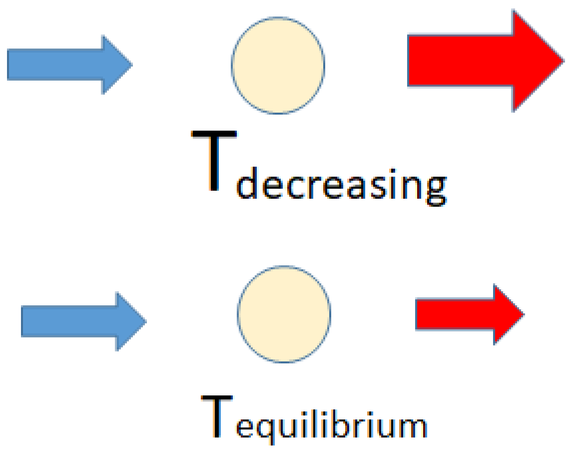
A planet reaches "equilibrium" when its overall average temperature remains the same, neither heating up, nor cooling down!

A good way to think about equilibrium is that the planet is in **radiation balance** or **energy balance**: *the energy it absorbs from its star is equal to the energy it releases or emits back into space*.

If the planet absorbs more energy (blue arrow) than it emits into space (red arrow), *it will heat up*.

When the temperature increases, the planet naturally emits more energy into space. So, when it heats up to a temperature where the outgoing radiation from the planet is equal to the incoming radiation absorbed from the star, the planet stops heating up and stays at that equilibrium temperature.





On the other hand, if the planet emits more energy into space than it absorbs from its star, the opposite will happen. The *planet will cool off* and find a lower temperature where the incoming and outgoing radiation are in equilibrium.

It's almost as if the planet had a natural thermostat to figure out the planet's "comfort zone." What we want to know is whether that comfort zone is comfortable for life or not!

Radiation absorbed:

The radiation absorbed by the planet depends mainly on three things:

- Size of the planet
- Distance from the star
- Absorptivity/reflectivity

Radiation emitted:

The radiation emitted or released by the planet is infrared radiation (what we sometimes call "heat radiation" because we can sense it with our skin, but not with our eyes) and also depends mainly on three things:

- Size of the planet
- Temperature of the planet
- "Blanketing" or the *Greenhouse Effect* due to an atmosphere

Since the size of the planet has an effect on both the absorption and emission of radiation, we are going to ignore that because if the size of a planet were to double, both the absorption and emission would double and cancel out. There are subtle differences that depend on the planet's rotation, but these can be ignored those at this level.

So, we will start by considering the quantity that has the easiest-to-understand effect on the planet's temperature: *distance from the star*.

Distance of a planet from its star:

As anyone who as ever sat around a campfire knows, if you want to get warmer you sit closer to the fire and if you need to cool off, you move farther from the fire. If planets were conscious beings, they would do the same thing! However, they are not - they are generally spheres of rock and metal or ice and gas. Planets form in a natural way at whatever distance from the parent star where conditions were right for planet forming.

So even though there are many reasons why planets turn out the way they do, the biggest and easiest to understand reason is **distance from its star**.

Optional Mini-activity: Appendix A: Radiation and Distance from a Star.

Distance: The following Sankey diagrams show the **effect of distance from the star** on the exoplanet's overall temperature. The blue arrows represent the energy that our sample exoplanet receives from its star (ultraviolet (UV), visible and infrared (IR)). The red arrow represents the IR energy that the planet radiates into space. The size of the red arrow is determined by the temperature of the planet and amount of emitted radiation is very sensitive to the overall temperature. (In other words, a small change in temperature leads to a large change in the radiation emitted into space!)

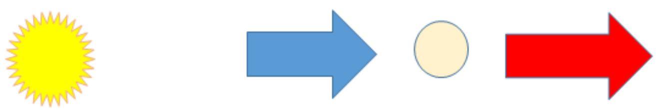
A planet *far from the star* receives a small amount of energy from the star. The planet has an equilibrium temperature that allows it to radiate the same amount of energy into space.

If the same planet were *moved closer to the star*, it would receive a greater amount of energy from the star. To reach an equilibrium temperature, the planet would have to radiate the same (larger) amount of energy into space.

How would the temperature of the planet change to make that happen?

