Using the 'Unlocking the Universe in 3D' Virtual Reality program

STUDENT WORKSHEETS with answers for teachers

This resource was developed by the Australian Research Council Centre of Excellence for All Sky Astrophysics in 3D (2017-2024) and funded by the Australian Government.

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LESSON 1: The components and scale of the Universe

STUDENT WORKSHEET #1 (TEACHER COPY with answers)

What is the Universe?

1. Write down all the words you know describing things in the Universe.
2. Use the Internet to go to NASA's 'What is the Universe website' https://science.nasa.gov/exoplanets/what-is-the-universe/

Scanning through the website, find and list the major components of the Universe (don't forget to scroll down):

Space	Matter	Time
Energy	Earth	Moon
Solar System	Other planets	Asteroids
Comets	Sun	Stars
Exoplanets	Milky Way	Other galaxies
Black holes	Atoms	Hydrogen
Helium	Carbon	Silica
Oxygen	Elements	Star clusters
Dwarf planets	Rogue planets	Moons
Ringlets	Meteorites	Radio waves
Dark matter	Dark energy	Molecules
Protons	Neutrons	Electrons
Photons	Gamma rays	Visible light
X-rays	Infrared light	Ultraviolet light
Radio waves		

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LESSON 1: The components and scale of the Universe

STUDENT WORKSHEET #2 (TEACHER COPY with answers)

Cosmic Survey: What are your ideas about the Universe?

Question 1: How big?

With your group, arrange the 7 images side by side, in a row, **in order of actual size** of the object (or group of objects) pictured. Order the images so that the smallest is on the left, largest on the right. When your group is satisfied that you have the best order, record the **names** of the objects in the spaces below:

Objects Ordered by Actual Size

________ ________ ________ ________ ________ ________ ________

1. 2. 3. 4. 5. 6. 7.

Smallest in Actual Size ... Largest in Actual Size

The correct order for the 7 images, from smallest to largest is:

Telescope	12 metres
Moon	3,200 kilometres diametre
Saturn	121,000 kilometres diametre
Sun	1,408,000 kilometres diametre
Pleiades	1×10^{14} kilometres across the cluster
Galaxy	1×10^{18} kilometres across
Hubble galaxies	1×10^{21} kilometres across the cluster

Students answering this question sometimes wonder whether Saturn is larger than the Sun (since they may know it as a 'giant' planet). They also wonder if, in the image of the Pleiades, 'Are we talking about the sizes of the individual stars, or all the stars in the picture?' You may need to explain that for this picture (and the Hubble galaxies), the challenge of the survey is to determine the relative size of the 'field of view' – all the stars (or galaxies) in the cluster.

Some notes:
It's hard to tell the size of objects from many of the images we see, since they look about the same size in the pictures. But the Sun is much larger than Saturn or any of the planets. In fact, a million Earths would fit inside the Sun.

Size counts in nature: Objects much larger than Saturn or Jupiter are destined to turn into stars such as our Sun. They collapse under their own weight and grow fiercely hot as their nuclear fires are kindled. At each scale in the Universe, gravity helps shape the structures we see.

Question 2: How far?

With your group, arrange the 7 images side by side, in a row, **in order of distance** of the object from Earth. Order the images so that the object closest to Earth is on the left, farthest on the right. When your group is satisfied that you have the best order, record the **names** of the objects in the spaces below:

Objects Ordered by Distance from Earth

________	________	________	________	________	________	________
1.	2.	3.	4.	5.	6.	7.

Closest to Earth — Farthest from Earth

The correct order for the 7 images, from closest to Earth to farthest, is:

Telescope	560 km above surface of Earth
Moon	402,000 km
Sun	1.5×10^{8} km
Saturn	1.3×10^{9} km (at its closest)
Pleiades	4×10^{15} km
Galaxy	3×10^{20} km
Hubble view of galaxies	5×10^{22} km

In this survey question, students often struggle with:

1. the distance of the Hubble space telescope (after all, it takes images of very distant objects and while NASA has sent some spacecraft out deep into the Solar System, the space telescope orbits fairly close to Earth's surface).
2. The relative distances of the Sun and Saturn – working this out requires knowledge about the relative orbits of the planets.
3. Depending on how much astronomy background students have had, the Pleiades may be placed inside the Solar System, or as the farthest objects in space. In general, most students (and adults) have a hard time understanding the relative distances of the last 3 objects.

Some notes:

How far away is that Hubble Space telescope? Many people believe that it is beyond the orbit of the Moon...but it's actually only 560 kilometres high. That's high enough for a clear view above the Earth's atmosphere...but low enough to enable it to be serviced by the astronauts aboard the space shuttle between 1990 and 2009).

Many people think the beautiful Pleiades cluster of stars must be further away than a cluster of galaxies, because they look smaller. But all the stars we see in the night sky are much closer than even the nearest galaxy.

A galaxy is made up of many billions of stars. Galaxies are so far away that we can't make out the individual stars in them. In fact, the roughly 5,000 stars we can see with our naked eyes (including the Pleiades) are just among the closest of the billions of stars in our own galaxy, the Milky Way.

Question 3: How old?

With your group, arrange the 7 images side by side, in a row, **in order of age** of the object, beginning with the youngest (most recently formed) object, and moving in order to the oldest. When your group is satisfied that you have the best order, record the **names** of the objects in the spaces below:

Objects Ordered by Age

____	____	____	____	____	____	____
1.	2.	3.	4.	5.	6.	7.

Youngest (Most Recently Formed) Oldest

For this question, the correct order for the 7 images is actually somewhat ambiguous and the subject of much current astronomical research! A 'best response' (one that most astronomers might give) is:

Telescope	a few years (1990)
Pleiades	25 million years
Moon	~4.5 billion years
Saturn	~ 4.5 billion years
Sun	~4.5 billion years
Galaxy	10 billion years?
Hubble galaxies	10 billion years?

