James Webb Space Telescope

Thermal Demonstrations with an Infrared Camera

An introduction to the James Webb Space Telescope

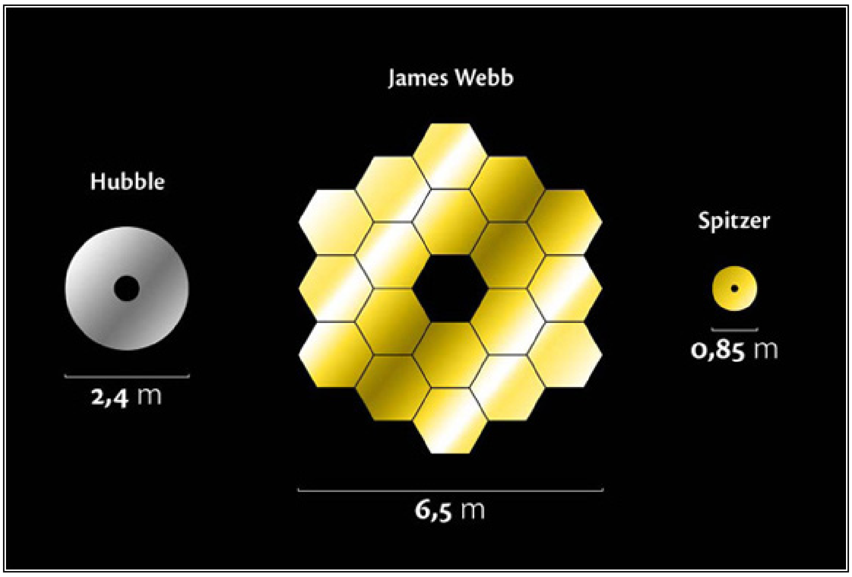
What is it?

The James Webb Space Telescope is an infrared observatory that, among other scientific investigations will;

- Study in detail how stars and planets form within dusty clouds
- Peer back into the history of our Universe to study the earliest stars and galaxies
- Hunt for undiscovered planets around distant stars

This huge, tennis court sized infrared telescope is larger than any other that we have sent into space. This huge size is for two reasons:

1) Being an infrared telescope, it will be observing our Universe in a longer wavelength of light than visible and as such it needs a much larger mirror. Below you can see a comparison between the size of the primary mirrors on the Hubble Space Telescope and the Webb Telescope.



Source: http://www.asc-csa.gc.ca/eng/satellites/jwst/webb-hubble.asp

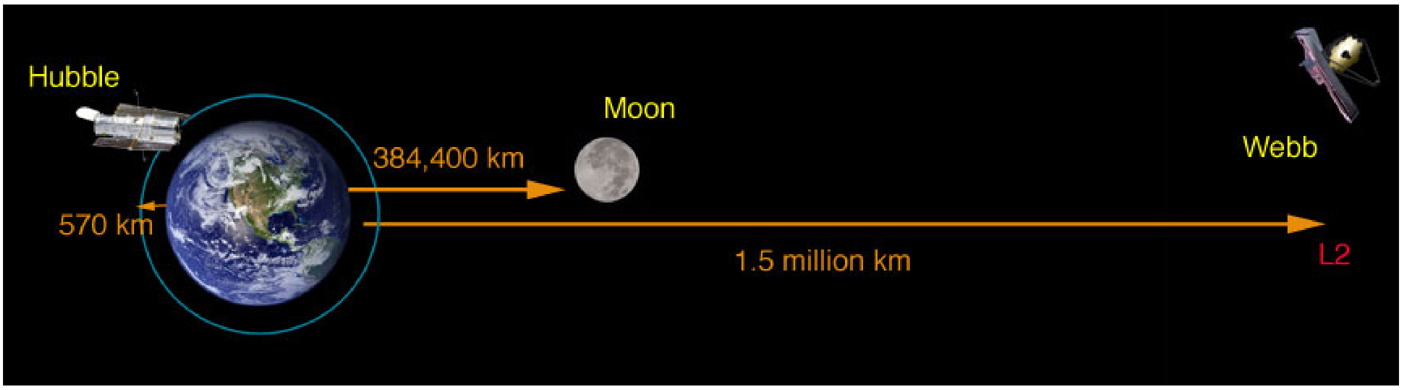
2) Since it will be capturing weak thermal signatures from distant galaxies, it needs to be protected from the infrared that the Sun is emitting and cooled to just 40K to avoid detecting its own thermal signatures. To do this, it is equipped with a revolutionary new sunshield concept that will keep all the sensitive instruments in the shade, and an active cooling system – or 'space fridge'.

In fact, this behemoth of scientific investigation is so large that it will not fit in any existing launch vehicle. To get around this it will be loaded onto its European Ariane 5 rocket folded up, and once safely in space an on its way to its final position will spend about two weeks carefully deploying the sunshield and then the mirror array. Below is an animation of the deployment of the Webb Telescope.

https://www.youtube.com/watch?v=vpVz3UrSsE4

Where is it going?