If the same planet were *moved even closer to the star*, it would receive still more energy from the star. To reach an equilibrium temperature, the planet would have to radiate the same (larger) amount of energy into space.

How would the temperature of the planet change to make the outgoing radiation equal to the incoming?



Draw a capital T in each of the planet images to represent the planet's equilibrium temperature. Use a large T for higher temperatures and a smaller T for lower temperatures.

How does this help explain the inner and outer edges of the habitable zones?

Absorptivity/reflectivity:

When light falls on an object (or planet), some of the light is *reflected* and much of the rest is absorbed. When we say "reflected" we do not mean the type of reflection you get from a mirror or a surface of calm water, where you see a perfect reflected image of your face or the trees at the edge of a lake. We are just talking about the scattering back of light that's falling on an object that allows you to see it!

Very simply, dark surfaces absorb more light and light surfaces reflect more light. Many objects (and planets) have a combination of dark and light surfaces.

For example, pictured below are two black & white cows:

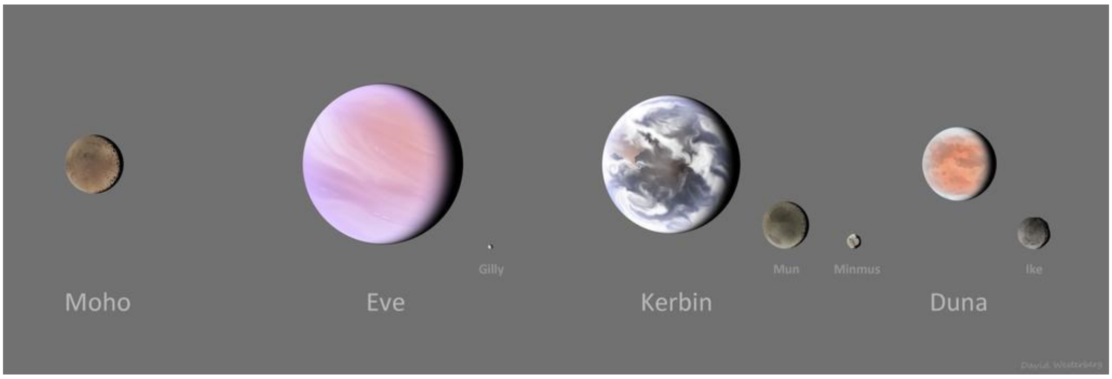
Which cow reflects more sunlight?

The one on the left or the one on the right?

Which cow absorbs more sunlight?

The one on the left or the one on the right?
Explain why.

Below are some simulated planets from the computer game Kerbal Space Program:



Of the first 3 large planets, which one absorbs the greatest percentage of light?

Moho Eve Kerbin

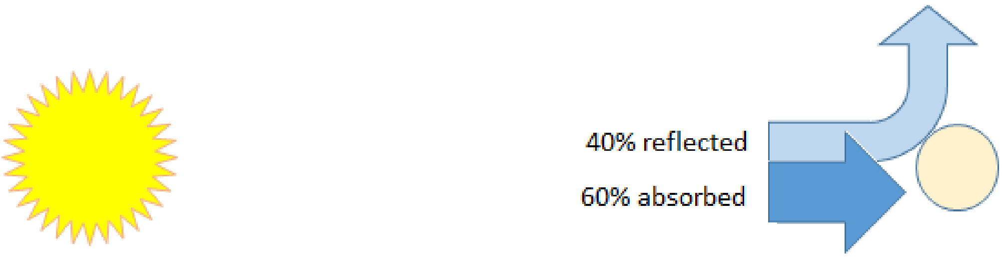
Of the first 3 large planets, which one reflects the greatest percentage of light?

Moho Eve Kerbin

Which is most like the black and white cows… about half absorbing and half reflecting?