In confronting this seemingly simple survey question, students are grappling with the big ideas of the Solar System's formation, the life cycles of stars, and the evolution of the Universe!

Some notes:
We think of stars as having been around for a very long time. In fact, our Sun is billions of years old. But new generations of stars, like those in the Pleiades, are continually being born.

The Pleiades stars are only about 25 million years old. If the dinosaurs ever gazed at the night sky...they wouldn't have seen the Pleiades, which hadn't been born yet!

What's older, the Sun or Hubble galaxies? Depends on what you mean by 'age'. The Sun is about 4.5 billion years old. But the Hubble 'deep-field' galaxies are among the most ancient and distant objects we can see in the sky. The light from them has taken about 10 billion years to reach us. So, they were born long before the Sun.

On the other hand, the Hubble deep field galaxies are young. Because light takes time to travel, telescope images of far-away objects let us look back in time. This image shows these galaxies as they were when they formed only a few billion years after the Big Bang...so many of the stars in these galaxies may be younger than our Sun. We're looking at an 'old' image of young objects!

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LESSON 3 (VR): Basic training and console training

STUDENT WORKSHEET (TEACHER COPY with answers)

Console training

You have collected data on three different space objects during the U3D console training.
Using the snapshots of the data fill in the following information:

SPACE OBJECT DATA

Space Object 1:

Mass (M⊙):_____0.12 M⊙___

Temperature (K):__3,042 K__

Space Object 2:

Number of protons:_8_______

Number of neutrons:_8______

Number of electrons:_8______

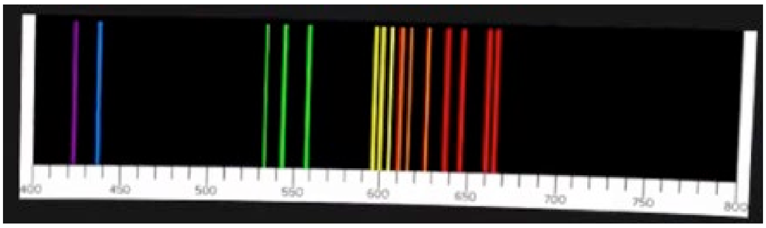
Atomic number:_8__________

Mass number:__16__________

Atomic mass:_15.999 amu____

Net charge:_-2_______________

Spectrograph printout:

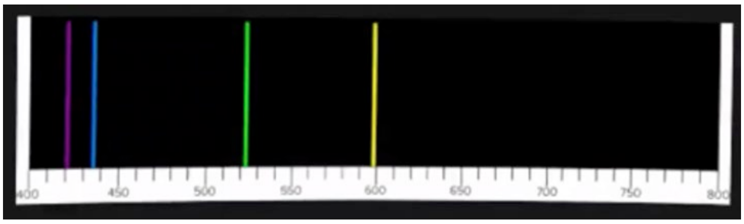


Space Object 3:

Mass (M⊙):_1 trillion M⊙ ___

Temperature (K):_Between 12K & 41 K_

Spectrograph printout



Questions:

Based on the visual information and the information collected by the scanner (in your table above), please answer the following questions:

1. Order the space objects from smallest to largest:

Object 2, Object 1, Object 3

2. Which object is the hottest?

Object 1 – 3,042 K is hotter than Object 3 (between 12 and 41 K)

3. Which object is the coolest?

Object 3

4. What type of space object do you think each object is? Can you identify each one by name?

Object 1 – star (Proxima Centuri): Object 2 – atom (oxygen); Object 3 – galaxy (Andromeda)

5. What element do you think Space Object 2 is? Why do you think this?

Oxygen – it's atomic number (the number of protons) is 8, which match Object 2's number of protons

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LESSON 4: Basics of the Big Bang

STUDENT WORKSHEET (TEACHER COPY with answers)

Scientific theories and evidence

1. List the scientific theories mentioned in the video 'Why science is NOT 'just a theory'.

   Big Bang Theory, the Theory of Evolution by Natural Selection, the Germ Theory of Disease, Plate Tectonics Theory, the Theories of Special and General Relativity and Quantum Theory.

2. List the three things that scientists mean when they say the word 'theory':

   1. A scientific theory puts forward a comprehensive explanation for things we observe in nature.
   2. A scientific theory provides strong evidence for that explanation.
   3. Perhaps most importantly, a scientific theory provides a way to make predictions about the aspect of the world it explains, which we can then test by further observation.

3. In the video 'Evidence for the Big Bang', what did Olber conclude about the Universe?

   Olbers concluded that since the night sky is dark, perhaps space is not completely transparent.

4. Which poet/thinker disagreed with Olber's conclusion that the Universe must be infinite?

   Edgar Allen Poe.

5. What assumption did Einstein make, thereby erroneously believing that the Universe was infinite and static?

   That the Universe is quite smooth (homogenous) with galaxies distributed evenly (isotopic).

6. What did Einstein's own general theory of relativity require spacetime to be?

   Dynamic and changing and therefore either expanding or contracting.

7. Who published results that were used to demonstrate that the Universe is indeed expanding?

   Edwin Hubble.

8. Which competing model proposed that the Universe was expanding, but has the same properties at all times?

   Steady State model.

9. Which piece of evidence resulted in scientists adopting the Big Bang Theory as the standard model of cosmology?

   Cosmic Microwave Background.