Rather than orbiting the Earth, the Webb Telescope will travel around the Sun while orbiting a very important position called the L2 Lagrange point. At this special position, it is the perfect distance away from the Sun to allow the gravitational pull of the Sun and Earth to combine to keep in in line with the Earth. This means that the sunshield can be permanently positioned between the telescope's sensitive instruments and sources of infrared radiation being emitted and reflected from the Sun and the Earth.



Source: https://jwst.nasa.gov/orbit.html

In the animation in the link below, you can see how, normally, an object orbiting the Sun further away than the Earth will lag behind the Earth. However, at the L2 point, the additional gravitational pull of the Earth is just right to give it an additional 'tug' which allows it to match the orbital period of the Earth despite being further away.

http://www.esa.int/Our_Activities/Operations/What_are_Lagrange_points

When the telescope arrives at L2, it will enter a halo orbit around this point which will keep it stable in this orbit.

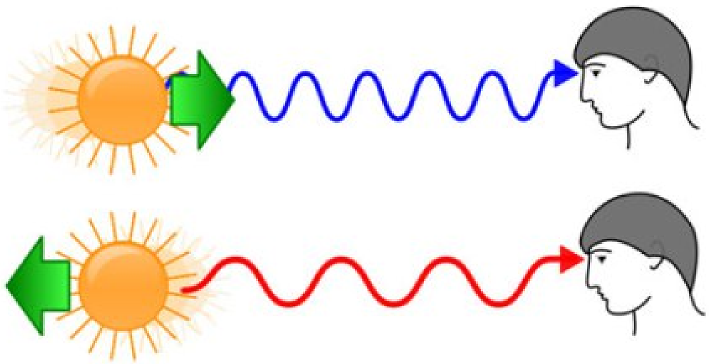
Why Infrared?

As is explored further later in this resource, infrared radiation is a type of light with a wavelength that is longer than visible light. This radiation is emitted by all objects, the result of molecular vibrations within the object (and in some other atomic processes). Hotter objects will emit more infrared radiation and so, infrared can be used as a measure of the temperature of the object. However, just like visible light, infrared can give us so much more information than just the temperature of an object. Infrared spectroscopy allows us to determine the molecular make up of distant clouds of dust and gas, telling us what is hiding within. Looking in near-infrared, the dust clouds become almost transparent allowing us to see through to the forming stars and planets cocooned within them. Mid-infrared lets us look at cool thermal emission from the clouds themselves. By carefully studying these two parts of the infrared spectrum, scientists can find out so much more about the hidden structures within our Universe.

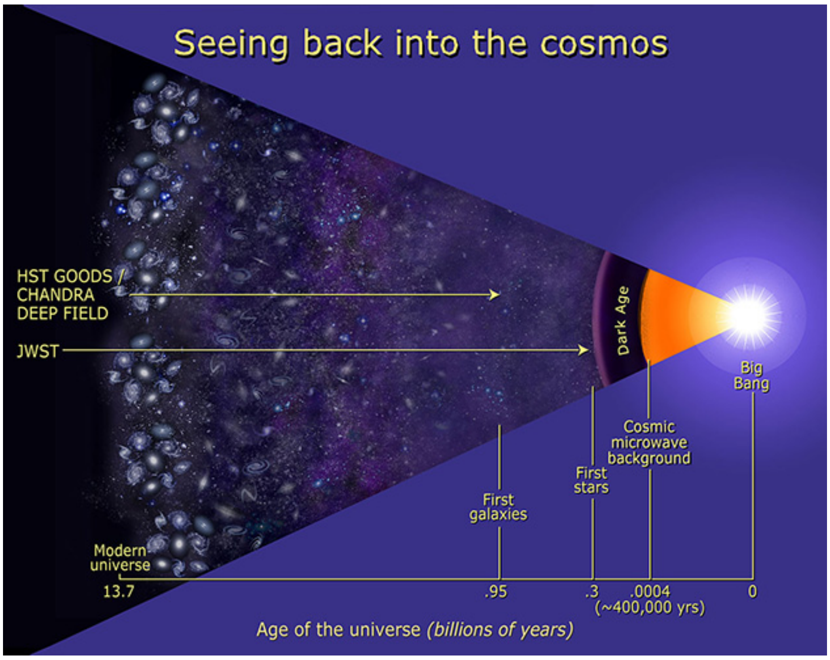
In addition, by using infrared, the Webb Telescope will be looking further back in time than any telescope before it.

Astronomy is effectively time travel. When you look at a star or object in space, the light that arrives at our eyes of telescopes has taken time to get to us, since light has a finite speed (3×10^8 ms^{-1}). The further away a star is, the longer the light has taken to reach us. When we observe this light, we are observing the object as it was when the light was emitted, not as it is now. So, the further away a star is from us, the older the light we observe from that star is.