Moho Eve Kerbin

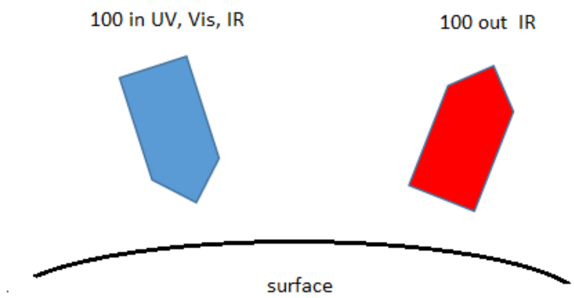
Earth is a bit like a black and white cow in that it has bright reflective clouds that reflect a lot of sunlight, but it also has dark land areas and water that absorb a significant amount of sunlight. The Earth's average reflectivity is about 40%, which means it absorbs about 60% of the energy it gets from the Sun. A Sankey diagram of the energy Earth receives from the Sun might look like this:



To keep things simple, in the equations to find the inner and outer edges of the habitable zone in *Investigation 2*, we assumed that the most likely properties of a habitable planet would be similar to the Earth, since Earth is the only planet on which we know life to exist. So, we used 40% reflectivity in deriving the simplified form of the equation. You can extend a habitable zone outward slightly by decreasing the reflectivity (making it warmer) and extend it inward slightly by increasing reflectivity (making it cooler). So that's why our habitable zones in *Investigation 2* may vary slightly from similar depictions of these exoplanet systems that you may have seen in science articles or on the internet.

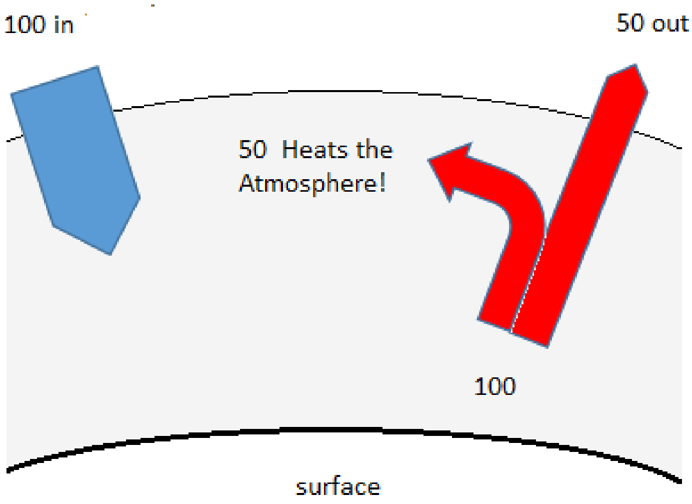
The "blanketing" effects of an atmosphere:

When you have a solid planet or moon with no atmosphere, the radiation balance is very simple. The surface absorbs a certain amount of energy from the Sun or star and is heated to a temperature where the solid surface radiates infrared energy into space at the same rate as it's absorbing from its star. (We are just using made-up units of energy to keep things simple. We say that the planet gets 100 units per second from its star and emits 100 units of energy per second back into space.)



Now, what happens when we add an atmosphere onto the surface of our fictitious planet? Well, a lot of things! To avoid getting confused with too many things at once, we are going to ignore the fact that an atmosphere can change the planet's reflectivity (with clouds) and also can absorb a small fraction of the incoming energy from the star. So, let's just say that the planet's surface still absorbs 100 units of energy each second. If we put on an atmosphere, it can act as a thermal blanket; holding in a large percent of the infrared radiation that the planet is trying to emit into space. We will call this insulating aspect of an atmosphere "blanketing." It is the aspect of an atmosphere responsible for the greenhouse effect!

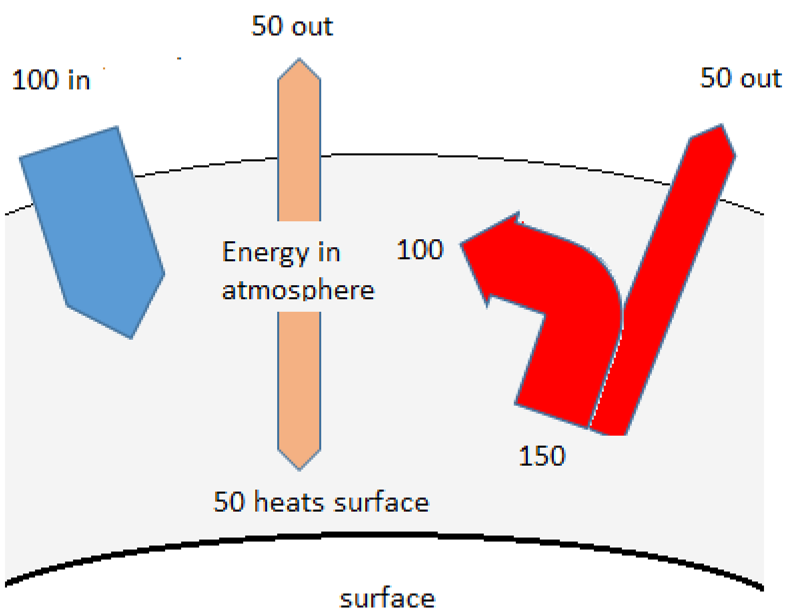
Now, as seen in the Sankey diagram below, we have more energy going in each second than out, because the atmosphere is only letting out 50% of the energy radiated from the surface. The other 50% is being dumped into the atmosphere.