10. Because this radiation was detectable in every direction and not associated with any particular source, where is its origin?

    From a time of thermal equilibrium, when the entire Universe was one opaque ball of plasma – the era of recombination.

11. What else can we use CMB radiation and recession velocities for?

    Turn back the clock using math – age of the Universe is 13.8 billion years old.

12. What other things does the model predict?

    Ratio of hydrogen to helium, ratio of baryons to photons, galaxies forming 13.4 bya.

13. What do we use particle accelerators for?

    Very early particle and energy predictions – mass, charge and other parameters.

14. What do we use bubble chambers for?

    To measure particle properties.

LESSON 5 (VR): The Oldest Light activity – Nucleosynthesis

STUDENT WORKSHEET (TEACHER COPY with answers)

Research Task 1: Exploring subatomic particles 10-20 seconds after the Big Bang.

What are the four different sub-atomic particles at **20 seconds** after the Big Bang?

Using the data you collected in 'The Oldest Light' activity in VR fill in the following table:

Subatomic Particle	Mass (amu)	Charge (no units)	Information
Electron	0.0005	-1	Smallest of the 3 subatomic particles with virtually no mass
Proton	1.0072	+1	Every element has at least one proton
Neutron	1.008	0	Neutrons are important for the stability of nuclei, except in the single-proton hydrogen nucleus
Photon	0	0	Photons get their energy from their momentum. If an object with no mass is to physically exist, it can never be at rest

Research Task 2: Exploring the first nuclei 2-20 minutes after the Big Bang.

1. What happened during the Big Bang Nucleosynthesis?

   As the Universe expanded and cooled, protons and neutrons began to combine to form these elements through nuclear fusion.

2. What nuclei had formed at **2 minutes** after the Big Bang?

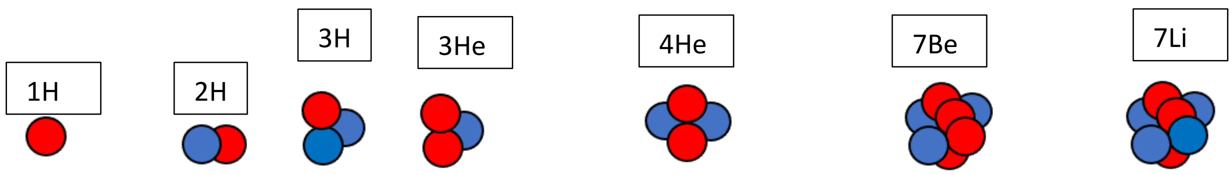
   Hydrogen-1 and Hydrogen -2

Using the data you collected in 'The Oldest Light' activity in VR, fill in the following table:

Nucleus	Number of protons	Number of neutrons	Information about nucleus
Hydrogen-1 (^{1}H)	1	0	The most common isotope of hydrogen, it is also a stable subatomic particle. Also called protium.
Hydrogen-2 (^{2}H)	1	1	Stable isotope of hydrogen. Also called heavy hydrogen or a deuteron

Hydrogen-3 (^{3}H)	1	2	Unstable isotope of hydrogen with a half-life of 12 years. Decayed into helium-3. Also called a triton
Helium-3 (^{3}He)	2	1	A light, stable isotope of helium. The only stable isotope of any element with more protons than neutrons (with the exception of protium).
Helium-4 (^{4}He)	2	2	The most common isotope of helium and very compact, it is 20% smaller than a deuteron
Lithium-7 (^{7}Li)	3	4	Stable and most abundant isotope of lithium
Beryllium-7 (^{7}Be)	4	3	Unstable isotope of beryllium (half-life of 53 days). Decays into lithium-7

3. Draw each nucleus (red for protons, blue for neutrons) and label them.



4. What do you notice about the naming of each nucleus?

   They have the names of elements ((hydrogen, helium etc) and a number

5. What do the nuclei have in common?

   They all have protons (not all have neutrons)

6. What does the number next to the name indicate?

   The Atomic Mass Number (number of protons + number of neutrons)

Research Task 3: Formation of nuclei in the Big Bang.

Questions:

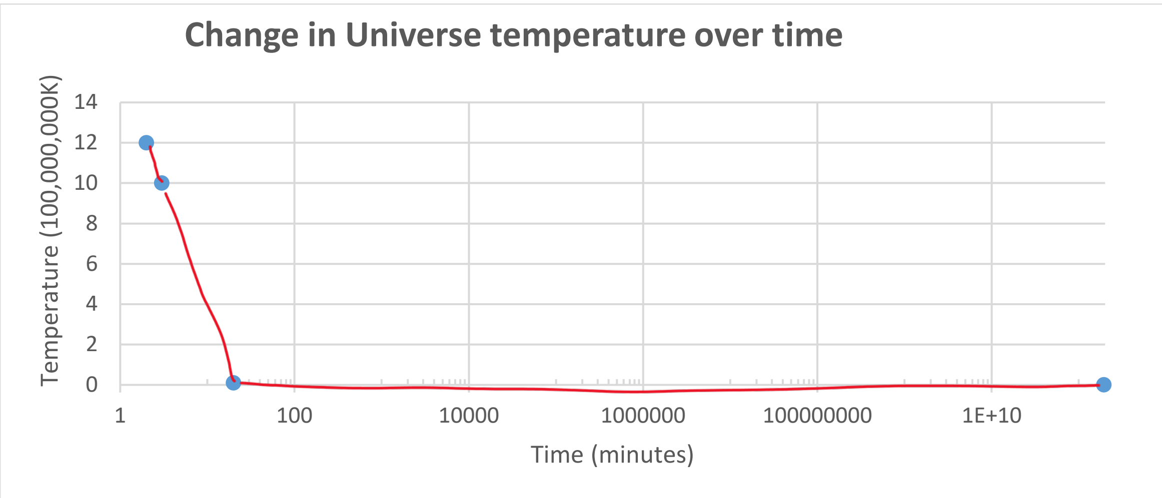
1. How has the temperature of the Universe changed from 2, 3 and 20 minutes after the Big Bang? (hotter, colder – by how much?).