So how does infrared allow us to look even further back than visible light? When you look at the light coming from distant galaxies, something interesting can be seen. The light appears redder than it should be. We see this effect with spectral lines coming from distant stars too. If you compare the wavelengths at which the spectral lines for a specific element occur in the lab and compare them to a distant object, the spectral lines for the distant objects occur at longer wavelengths. On local scales this effect, known as doppler shift is caused the recessional (moving away) motion of galaxies causing the light to be 'stretched' producing a longer wavelength. On cosmological scales, the space a distant galaxy is moving through in the Universe has expanded over the course of its journey. This stretching of space itself extends the wavelength of the light emitted by the galaxy and the light becomes redder. This effect is known as cosmological red shift.



Source: https://en.wikipedia.org/wiki/Redshift



There is a limit to how far back a visible telescope can look. Eventually, for the oldest, most distant galaxies, the light that has travelled to us from them has been red shifted so much that its wavelength is no longer in the visible spectrum. It is stretched all the way into the infrared. By using the world's most sensitive space based infrared telescope, scientists will be able to see the light from these stars, and as a result look further back in time, closer than ever before to the beginning of our Universe.

Source: https://jwst.nasa.gov/comparison_about.html

Demos and Teaching Points – Infrared and Thermal Transfer

The following resources have been written to give you ideas of demonstrations that you can do using an infrared camera in the classroom, as well as ways that you can link these demos to the Webb Telescope and the curriculum. For those who do not have access to an infrared camera the demonstrations have been recorded in the videos that accompany this resource. Please refer to the IR camera loan schemes and where to buy document for details on how you can acquire an infrared camera for your school.

Discussion of why the Webb Telescope is using the infrared part of the electromagnetic spectrum to observe the Universe allows you to bring in several aspects of the science curriculum into your classroom. These include the different parts of the electromagnetic spectrum, properties of waves and the idea of redshift.

Unless otherwise credited, all images in this section are from the National Space Academy

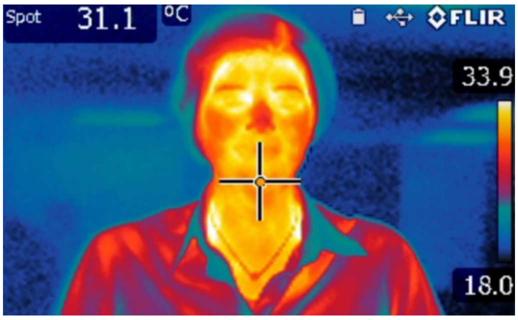
1) All objects emit infrared radiation

Demos:
Looking at students and objects around the room with the IR camera

Teaching points:
What is heat?
Insulators
Energy losses during transfers

You will need:
IR camera
Projector

What to do:
Turn on the infrared camera and pass it over the class. Explain that while many people think that infrared and heat is the same thing, it is a little more complex than that. Infrared radiation is a type of light, a part of the EM spectrum with a longer wavelength than visible light. It is emitted by all objects (as a result of molecular vibrations) and since there is a correlation between the temperature of an object and the amount of infrared light that it will emit, we can use infrared radiation as a measure of an object's temperature.



This allows us to use the infrared camera as a remote sensing instrument – that is, a way of getting information from the class without physically needing to go up to them or be in contact with them. Demonstrate this by seeing what you can find out about the students from the infrared image. Who has cold hands or noses (represented by darker colours on the screen). Who is the hottest person in the room (the more yellow/white an object is the hotter it is)?

You may wish to warn students that if they have poor circulation this will show up on the IR camera as colder extremities to avoid potential embarrassment to students. Also, please note – pregnant women will have a visible increase in thermal trace in their stomach region.

You can also look at how eyebrows and hair are good insulators as seen by the fact that these parts of the face look darker – indicating that less IR is able to pass through these areas since they are insulating well.

Other things you might want to try:

How thermally efficient is your school? If you are doing this demo in the winter, you could go outside and point the camera at the roof of your school. Look for areas where you have a strong thermal signature and ask students to suggest whether they think the material in the roof is doing a good or a poor job of insulating.

Image source: https://eqdisc.co.uk/

You can also use the IR camera to demonstrate energy losses. Aim the camera at your laptop or computer, or if you can see them, look at the part of the wall next to the plug sockets and you should be able to see a thermal signature caused by waste heating as energy follows the electrical pathway through the wires. Discuss with students why this is a problem and what other ways they think energy can be lost during transfer. Get a student to drag their shoe along the ground and show the thermal signature produced by friction between the shoes and the floor.

How does this relate to the Webb telescope?

While we can easily see stars in space thanks to the visible light that they emit, dust and gas is far harder to observe. However, due to heating of the dust and gas by starlight, these clouds do emit in the mid-infrared. The Webb Telescope's MIRI instrument will be mapping the structure of these huge dust clouds in space that hide warm planets and proto planetary disks.

