**News from the Cosmic Microwave Background TAPT Feb. 2014**

This lesson assumes that the students have already learnt about the cosmological red-shift as evidence of the expansion of space over the past 14 billion years. It uses this expansion to develop an understanding of the predictions of the Big Bang theory – especially the cosmic microwave background.

The first part is suitable for grades from 9 to 12. The second part is probably only suitable for senior grades like grade 11 Physics (Vibrations and Waves) and grade 12 Earth Space Science (Cosmology). There are PowerPoint slides that go with these sheets which have extra illustrations.

In March 2103 the map of the Planck Satellite survey of the Cosmic Microwave Background was released. It is the oldest picture of the universe. It looks like a random bunch of speckles, but it provides a lot of very precise information about the universe; what it is made of, how it evolved and what its future will be like.

**Part 1: What is the Cosmic Microwave Background?**

1. The galaxies appear to be moving away from us. The farther they are – the faster they are receding. This suggests that the universe was once much

A) smaller B) denser C) brighter D) all three  
How can you illustrate your answer using bubble gum, sponges and flashlights?

The objects have been introduced to increase learning by providing concrete images for abstract ideas, to increase conceptual understanding by requiring students to translate their understanding into another form and to encourage clear communication of ideas.

The matter in the universe used to be squeezed into a smaller space, so it would have been denser - like bubble gum before becoming a bubble. The sponge can be squeezed and then allowed to expand to show the changing size and density. The flashlight can be pointed at a wall and then pushed closer. As the circle of light gets smaller - the light gets more intense. This shows that energy as well as matter was more concentrated.

1. Blow on your hand using a wide, open mouth. Blow on your hand with a small, pursed mouth. This suggests that the early universe was much
2. hotter B) colder Explain using the blowing activity.

When you blow with pursed lips, you cause the air to expand as it leaves your mouth, and it cools considerably as it expands. If expansion causes things to cool, then contraction should cause the universe to become hotter. This can be shown with this PhET simulation. <http://phet.colorado.edu/en/simulation/gas-properties> This is another example of compression concentrating energy.

1. A higher temperature means that particles in the universe are moving faster and colliding more frequently and with more energy. This suggests that the universe used to be more
2. uniform B) uneven

Explain by referring to what happens if you stir a mixture of oil, vinegar and spices or heat ice water.

Stirring vinaigrette simulates the increased movement from heating and the three visible phases become one smooth mixture. Heating a magnet jumbles the domain directions and results in a piece of iron without two clear poles. Heating ice water takes the two phases and turns them into one.

1. What is true about the Big Bang theory?
2. It is a very successful television show
3. It used evidence for an expanding universe to infer that it used to be very small, dense, hot and uniform.
4. It successfully predicted a number of other features including the cosmic microwave background.
5. all of the above

We might as well mention the show and get it over with!

The lesson so far, has had the students use the expanding universe to infer the ideas in answer B.

The reason why this model is called the Big Bang theory instead of model, is because it not only explains what has already been observed but has also predicted new features that have been confirmed. (In science, a theory is not a vague guess or hypothesis it is a model that has been tested repeatedly in a variety of ways and been successful. It uses a few key ideas to explain and predict a lot of observations.) Next we look at the most important confirmed prediction – the cosmic microwave background

1. According to the Big Bang theory, the universe used to be a hot soup of electrons, protons, neutrons and light. Once the universe had ‘cooled’ to 3,000 K, electrons would be able to join with protons to form hydrogen. Now that the electrons are bound up with protons, the light is able to pass by without being scattered off free electrons; the universe became transparent. How can you model this change in a ‘dance’?

This can be done most quickly by telling the students how to move. For example, you could have half of the students be electrons and half protons. (We’ll skip the neutrons for now.) They move rapidly and randomly and gently bounce off each other. As time goes by, they slow down and the electrons and protons start to stick briefly to each other when they collide. Finally, at some point they will be going slowly enough that further collisions do not break up the pairs. This process is repeated with a few students acting as light particles. When they come near an electron, the electron they have to stop and shake hands for a while before being sent off in new direction. However, if the electron is bound to a proton, they are ignored and can travel unimpeded.

If you have more time, the students can figure out for themselves how they can act out this process. They will learn more this way.

The dance could also be extended to show how deuterium and helium was formed in the Big Bang. If a neutron bumps into a hydrogen atom it will form deuterium. If two deuterium atoms collide, they will form helium. The formation of lithium (3 protons and 4 neutrons) and all the other elements requires the higher pressure and temperatures of the core of a star.