   Complete the table below from the data you collected.

Time	Temperature (K)
2 (minutes)	1,200,000,000
3 (minutes)	1,000,000,000
20 (minutes)	10,000,000
380,000 (years) = $1.997 * 10^{11}$ mins	2.725

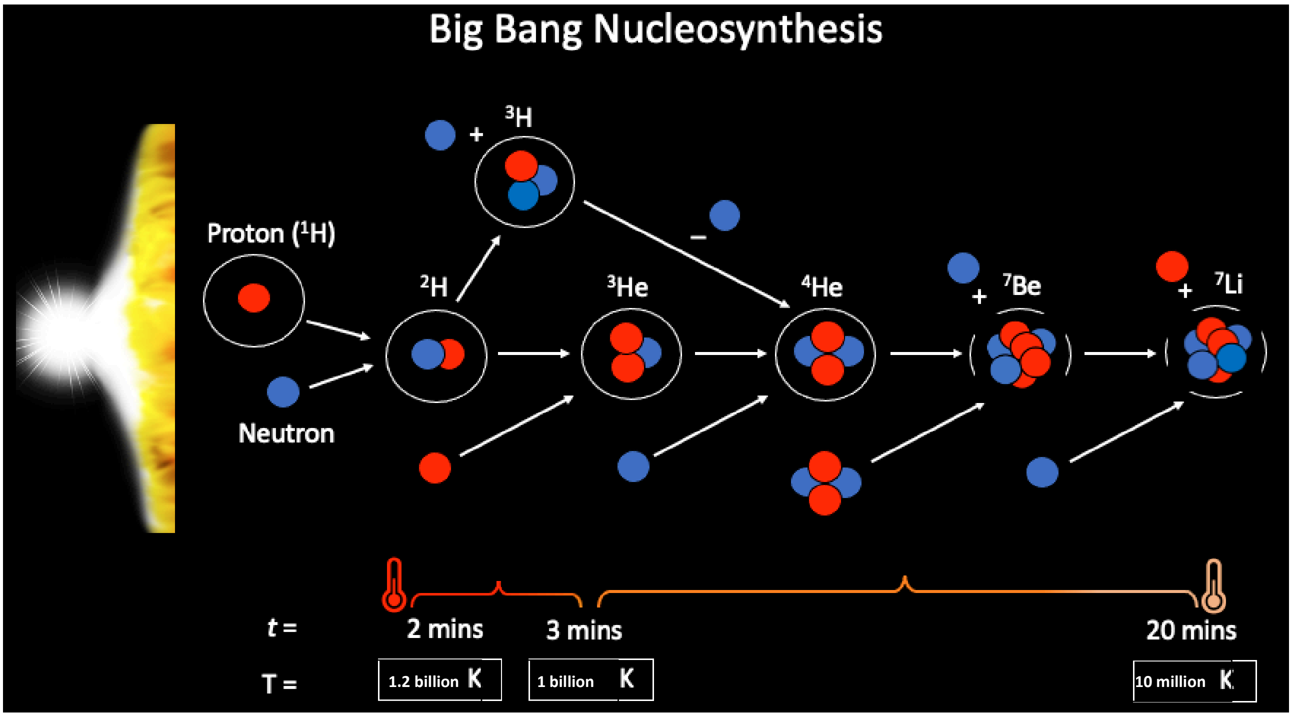
The time the temperatures are taken goes from minutes after the Big Bang to hundreds of thousands of years. <u>You will need to convert years to minutes</u>, which will give you an answer that uses scientific notation (e.g., 3.8 x 10^5).
HINT: use
https://www.google.com/search?q=convert+years+to+minutes

2. Use the data from the table above to plot the change in temperature in degrees Kelvin (horizontal axis) over time (in minutes). You are dealing with *huge* variations in numbers, so you will have to note the following:
   a. The highest temperature is in billions of degrees Kelvin, and the lowest is in single digits. This means your vertical axis (temperature) is measured in billions of degrees Kelvin, and the smaller numbers will look very close to zero).
   b. To fit all this into a graph that makes sense, we use a logarithmic scale on the horizontal axis. Instead of equal increments, we use a power of 10—each value increases by a factor of 10.



3. Join your plotted data points to see the changes over time.

Using the data you collected on the Big Bang Nucleosynthesis in VR, complete the graphic below by drawing the elements' nuclei and the temperature at which they formed.



Isotopes that can form:

- Deuterium (one proton and one neutron in a nucleus)
- Tritium (one proton and two neutrons in a nucleus).
- Helium-3 (two protons and one neutron in a nucleus)
- Helium-4 (two protons and two neutrons in a nucleus).
- Beryllium-7 (four protons and three neutrons). The Beryllium changes into lithium quickly because it is unstable.
- Lithium: Lithium-7 (three protons and four neutrons).

Questions:

1. Only the nuclei of simple atoms had formed at this stage of the Universe. Why are there no electrons in shells or electron clouds?

   It was still too hot for electrons to stay around the nuclei.