2) Thermal Reflection

Demo:
Looking at people with glasses and reflections off a whiteboard/window

Teaching points:
Infrared is a type of light and can be reflected by a suitable 'shiny' (to infrared) surface
This reflection of infrared drives effects such as the greenhouse effect

You will need:
IR camera
Student wearing glasses
Whiteboard/large window within easy reach of the camera
Optional extra – mylar survival blanket

What to do:

a) **Glasses reflecting infrared**

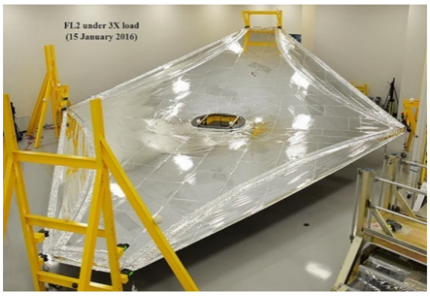
If you have any students in your class that wear glasses, then aim the infrared camera at them. They will look as if they are wearing sun glasses and the glasses will appear black on the screen. Ask students what they think is happening to the infrared that is being emitted from the eyes and explain that the glass is reflecting it. Since infrared is a wave, just like

visible light it can be reflected from a suitably shiny surface. Since the wavelength of infrared is longer than visible light, it can be reflected more coherently from a less smooth surface (like glass). You can then stand a few students in front of a window. Point the camera out of the window and show that you cannot see any of the infrared traces from outside, since they are reflected in the opposite direction. However, when you get the angle right, while still pointing the camera at the window, you will be able to see infrared reflections of your students. The window is acting as an infrared mirror.

b) Optional Extra - Using a reflective blanket

Show students an image of a marathon runner wrapped in a mylar foil blanket and ask them why such a thin blanket does a good job of keeping you warm. Ask for a volunteer and aim the IR camera at them showing that we can see all their thermal details. Hand them an emergency mylar blanket and if you have already done the bin bag demo recap that the bin bag was transparent to infrared. Get the student to hold the mylar blanket in front of themselves and you will not be able to see any of their thermal information through it since most of the infrared that they are emitting has been reflected by the blanket. The blanket is opaque to infrared.

How does this relate to the Webb Telescope?



There are two main ways that you can link reflection of infrared radiation to the Webb telescope. The most obvious is the huge sunshield that is made from five layers of Kapton, a material that certainly looks like the mylar emergency blanket. It is extremely important for as much of the thermal radiation that hits the sunshield to be reflected into space, away from the sensitive instruments on board.

Image source: NASA

The second application is in the primary mirror of the telescope itself. Like all telescopes, the infrared light needs to be collected and focused to turn it into useful information. To see the kind of distant, faint objects that the Webb Telescope scientists want to investigate, Webb needs a large mirror. A telescope's sensitivity (how faint an object it can see) and resolution (how much detail it can see) are both related to the size of the primary mirror collecting light from the objects. The bigger the area, the more light can be 'captured' and the higher the resolving power.

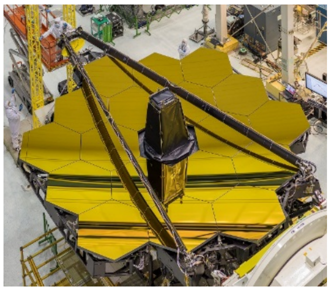
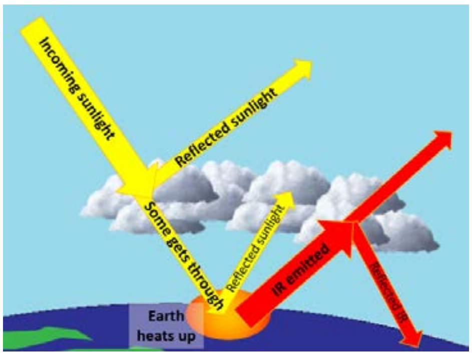


Image source: NASA

Since this will be the largest mirror ever launched into space, scientists and engineers had to come up with a new light but stable solution. The primary mirror is made up of 18 hexagonal mirror sections made from beryllium and coated with gold. The hexagonal shape was used because it allows a folding, roughly circular mirror to be constructed without wasting any space while it is folded up and leaving no gaps in the mirror after deployment. It's distinctive colour comes from the gold coating, which is used because it reflects infrared light more effectively than other materials.

Why else is this important?

This reflection of infrared radiation is the principle behind the greenhouse effect. Light from the Sun hits the surface of the Earth and causes heating. This heating emits infrared radiation, some of which is then reflected by greenhouse gasses such as carbon dioxide back down to the Earth causing further heating and the process continues.



3) The Bin Bag Nebula

Demo:

Using a student to represent a star and a bin bag to represent a nebula

Teaching points:

Materials can be opaque, transparent, or translucent to different wavelengths of light
Stars are formed in nebulae

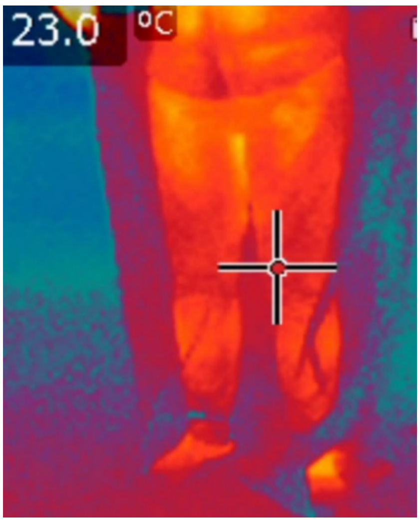
You will need:

IR camera
Projector
Black bin bag

What to do:

Explain that there are many reasons why astronomers might want to use infrared radiation to study regions of space and that you are going to demonstrate one of them. Ask students if they know where stars form. Explain that stars form in a huge region of dust and gas in space called a nebula. You may wish to show a picture of a nebula such as the Carina Nebula below (in the visible spectrum) and explain that this dust and gas often obscures these stars at visible wavelengths.