> *So, what happens to the temperature of the atmosphere and surface once we put the atmospheric blanket on? How does this eventually restore the radiation balance?*

The blanketing caused by the atmosphere blocks so much of the radiation of the planet's surface that it makes the temperature of the atmosphere rise. The atmosphere then radiates some of this extra energy to space, but some of it also warms the surface and brings the planet's surface temperature in line with the atmosphere!

This feedback loop is called the greenhouse effect. *The temperature of the atmosphere and the surface rises until the atmosphere radiates enough energy into space to make up for the energy it initially blocked!* The Sankey diagram below shows this effect using estimated numbers.



In the diagram, the planet's atmosphere is heated to a high enough temperature to emit another 50 units into space and also to dump another 50 units into the surface, which increases the output of the surface to 150 units. Since an atmosphere isn't as efficient at radiating energy as a solid surface is, the atmosphere may end up heating to a much higher temperature than you'd expect before the planet reaches equilibrium.

That's not always a bad thing. If not for the gases in our atmosphere responsible for blanketing, the Earth's average temperature would be well below freezing! So, a little greenhouse effect is a good thing.

In our equation for habitable zones in *Investigation 2*, we used a factor called an *emissivity factor* of 0.5 for the Earth. This means that the Earth is only half as efficient as a perfect radiating object would be because of the blanketing by its atmosphere! Again, it's possible to widen the habitable zone by being more free with your choice of emissivity, but we decided to use an Earth-like planet for simplicity.

Global warming, climate change and atmospheric blanketing:

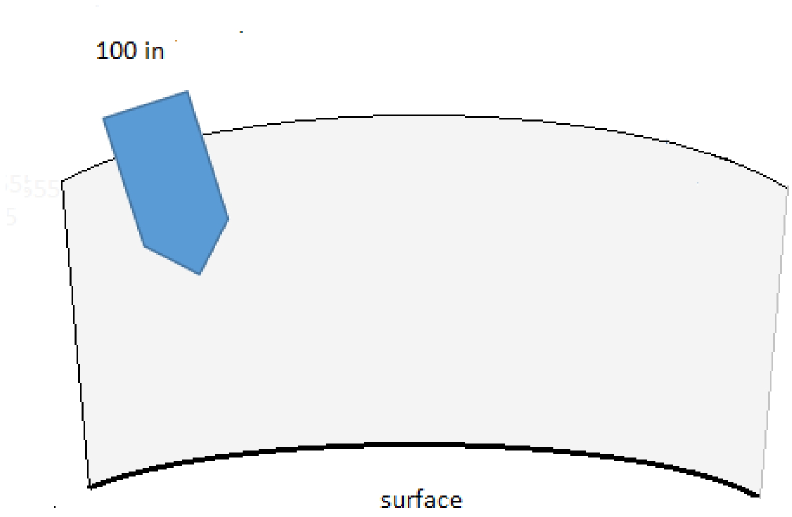
The main greenhouse gas responsible for the blanketing in the Earth's atmosphere is carbon dioxide (CO_2). Water vapor and methane contribute as well, but CO_2 is the biggest problem.

Astronomers have been using Venus as the "poster child" for global warming for years. The Earth has a tiny amount of CO_2 compared to Venus. Venus has an atmosphere that is so thick and is so rich in CO_2 (96%) that its blanketing of surface radiation is over 99%! It's also closer to the Sun than Earth, so it intercepts more solar radiation than Earth does. To attain radiation balance, Venus' atmosphere had to heat up to a ridiculous temperature of 460 °C! You can think of Venus as someone hiking through the Sahara Desert with a winter parka on. It's severely overheated!