2. How did heavier elements than this (the rest of the periodic table) form? When did this start to occur?

   Formed mostly in aging stars – stars start forming about 400,000 years after the Big Bang.

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LESSON 6: Evidence for the Big Bang – The Cosmic Microwave Background

STUDENT WORKSHEET (TEACHER COPY with answers)

The Cosmic Microwave Background

Watch the video 'Picture of the Big Bang (a.k.a Oldest Light in the Universe) – Minute Physics', YouTube, https://www.youtube.com/watch?v=_mZQ-5-KYHw&t=0s (4.00 min) (stop at 3.12 min).

Questions:

1. How long has the Cosmic Background Radiation been travelling to Earth?

   13.7 billion years

2. Based on the instruments that observe this 'light', what part of the electromagnetic spectrum is the light travelling in when it reaches Earth?

   Microwave

3. What's the proper name for the 'red-hot cosmic soup' of protons, neutrons and electrons shown in the video? (you might have to Google it or ask your teacher!)

   Plasma

4. At what temperature did the protons and electrons finally connect to each other?

   To just below the temeratiure of the Sun

5. Why was the light released from the electrons when they became attached to protons to form hydrogen atoms?

   There are fewer free electrons for light (photons) to interact with

6. The light from the freed photons gets stretched from what sort of light?

   Original sunlight-white (to cool microwave)

7. What is the temperature of empty space?

   Currently around 2.725 K (-270°C)

8. What is our best understanding of the small and seemingly random but noticeable bumps in the Universe at that time?

   Quantum fluctuations

9. These hot or cold spots were hotter or colder than their surroundings by a factor of what?

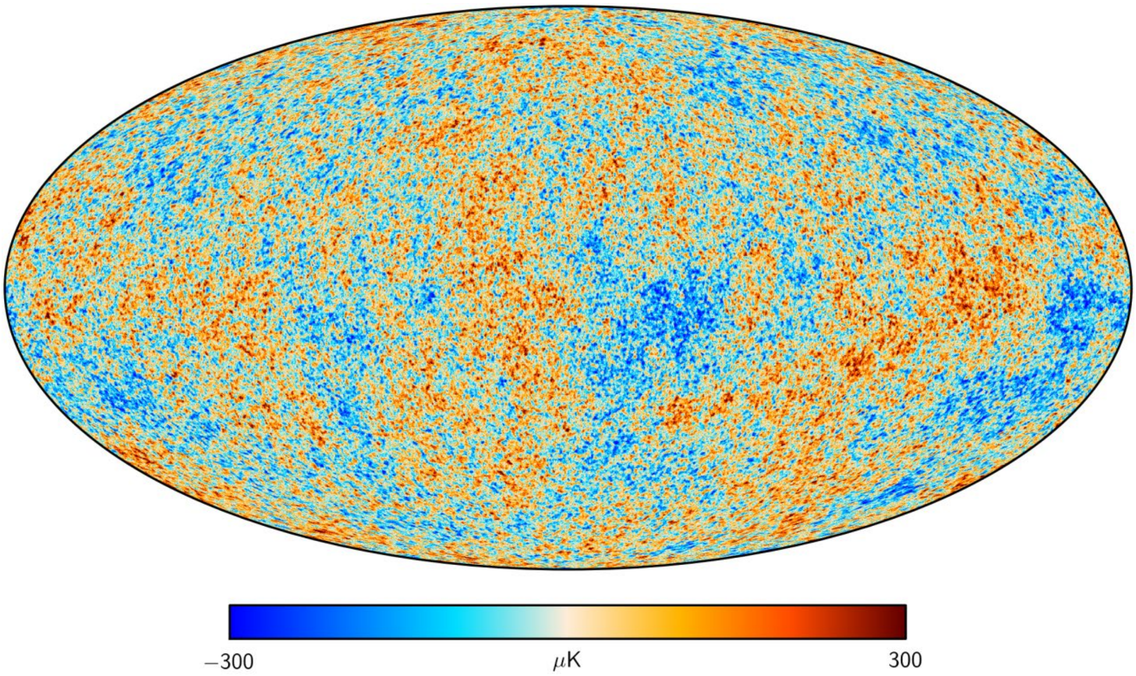
   1:100,000

10. These tiny variations eventually coagulated and coalesced to form what?

    All the massive structures in the Universe that we see today – planets, stars, galaxies, and superclusters of galaxies

In the Oldest Light activity in VR, you recorded the tiny fluctuations in temperature between the warmest parts of the CMB (red) and the coldest parts (dark blue). Copy those numbers into the table below.

Temperature	**Red CMB**	**Dark Blue CMB**	**Variation in temperature**
Kelvin (K)	2.7251	2.7250	0.0001
Celsius (°C)	-270.4249	-270.425	-0.0001



Questions:

1. The small temperature differences are presented in this “map” of the CMB using the WMAP satellite and observations from the Teide Observatory. It is called an **anisotropy map.** What does the word ‘anisotropy’ mean?

   Not uniform

2. What is causing these very tiny fluctuations in temperature in the CMB?

   Different densities

3. If the blue spots are colder, is the matter there **more or less dense** than the warmer red spots?

   More dense than the warmer spots (they are ‘gravitational wells’)

4. Why is the pattern of the CMB important? What do scientists think is the link between the density of matter (and dark matter) and the evolution of of the Universe?
   It will tell us a lot about how and why galaxies formed and how the Universe expanded and the geometry and shape of our Universe.