Ask for a volunteer and explain that they are going to be a star. Specifically, they are a young bright star that has just formed within the nebula. Take a black bin bag and explain that in this demo the bin bag is representing the nebula. Ask the student to step into the bin bag carefully and discuss with the class how the student is partially obscured from sight because the bin bag is opaque to visible light. Aim the infrared camera at the student in the bin bag and watch as students are surprised that they can now see the student star in the bag. Explain that infrared can pass through some materials that visible light can not due to its differing wavelength.



How does this relate to the Webb Telescope?

Show students a picture of the carina nebula in the visible spectrum and ask them how many stars they can clearly see. Explain that just like the bin bag the dust and gas in the nebula is obscuring a huge number of stars from study. However, if you look at the same nebula in the infrared part of the spectrum, the detail is able to emerge from the clouds and suddenly many more stars are visible to us. This is exactly what the Webb Telescope will be doing when it surveys regions of space – peeking below the dust blankets that cover these stars.
The bright pink stars in the infrared image are in fact 'baby stars' - stars that have just formed out of the stellar nursery whose dust is obscuring them.

Image source: NASA

We can also use mid-infrared radiation to get more information about the structure of warmer, dusty, gaseous regions. Over time, infrared radiation from stars will begin to heat up the dust and gas, though only a few sections will be able to be seen in the visible part of the spectrum. So, using mid-infrared allows us to detect these weak heat signatures and can give us an insight into the structures of these complex stellar nurseries. The Webb Telescope will not however be able to image the cooler gas regions – that can only be done in the far0infrared region, as in the image below of the Taurus molecular cloud. The infrared heating of the gas reveals the filament structure within.

4) Thermal transfer

Demos:
Footprints on the floor
Thermal handprint on a text book

Teaching points:
Methods of heat transfer – conduction, convection, and radiation

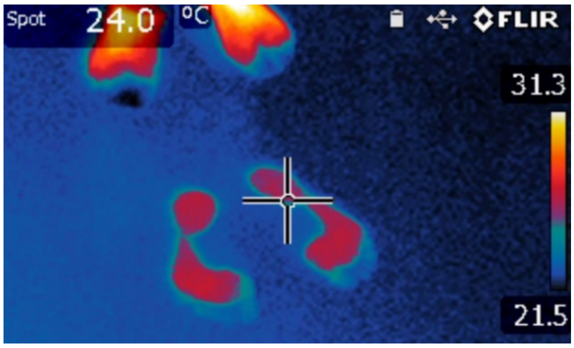
You will need:
IR camera
Projector
Text book

What to do:

a) Student model of conduction

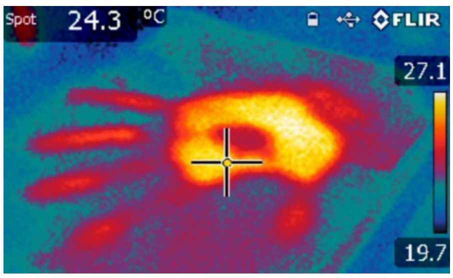
Recap or discuss with students what the three methods of heat transfer are. To demonstrate conduction initially you may wish to select a few students and line them up to represent the atoms in a solid. Explain that you are going to act as the heat source and will begin to 'heat' the student closes to you. Ask what is happening to their kinetic energy as they are being heated and get the student to start to sway side to side to represent the increasing kinetic energy. As they meet the next particle along, that one will begin to move side to side. And if they are moving more what is happening to their thermal energy? It is increasing. Repeat this process all along the line and explain that this was only possible due to the particles being in contact with each other. This is a representation of conduction.

b) Demonstrating conduction using the IR camera



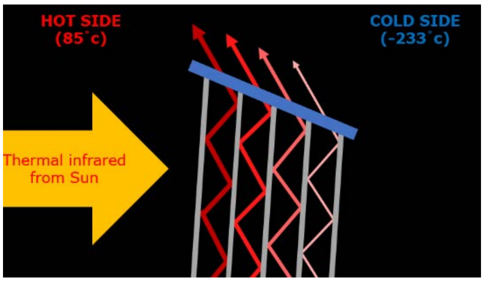
Ask for a volunteer who has shoes that can easily be removed. Ask them to remove their shoes and stand completely still in one spot for about 30 seconds. While they stand their aim the IR camera at their feet and show that the feet are much warmer than the floor. Ask students what they think will be happening to this heat energy, remembering that heat always flows from hot to cold.