1. The light that was around when electrons and protons combined has been travelling for a long time and during this trip the light will have become
2. redder B) bluer C) stretched D) squished

Explain: As the light travelled, the space it was travelling through expanded and stretched the wave.

This is easiest to model with a plastic Slinky. The coils even look like waves when viewed from the side. Another way to show this is with a balloon or tensor bandage with a wave drawn on it. These models have the advantage that the wave is separate from the medium that is stretching. The models also show the energy becoming less concentrated in a variety of ways.

Some students may choose ‘redder’ because they have already heard this called a red-shift. An EM spectrum chart can be used to show how the red-shift refers to a direction, not the final colour.

1. The original wavelength of the light was 1 m or one millionth of a metre. The universe has expanded 1,000 times in all directions and so the light should now be
2. visible light: 1 m B) microwaves: 1 mm C) microwaves: 1 cm D) radiowaves: 1 m

Draw waves with this wavelength – actual size.

It should be 1000 x 1/1,000,000 or 1/1000 of a metre or 1 mm. This is almost impossible to draw. This is a small microwave wavelength. They are almost infrared.

1. Microwaves are invisible to our eyes but they can be detected.
2. How far apart are the hot spots in a microwave oven?

You can measure the wavelength of a microwave oven by melting marshmallows or chocolate chips etc. (You will need to disable the turntable by removing it and putting something over the axle.) If you put these on top of graham crackers, it will be easier and less messy to hand them to your students who can then eat the results. The marshmallow results aren’t as clear because they expand. However, combined with chocolate chips they make s‘mores! I recommend chocolate chips on top of the crackers and then separately marshmallows on top of crackers. This lets you see the chocolate chip results best.

The spaces between hot spots will be around 4 +/- 1cm. These microwaves are much bigger than the 1 mm microwaves for the early universe.

1. The wavelength can be calculated by dividing the speed of the waves - 3.00 x 108 m/s - by the frequency given for the microwave oven - 3450 x 106 Hz.

Wavelength = 3.00 x 108 m/s /3450 x 106 Hz = 8.70 cm.

1. How does the calculated wavelength value compare to the separation of hot spots? Explain.

It is double the spacing found for the hot spots. The microwaves form standing waves and the distance between hot spots is a half-wavelength. This can be modeled with a Slinky forming standing waves.

c) Draw waves with this wavelength – actual size.

.You can just get one wavelength across the width of the page.

d) What other household items can detect the radiation?

About 1% of the static on an analogue TV or FM radio is from the early universe. These devices are designed to pick up much longer wavelengths, but are also able to pick up the 1 mm radiation.

1. Physicists predicted that 1-mm microwaves should be hitting the Earth from all directions. These waves were detected by accident. Who should get the Nobel Prize for this discovery - the theorists or the experimentalists? Why? Wilson and Penzias got the prize. They were the experimentalists. Dicke and his team had made the most recent detailed predictions and were about to build a detector. They got nothing! There were other theorists who made predictions much earlier and even other experimentalists who detected the CMB earlier but didn’t realize what it was. The CMB was an important discovery, but you could argue that they gave it to the wrong people.

The Big Bang predicted that the early universe should be very smooth. The CMB is a picture of the early universe and it is incredibly smooth. However, there had to be some unevenness to produce the galaxies and clusters of galaxies that exist. Satellite observations have increased the resolution and contrast of the CMB – especially in the last 20 years.

1. The temperature of the CMB is 2.7254**8** +/- 0.0000**2** K. How does this compare to the roughness of the Earth which has mountains and valleys that vary its radius by +/- 0.1%? The CMB temperature variation is \_\_\_\_\_\_ times smaller than the Earth’s roughness.
2. 10 B) 100 C) 1,000 D) 10, 000

The variation is +/- 0.001% or 100 times smaller than the Earth’s roughness. When we look at a picture of the whole earth we can’t see this variation. It will be 100 times harder to see the variation of the CMB.

To make this tiny variation visible, only the differences from the average are shown.

1. The top map shows the microwave data +/- 0.0035 K. It looks like a yin yang symbol in red and blue. The left half is blue and therefore
2. hotter B) colder C) moving toward us D) moving away   
   Explain:

First we observe the shift in the frequency of the light and then we need to infer what it means. There is no reason why the left half of the universe should be hotter than the other. This means it is a Doppler shift we are moving relative to the CMB. It could be that the CMB is moving relative to us but the simplest explanation is that we are moving toward the left and away from the right at 371 km/s.