Although the Earth's atmosphere is thinner and has much less blanketing than Venus, we also have something that Venus does not. Life. Life that depends on a delicate ecosystem that is sensitive to small fluctuations in average temperature!

Carbon dioxide is produced every time something *burns*. (A reaction called "combustion.") When the percentage of CO_2 in the atmosphere increases, so does the effect of the blanketing in our atmosphere.

On the incomplete Sankey diagram below, sketch the arrows you'd need to balance the radiation for the Earth if we add even more blanketing due to CO_2 than in the previous diagram. (Just use "guesstimates" for numbers.)



What will this do to the temperature of the atmosphere and the surface?

Humans have been using combustion for staying warm and cooking for centuries. Yet, the increase in the percentage of CO_2 in the atmosphere did not start to significantly increase until the industrial revolution in the early- to-mid-1800s. But it's not just the *amount* of fuel that has been burned since then that matters, it's the *type* of fuel! Until the industrial revolution, the primary fuels used for combustion would have been firewood or peat or even animal oils. These are often called *biomass* fuels because they are made from recently living things that have just *recently* removed CO_2 from the atmosphere.

What process removes CO_2 from the environment to become biomass, such as trees (for firewood), corn (for ethanol) or peat (decayed plants)?

Roughly how long ago was the CO_2 removed from our atmosphere to make a log of firewood? (ie Months? Years? ...)

Was Earth's environment different when the tree that made the log began consuming and locking away CO_2 to how it is now?

How long ago was the CO_2 removed from our atmosphere to make the plants that turned into fossil fuels?

Would the Earth's environment have been drastically different at that time?

Since the industrial revolution, the primary fuels used for combustion (whether for heating or machinery) are fossil fuels (coal, petroleum, natural gas). The reason they are called "fossil" fuels is because they are derived from biomass typically from over 300 million years ago!

This is the main issue with climate change and global warming. Burning biomass fuels releases CO_2 into the environment, and that *can* be a problem if the trees are not re-planted. (Deforestation is a significant contributor to climate change also.) But the CO_2 released from a log on a campfire was only taken out of the atmosphere a few years or, at most, a few decades ago; when the Earth's climate and CO_2 percentage was not much different than it is now.

Fossil fuels release CO_2 into the atmosphere that has been (safely) locked away under-ground as hydrocarbons for 300 million years; from a time when the Earth was a *much* different place with a *much* different climate! Even the Sun has changed significantly in that time. The *Sun was about 2.5% dimmer at that time* compared to its brightness today! So, the greater amount of CO_2 in the atmosphere 300 million years ago was use-ful for life on Earth at that time because it gave a little extra greenhouse effect to keep the environment warm despite less heating from the Sun than we have today. Today, however, with a brighter Sun, putting back all that CO_2 into the atmosphere would be catastrophic.

Appendix A: Activity: Energy absorption with distance from light/ heat source

There are several very simple ways to demonstrate the difference in planetary heating due to distance. For example:

- Plug in an electric heater and ask students to stand at various distances from the heater and report how warm they feel.
- Using the same electric heater, place three thermometers at 3 different distances from the heater and allow them to reach a stable temperature. Record the temperatures.

Another method that allows for more measurement uses either a light meter or a light meter app on a smart phone to measure the intensity of a light bulb at various distances.

This should be done in a darkened room with as little ambient light as possible. Place a light bulb (preferably without a shade or reflector… this will also work best with a dark background behind the light source) at a small distance from your light meter.

Record the light meter reading in lux as “intensity 1.” Intensity 1: ________________

Double the distance of your light meter from the light source, and record the intensity in lux. Intensity 2:________________

Finally, move to 3 times the original distance between the light meter and lamp. Record the intensity. Intensity 3: _________________

Did the intensity increase or decrease as the distance increases?

Divide intensity 1 by intensity 2. Ratio I_1/I_2 = Round to nearest whole number:

Divide intensity 1 by intensity 3. Ratio I_1/I_3 = Round to nearest whole number:

Do you see any relationship between the rounded ratios and the increase in the distance between the lamp and the light meter?

Can you explain why you think this might happen?

What further measurements could you make to establish a clear pattern between distance and light meter reading?