After about 30 seconds get the student to take a step back and observe how a perfect set of thermal footprints has been left behind. Thermal energy has transferred into the floor through conduction. You can then get the student to go for a slow walk around the classroom and track their thermal footprints that get left on the floor.



Another impactful way to demonstrate conduction involves observing heat transfer through a magazine or text book. Take a thick textbook, preferably with thin pages. Ask for a volunteer and get them to rub their hands together to make sure that they are warm. Get the student to place their hand, palm down on the text book and leave it in position for about 30 seconds. While they do this get the class to make a prediction of how many pages the heat will be able to transfer through to in 30 seconds. Aim the IR camera at the top of the book and get the student to remove their hand and start flicking through the pages slowly (making sure you keep their fingers out of the shot since the camera will auto calibrate and the warm fingers will lesson the visible impact of the hand print). You should be able to make it through about 20 – 50 pages before the hand print becomes invisible!

How does this relate to the Webb Telescope?



At the size of a tennis court, the Webb Telescope's sunshield is a true feat of engineering. Constructed from five layers of a special material called Kapton, it is a light but effective way of preventing thermal transfer from the hotter, sun facing side of the telescope, to the side that must be kept below 50 Kelvin (-223°C) in order to pick up the faint emissions from distant objects. Conduction is the reason that the sunshield uses five thin layers rather than one thicker layer. If a single layer were to be used, heat would be able to conduct through this and get radiated from the surface of the sunshield facing the instruments. By using five thinner layers, the vacuum of space can be used as an additional barrier to heat transfer between each one, and while a some of the initial incident heat will be radiated to the next layer, much of this will be reflected away and only a small proportion will conduct through to be re-radiated to the next layer and so on. This means that most of the instruments on the Webb Telescope will be able to function using purely passive cooling and makes the telescope far more efficient. Crucially, it also means that unlike previous infrared space telescope missions, the life span of the Webb Telescope will not be limited by the loss of coolant over time.

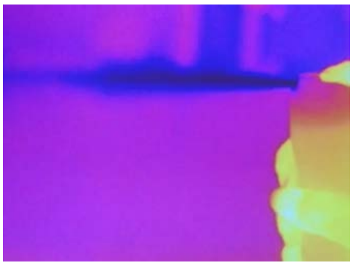
5) Expanding gas and cooling

Demos:
Compressed air 'cryo-cooler'

Teaching points:
Gas laws and temperature drop on expansion

You will need:
IR camera
Projector
Can of compressed air

What to do:



Ask for a volunteer from the class and hand them a can of compressed air. Get them to point it away from themselves and aim the IR camera at the nozzle of the can, making sure that the student's hand is in the frame of the camera. Get the student to press the nozzle on the top of the can and see the extremely cold air emerging from the nozzle. If possible, use the temperature spot to get an estimated temperature of the expanding gas and compare this to the temperature of the can itself. Why is the gas so much cooler than the can?

Explain that when a gas expands, the temperature of the gas drops and that this is the principal behind devices such as fridges and freezers that use compression and then expansion of gas to produce a low temperature.

How does this relate to the Webb Telescope?
While most of the instruments on the Webb Telescope can function at a temperature attainable by passive cooling alone, one important instrument cannot.

The Mid InfraRed Instrument – or MIRI – is one of the four instruments which will fly on Webb, and one to which the UK has made an enormous contribution. It will cover the mid-infrared part of the electromagnetic spectrum. These wavelengths (5-28 microns) are perfect for observing the light from distant galaxies, dust that has been heated by starlight, newly formed stars, and planetary disks (regions where planets are likely to form around stars).

To observe in the mid-infrared, MIRI needs to be extremely cold - far colder than the 40 Kelvin operating temperature of the rest of the Webb Telescope. It must be cooled down to just 7 Kelvin, or 7 degrees above absolute zero. To do this, engineers have created an extremely sophisticated 'space fridge' called a cryocooler. Helium gas is compressed and allowed to expand near the MIRI instrument, drawing thermal energy away from it. By using a closed system like this, MIRI will not lose coolant like previous infrared space telescopes and this allows the mission to potentially run far beyond its initial planned lifespan.