LESSON 7: The Electromagnetic Spectrum, spectra and redshift

STUDENT WORKSHEET (TEACHER COPY with answers)

Light: Crash Course Astronomy #24

Questions:

1. If light is a wave, what are the things doing the 'waving'?

   Electric and magnetic fields

2. What is the distance between the crests in a wave called?

   Wavelength

3. What is the link between wavelength and energy?

   The shorter the wavelength, the more energy (longer = less energy)

4. Which colour light has the shortest wavelength? Which has the longest?

   Blue light; red light

5. Which part of the electromagnetic spectrum can our eyes see?

   The 'visible' part

6. What sort of electromagnetic waves have the shortest wavelengths (and most energy)? Which ones have the longest wavelengths (least energy)?

   Gamma; radio

7. What is one way for matter to get rid of energy?

   Emit light

8. What do astronomers call light with a shorter wavelength? What about a longer wavelength?

   Blue; red

9. What analogy can we use to describe the very specific volumes of space around a nucleus that an electron is allowed to occupy?

   Staircase, where the landing is the nucleus

10. What happens when an electron steps down to a lower energy state?

    It gives off energy (light)

11. If different atoms have different 'staircases', how can we tell what atom it is when an electron jumps down a step?

    Gives off a different colour of light

12. What is a spectrometer?

    A device that can precisely measure the wavelengths of light emitted by an object

13. If an object in space is headed toward you, what happens to the wavelength of light emitted from the object? What about if it is headed away from you?

    Wavelengths get compressed; wavelengths get stretched out

14. What is the spoiler alert in the video?

    The Universe is expanding

15. What are some things spectroscopy allows us to analyse in astronomy?

    Temperature, density, spin, motion and chemical composition

LESSON 8 (VR): Exploring the First Atoms in the Cosmic Dark Ages

STUDENT WORKSHEET (TEACHER COPY with answers)

Exploring the First Atoms

Research Task 1: The five stable atoms of the neutral Universe.

Complete the table using the data you collected in VR.

Name	No. Protons	No. Neutrons	No. Electrons	Atomic Number	Mass Number	Atomic Mass (amu)	Net Charge
Hydrogen-1 (^{1}H) atom	1	0	1	1	1	1.00797	0
Hydrogen-2 (^{2}H) atom	1	1	1	1	2	2.01410	0
Helium-3 (^{3}He) atom	2	1	2	2	3	3.01603	0
Helium-4 (^{4}He) atom	2	2	2	2	4	4.00260	0
Lithium-7 (^{7}Li) atom	3	4	3	3	7	7.01600	0

Questions:

1. What do you notice about the number of protons in an atom and its atomic number?
   They are the same
2. Does the atomic number change for different isotopes of the same atom (e.g. Hydrogen-1 vs Hydrogen-2)? No – the number of protons/atomic number is what makes hydrogen hydrogen and helium helium etc.
3. Does the number of neutrons affect the atomic number?
   No
4. Does the number of neutrons affect the mass number?
   Yes
5. What is the difference between the mass number and the atomic mass of an isotope? (you may have to get help with this – ask your teacher or look it up):
   Mass number is the number of protons plus the number of neutrons. Atomic mass is the average of values for many atoms in a given sample of a chemical element (which would include isotopes of the same element).
6. What do you notice about the net charge of all of these atoms? What would happen if you added electrons?
   Zero. It would be negative by the amount of electrons you added.

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LESSON 9 (VR): The Epoch of Reionisation – Exploring the EoR and the first stars

STUDENT WORKSHEET (TEACHER COPY with answers)

Research Task 1: What happened during the Epoch of Reionisation?

Questions:

1. What is happening during the Epoch of Reionisation (EoR)? Circle your answer.
   A. The Universe remained cold, dark and featureless.
   B. Planets were formed for the first time.
   C. The first stars and galaxies emitted UV light. The Universe became transparent.
   D. The Universe stopped expanding for 600 million years.

2. In a paragraph summarise the transition of the Universe from the Cosmic Dark Ages to the end of the Epoch of Reionisation?

Example: At the end of the Cosmic Dark Ages the Universe was filled with a dense fog of neutral hydrogen. Gradually, tiny bits of mater were pulled together under gravity forming the first stars and galaxies. They emitted intense ultraviolet light reionising the surrounding hydrogen gas leaving transparent 'bubbles'. These transparent regions eventually met and the Universe was transformed into a bright place fileld with galaxies.

Research Task 2: the first stars

Complete the table using the data you collected in VR.

Property	Star #1	Star #2	The Sun
Radius ($R_\odot$)	4	14	1
Luminosity (million $L_\odot$)	1	30	1
Lifespan (million years)	3	3	10,000
Composition	H, He	H, He	H, He, O, C, Ne, Fe
Temperature (K)	100,000	110,000	5,778
Mass ($M_\odot$)	100	1000	1

Questions:

Using this website - 'What were the first stars like?', Webb Space Telescope website, https://webbtelescope.org/contents/articles/what-were-the-first-stars-like and the data you have collected above, answer the following questions on what the first stars were like compared to our Sun and how they influenced the Epoch of Reionisation.

1. How many years after the Big Bang did the first stars start to form?
   200-400 million years after the Big Bang

2. Astronomers call the first stars in the Universe 'Population III' stars. What elements were in Population III stars? How does this compare with our Sun?
Hydrogen (H) and helium (He)

3. How big (or massive) were Population III stars compared to the mass of our Sun?
Tens to hundreds of times the mass of the Sun

4. How long did the first stars live for? How does that compare to the expected lifespan of our Sun?

   Less than a million years

5. Temperature and brightness of a star are directly related to what?

   Its mass (the hotter and brighter a star is, the more massive it is)

6. If the first stars were 100 times the mass of our Sun, what would be the surface temperature and the brightness (luminosity) of the first stars?