Note: This does not mean that we have a stationary frame. This is just our movement relative to the average CMB. This is similar to how the frame of the ‘fixed stars’ is sometimes used as a reference.

1. When the Doppler Effect due to our movement through space is removed and the sensitivity is increased to +/- 0.00002 K, we see a red band stretching across the centre. This band is due to the radiation from the
2. Earth B) Solar System C) Milky Way D) Local Cluster  
   Explain: Only the Solar System and the Milky Way are flat discs that will look like a line in cross-section. The Solar System has only a few planets that would be radiating – whereas the Milky Way has billions of stars. The third image has the Milky Way’s contribution removed to show what the CMB looks like.

Watch **Minute Physics: Picture of the Big Bang**

<http://www.youtube.com/watch?v=_mZQ-5-KYHw> (Part 1: 0:00 – 2:02, Part 2: 2:02 – 3:06)

This video goes really, really fast. You could show it at the start as an introduction – but I think it is better to show it afterwards as a review. It is short enough that you could show it both times. The first 2 minutes review what has already been discussed and the next 2 minutes are a preview of what is coming up.

**Part 2: What did the Big Bang sound like?**

The CMB is coloured to show the tiny variations in temperature. The red regions warmer and they will also be denser. Sound waves are variations in density, so this is a picture of the sound the universe was making almost 14 billion years ago.

1. The frequency of the sound has been multiplied by 1026 so we can hear it. It has also been modified to show how the sound evolved over the first 760,000 years. <http://faculty.washington.edu/jcramer/BigBang/Planck_2013/BBSnd100.wav> c) John G. Cramer - 2013
2. What happens to the pitch and volume at the start? Why? The frequency drops as the universe expands. The universe did not all become transparent at once, so the volume builds from an initially quiet sound.
3. What will happen to the pitch and volume as the universe continues to expand?
4. both will increase B) both will decrease

C) pitch will increase, volume decrease D) pitch will decrease, volume increase

Explain:

The pitch will continue to decrease as the wavelengths get stretched more and more. Eventually the volume will also decrease as the energy is spread over a larger and larger space. For more details; <http://faculty.washington.edu/jcramer/BBSound_2013.html>

The universe is not vibrating as a whole. It is many of many little drums. <http://www.youtube.com/watch?v=v4ELxKKT5Rw> video of a resonating rubber circle

<http://www.physics.miami.edu/~nearing/mathmethods/drumhead-animations.html> animations

A drum head is a simplified model of the vibrating universe. However, it is not a good match in two respects. The drum head is flat – but should be spherical. It has transverse vibrations, but the CMB is a result of sound which is made of longitudinal vibrations. The video and animations show vibrations of individual harmonics but these are combined in the CMB.

1. You can calculate the size of the largest ‘drum’. The sound waves were travelling at 2/3 of the speed of light for the 400,000 years since the Big Bang.
2. How far (in light years) could they have travelled? The universe has expanded by 1.000 since then, How big should the ‘drums’ be now?
3. 300 B) 300, 000 C) 3,000, 000

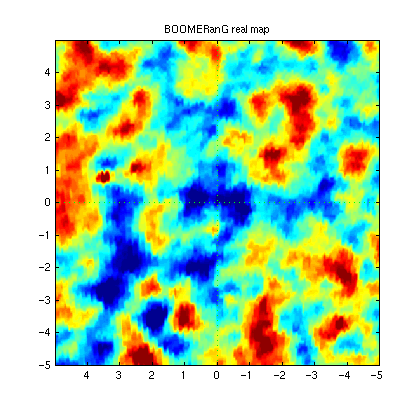
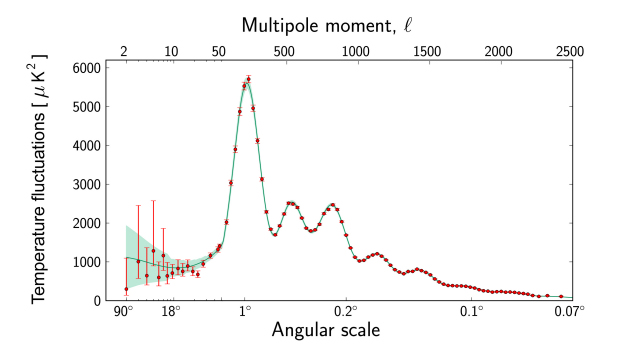
The mathematics to determine the size of the fundamental vibration involves a cosmic-sized triangle. The base is the farthest distance that the sound waves could travel during the first 400,000 years between the Big Bang and when the CMB was formed. This object will have been enlarged 1,000 times since that time to become 300,000,000 light-years across.