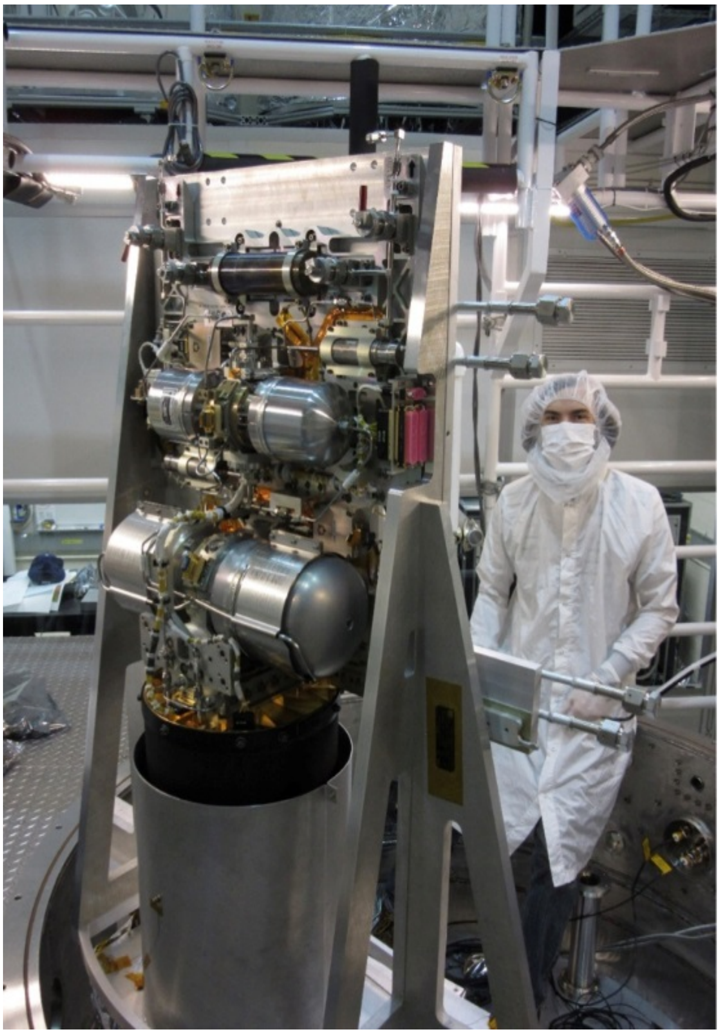


Image source: NASA

Additional Activities Related to the Webb Telescope – Redshift Demos

Additional Activities Related to the Webb Telescope – Redshift Demos

Teaching points:
Red shift
Big Bang theory
Doppler effect

a) Visual demonstration

You will need:
Elastic exercise band
Thick pen

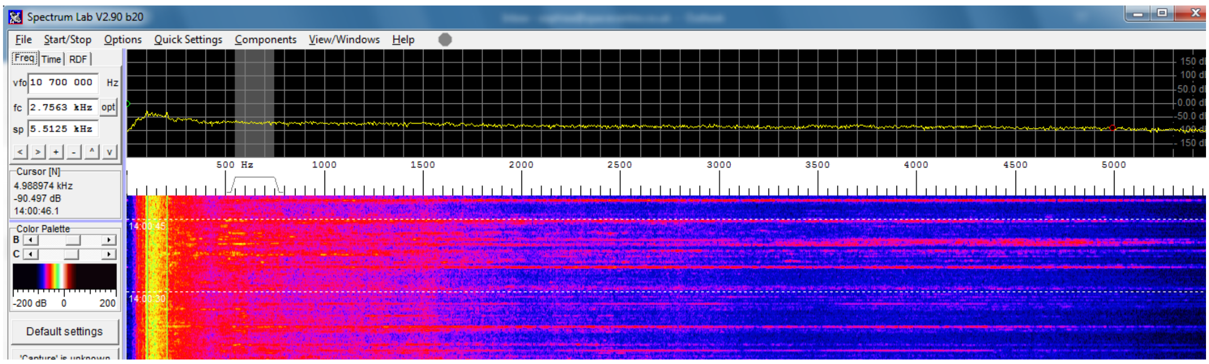
What to do:
Use the thick pen to draw a wave on the exercise band. Try to get two or three full wavelengths onto the band. Ask for a volunteer and explain that in this model, they are representing a distant galaxy, and you are representing an observer on the Earth. Hand them one end of the redshift band and move yourself to a distance away so that the band is tight but not stretched. Get the student to slowly move away until the tension in the band becomes high enough that you want them to stop. Ask the class what has happened to the wavelength of the light being emitted by this galaxy, and what that would do to the colour of the light. Explain that no matter what direction we look in, we observe this redshift effect and that this is one of the main pieces of evidence for the Big Bang. You can then get them to walk towards you and observe that now the wavelength of the light is shortening – becoming bluer. Explain that on a local level we do see this occurring, for example with the light coming from the Andromeda galaxy. Ask students what they think this means the Andromeda galaxy is doing and explain that at some point in the very distant future our galaxy will collide with Andromeda!

b) visual demonstration with a computer

You will need:
Computer with spectrum labs software installed (connected to a projector)
At least one device (mobile phone/tablet) with a tone generator downloaded

First install Spectrum Lab:

Spectrum Lab is a free piece of software that is used to analyse the frequency of sounds using a microphone. It is included in your training academy resources, but can also be downloaded from http://www.qsl.net/dl4yhf/speclab/install_speclab.zip .



When you open Spectrum Lab you will see a rolling ‘waterfall’ showing you all the frequencies of sound that are present in the room. You can zoom in and out of a particular frequency range by right clicking on the black graph box at the top and selecting zoom in/zoom out.

Open the tone generator on the device and select a tone frequency of about 5000 Hz. As this plays you will be able to see a strong peak, and a very bright line on the waterfall that corresponds to this frequency. Zoom into this frequency so that the width of the whole bar is about 100Hz.