   Surface temperature around 100,000 kelvin and luminosity of 1 million Suns

7. If the first stars were extremely hot and bright, what sort of energy did they give off? What did that light energy do to surrounding fog of neutral hydrogen that filled the Universe during the Cosmic Dark Ages?

   High-energy ultraviolet radiation

8. What do computer models show happened to the first stars that were greater than 10 and less than about 140 times the mass of the Sun (how did they die)? What would remain of these stars?

   They ended in supernovae explosions. The metals (every element NOT hydrogen or helium) that formed in their cores would have been blown out and dispersed into the surrounding Universe. The remains of these stars would have collapsed to form neutron stars or black holes

9. What would have happened to even larger metal-free stars (up to about 300 solar masses)?

   A strange type of supernovae that left no black hole – everything would have exploded into the Universe

10. If we could use space telescopes, like the Hubble or JWST, to look back into space-time and see billions of light years away from us, what part of the electromagnetic spectrum would astronomers be looking at to see ancient galaxies that contain first-generation stars, given the light has been redshifted and stretched from the UV radiation they are emitting?

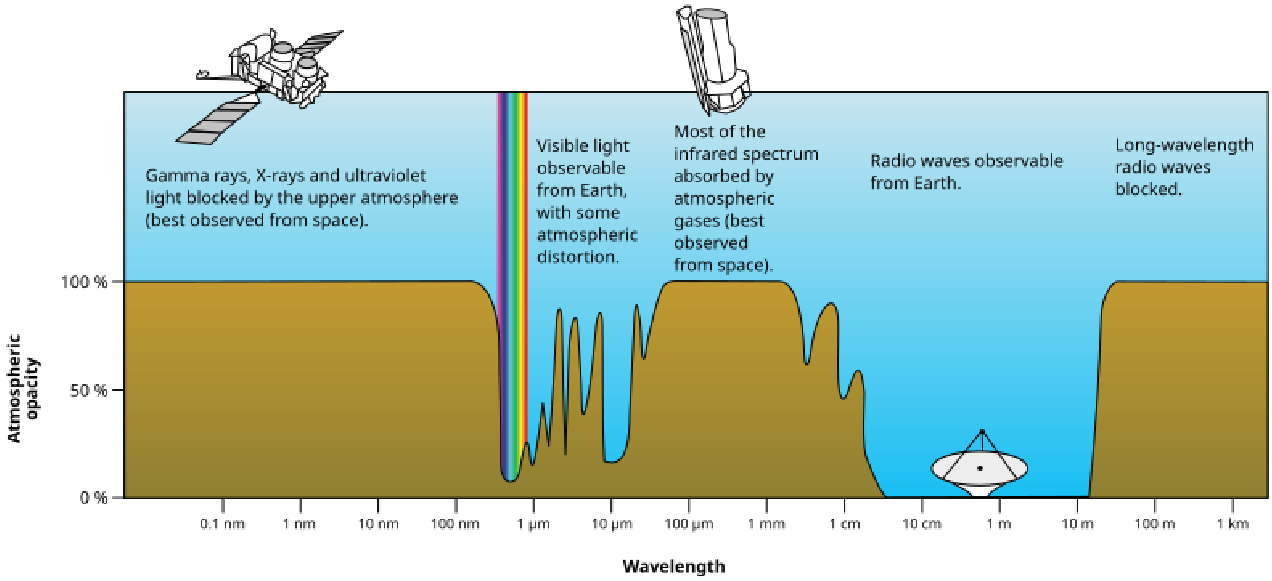
    Red and infrared light

LESSON 10 (VR): Signal from Cosmic Dawn – the 21 cm line

STUDENT WORKSHEET (TEACHER COPY with answers)

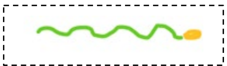
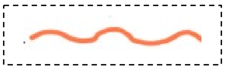
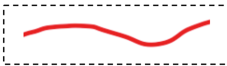
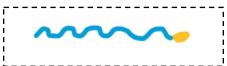
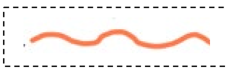
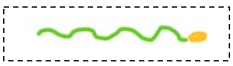
Signals from Cosmic Dawn

A significant advantage radio astronomers have over IR, UV and high-energy astronomers is the atmospheric window. Our atmosphere is completely transparent to radio waves , so we don't need to send large radio antennas to space (like we usually have to do with IR/UV/high-energy astronomy satellites) in order to efficiently expose our instruments to the sky.



Electromagnetic opacity of the Earth's atmosphere (Wikimedia Commons)

You have collected data from four points in space-time. Use the information from your snapshots to complete the following table. In the dashed boxes, draw the models of the waves you saw.

	340 million years after the BB (beginning of EoR)	**1 billion years after the BB (end of EoR)**	**6 billion years after the BB**	**13.8 billion years after the BB**
Wavelength	*Emission 1* 21 cm 	33 cm 	1.5 m 	3.0 m 
	Wavelength	*Emission 2* 21 cm 	95 cm 	1.9 m 
		Wavelength	*Emission 3* 21 cm 	42 cm 

Take a note of the “z =” number:

Time after Big Bang	Redshift (z)
340 million years	-13
1 billion years	-8
6 billion years	-1
13.8 billion years	0

Research questions:

1. What created the red wave?

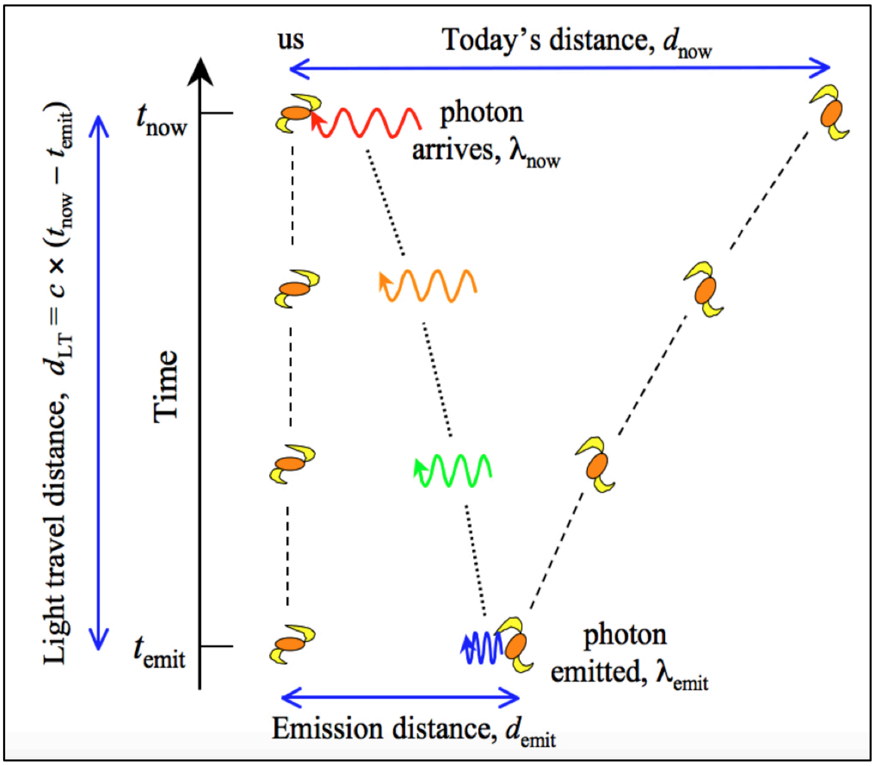
   A photon emitted by a neutral hydrogen atom (bonus points for adding as it undergoes spin-flip)

2. Where did it originate?

   From the Epoch of Reionisation (where neutral hydrogen was ionised by UV light from the first stars and galaxies)

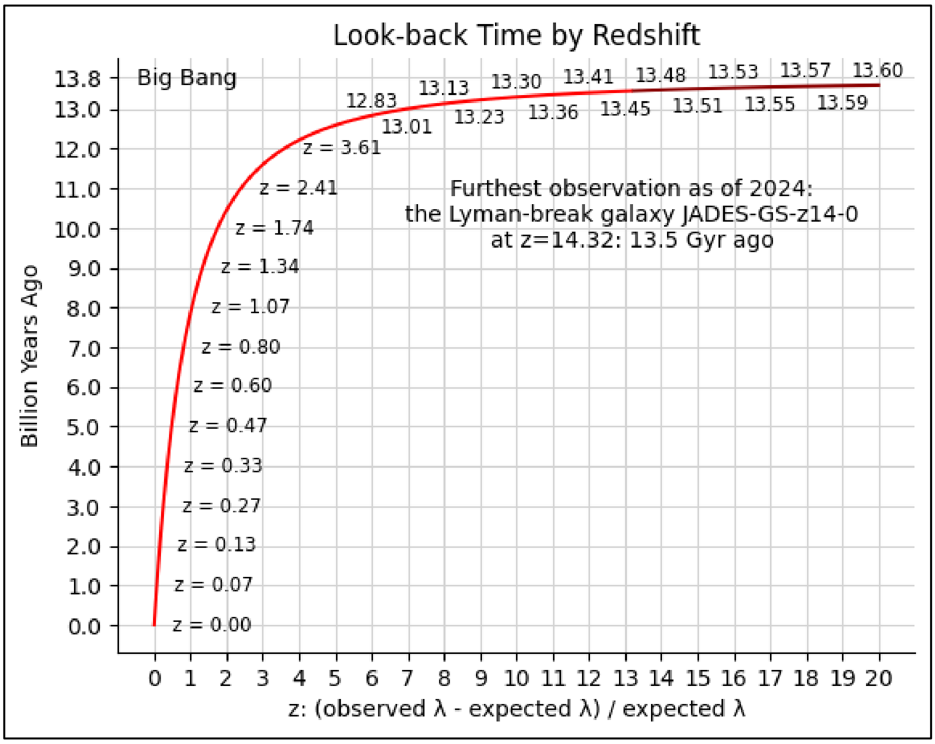
3. How far has it travelled?

Here is some information to help you answer this question: In astronomy, a **light year** is the distance light travels in a year (roughly 9.46 trillion kilometres) and so is a unit of **distance**, not of time. Because the Universe is expanding, the distance between objects is expanding, too. The distance travelled by the photons is called the **light travel.** This is shown in the diagram below:



Distances in cosmology

We can work out how far that photon has travelled to us using this diagram:



Sandizer, CC0, via Wikimedia Commons

a. If our photon from the red line has a *z* value of 13 at the present time, use the graph above to calculate how many billions of years it has travelled: Z= 13.1, then billion of year ago = 12.83

b. Use the Omni Light Year Calculator https://www.omnicalculator.com/physics/light-year to work out how many light years the photon has travelled – use billion years (byrs) for time and light years (1y) for distance: 12.83 billion years ago = 12,830,041,235 light years away

4. Has it changed over time?

Yes – it has stretched (from 21cm to 3m)

5. If so, what caused this change?

The expansion of the Universe over time as the photon travels towards Earth.