1. The light has been travelling for 14 billion years. This forms the altitude of a long, narrow triangle. (The answer from the previous part is the base of the triangle.) What angle should it make when it reaches us?

The height is determined by the time the CMB took to get to us which is 1.4 x 1010 light-years. The angle is very small so that sin () ~ tan () = (3 x 108)/ (1.4 x 1010) = 2 x 10-2,  = 1o. These should be 1/360th of the map. They are the speckles that stand out most.

1. The 1o spots are the fundamental vibration. Are there other harmonics? If the universe was vibrating like a long spring, what size would the second and third harmonics have?
2. 1/2 o , 1/3 o B) 2 o, 3 o C) 1/2 o , 1/4 o D) 2 o, 4 o

The size of the next two harmonics would be smaller and with a size of 0.5 o and 0.3 o. These are too hard to be seen on the full map, but can be seen on the close-up.

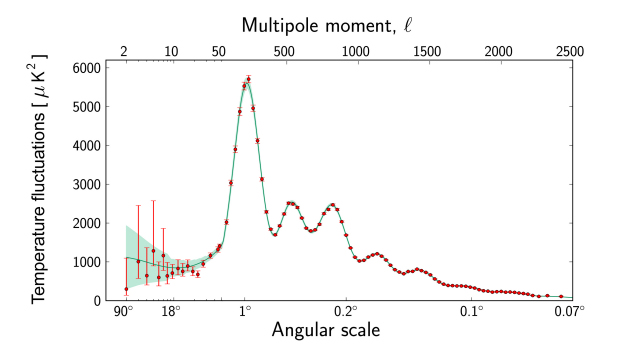


1. The map of the CMB has been analysed to find the harmonics and their strengths. How many harmonics did they find?
2. 2 B) 3 C) 4 D) 5

The fundamental is the first harmonic and there are four other clear harmonics.

1. Build a similar wave using the PhET Fourier simulation. How big should the second harmonic be compared to the first?
2. 5800/2500 B) (5800/2500)2 C) (5800/2500)1/2

Have the sound switched on so you can hear how the sound changes with the addition of harmonics. The fundamental should be largest – make it have amplitude of one unit. The next two should have an amplitude of the square root of (2500/5800) = 0.66 because the power spectrum’s vertical axis is proportional to amplitude squared. The next two should have amplitudes of 0.41 and 0.37. The spectrum and PhET simulation look as follows;



It is easier to see how a complex tone can be built up by adding together simple waves than it is to dissect a complex wave into its components. (This is what Fourier analysis is used for.) This simulation has a great Wave Game that lets students practice these skills.

The waves are a result of gravity pulling matter closer and radiation pressure pushing it apart. The size of the first harmonic can be used to measure the total amount of mass and energy in the universe. This amount is way bigger than all of the stuff we are familiar with – protons, electrons, photons etc. We don’t know what the other 95% of the universe is made of but we know that it comes in two types - dark matter and dark energy.

1. The size of the harmonics indicates how much of the universe is made of each part. Dark matter responds to gravity but not to the radiation pressure. Compare standing waves formed by a long spring on the ground vs. one in the air. How does gravity change the wave?

Without gravity, the crests and troughs are the same. With gravity, the troughs are bigger than the crests. With gravity, the period of the of the harmonics increase Similar changes occur when the amount of atomic matter and dark matter are changed.

1. How does each type of matter affect the graphs?

<http://background.uchicago.edu/~whu/intermediate/baryons3.html> <http://background.uchicago.edu/~whu/intermediate/driving2.html>   
The more matter of either kind, the more the odd numbered peaks are enhanced. This is analogous to the larger troughs. The pattern shifts slightly right with atomic matter and slightly left with dark matter which is like the increased period with mass. The first peak increases with baryonic matter and decreases with dark matter. This has to do with how the dark matter doesn’t interact with the radiation in the hot primordial soup, but atomic matter does.