Ask for a volunteer and hand them the tone generator. Get them to face away from the computer, hold the generator behind them and then walk away across to the other side of the room quite briskly. As they walk away the sound will be doppler shifted to a lower frequency and this will be noticeable as a visible shift in the frequency of the tone on the software.

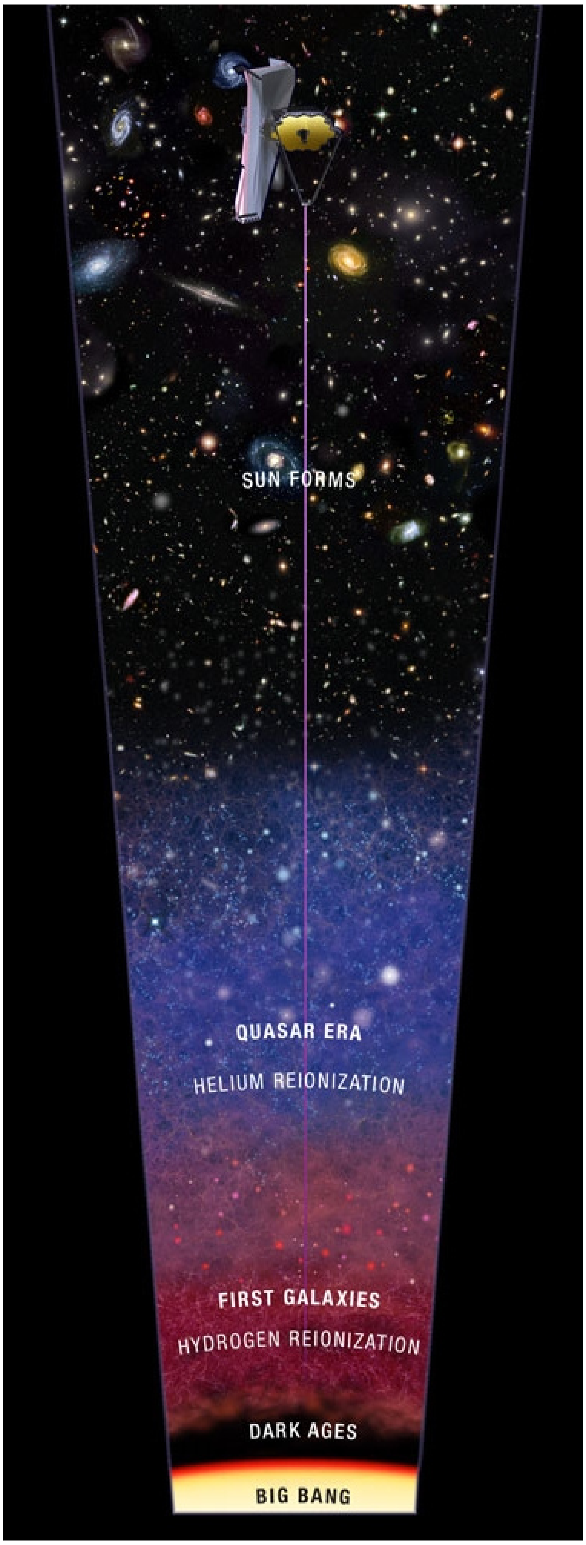


Image source: NASA

Since frequency and wavelength are inversely proportional (you may want to write the wave equation on the board at the front) ask students what has happened to the wavelength of the sound. It should be clear that is has got longer – doppler shift in action. This can then be applied to the idea of light being red shifted.

Extension: You could have several tone generators present, each one set to a different frequency. Hand these to several members of the class and stand them different distance from the computer. Get them to attempt to replicate what we observe for real in the Universe (the most distant stars showing the highest level of redshift) and hopefully the students further away will realise they need to run faster!

How does this relate to the Webb Telescope?

One of the key science goals of the Webb Telescope is to detect the first stars and galaxies to form after the Big Bang. These objects have been moving away from us (and indeed, everything else in the Universe) for billions of years and as such have an extremely large red shift. This red shift is so large, that the light that we see from these objects has shifted out of the visible range of the EM spectrum, and into the infrared. By using the world's most sensitive infrared telescope we will be able to see these stars for the first time and deepen our understanding of how the structure of the Universe has changed and evolved since light could first be observed.

Cosmic Dark Age?

So why is there a point beyond which we will not be able to see? Immediately after the Big Bang, our Universe was an extremely hot soup of quarks (the building blocks of particles) and then protons, neutrons and electrons. These free, uncaptured electrons would scatter any light causing the Universe to be fuzzy, and opaque. As the Universe cooled, these protons and neutrons were able to combine to form the first ionised atoms of hydrogen, which began to attract electrons turning them into neutral atoms. Now there were fewer free electrons to scatter the light, and it could finally travel unhindered through the Universe. And while it would still be a few hundred million years before the first sources of light would form, the Universe had emerged from its Dark Age.