1. The universe `rings` differently if you change the amounts of atoms, dark matter and energy. Go to the **WMAP** **Build a Universe Game** <http://wmap.gsfc.nasa.gov/resources/camb_tool/index.html> Choose “Make full screen in new window”.
2. Move the sliders for atoms, cold dark matter and dark energy to get a good match. What proportions did you need? Hint: The amount of dark energy is greater than dark matter which is greater than atoms and the universe is flat. 4%, 22%, 74 %. This is based on WMAP, the previous survey. These numbers have been altered slightly by the Planck data.
3. Is the age of the universe correct? How can you fix that? 13.7 billion years

For more detail go to <http://wmap.gsfc.nasa.gov/mission/sgoals_parameters_geom.html>   
Planck gives 13.82 billion years. The adjustments are largely due to the improvements at measuring the vibrations at small angles because of better resolution.

1. The earlier surveys were not able to detect any peaks after the first three. The Planck satellite had greater resolution and clearly shows a fourth and fifth peak. These provide the seeds for the formation of galaxies and clusters of galaxies. <http://cosmicweb.uchicago.edu/filaments.htm> Why does the universe become less smooth?

Gravity pulls matter together and radiation pushes it apart. Gravity can overpower the radiation pressure if there are spots with a high enough density. This depends on the density at the start and the variation in density. In this simulation we see how the densest regions become even denser and eventually form galaxies in clumps and filaments.

1. Gravity pulls matter closer and radiation pushes it apart. Stars and galaxies can’t form unless gravity wins. Gravity will only win over radiation if the original density in a given spot is high enough. This will only occur if the average density (Omega\_m, vertical) is high enough and/or if the variation in density (sigma\_8) is great enough. These initial conditions affect what the universe will become. <http://www.learner.org/courses/physics/interactive/lab_interactives/cosmic.html>
2. Set the initial conditions for completely uniform (far left) and the highest desnity (very bottom) value. **Predict** what the universe will look like. **Observe** what the universe looks like and how this appears on the graph.

The universe stays smooth and is all at a high density – a sharp peak to the far right.

1. Keep the conditions completely uniform but give it the minimum density (very top).   
   **Predict** what the universe and graph will look like. **Observe** what the universe graph look like.

The graph will still be a sharp peak, but shifted to the left. The image will be uniform but much darker.

1. Set the conditions for maximum variation (far right). **Predict** what you will see with minimum density.

There was enough variaton to form galaxies – but the gaps between the galaxy filaments are much bigger. There is much more empty universe.

1. Set the conditions for maximum variation (far right). **Predict** what you will see with maximum density.  
   It looks very similar to our present galaxy – both in the image and the graph. This suggests that the best values must be close to these.
2. What combination best matches our universe? 0.25 (two away from maximum density), 0.8 (one away from maximum variation)
3. The data from the Planck satellite has provided firm support for the Big Bang, dark matter and dark energy. What problems has it exposed?

The map shows that on the large scale the universe is not the same in all directions. The bottom right quarter is extra hot with a very cold spot. This shows up in the power spectrum where the error bars barely fit the spread of the different big bang models and in one case – it doesn’t fit at all.

For more information about the details of the CMB try;

1. **Parameters of Cosmology** [http://**wmap**.gsfc.nasa.gov/mission/sgoals\_parameters.html](http://wmap.gsfc.nasa.gov/mission/sgoals_parameters.html) You will find lots more for teachers and students at WMAP’s site
2. Wayne Hu **Ringing in the New Cosmology** 2001  
   <http://background.uchicago.edu/~whu/intermediate/intermediate.html>

This is a very detailed explanation of the power spectrum with lots of analogies and animations. At the time of writing he was describing predictions. These have since been confirmed by WMAP and Planck. Also try his Scientific American article **Cosmic Symphony** 2004 <http://background.uchicago.edu/~whu/SciAm/sym1.html>

1. **Physics for the 21st C: Unit 11: Dark Energy** 2010 (30 minute video) The first half looks at the supernova evidence that the expansion of the universe is increasing. The second half (15:00- 27:00) looks at CMB evidence for dark energy. While you are there, check out the rest of the course on modern physics designed for high school teachers. [http://www.learner.org/courses/**physics**/unit/unit\_vid.html?unit=11](http://www.learner.org/courses/physics/unit/unit_vid.html?unit=11)
2. **Planck’s View of the Universe** 2013 (3:22 minute video)

[http://spaceinvideos.**esa**.int/Videos/2013/10/Planck\_s\_view\_of\_the\_Universe](http://spaceinvideos.esa.int/Videos/2013/10/Planck_s_view_of_the_Universe) You will find lots more for teachers and students at this site of the European Space Agency.