TEACHER NOTES – ASTRONOMY IN THE NEWS #25

RECORD GRAVITATIONAL WAVE DETECTIONS

Slide 2 – Background Science: Gravitational Waves

We all appreciate what electromagnetic radiation is as it makes up all the radiation that we interact with. However, gravitational radiation and gravitational waves are not something we feel the impact of.

Gravitational waves are a form of radiant energy, like electromagnetic radiation, but it is gravitational radiation that is transported, but still at the speed of light. They were predicted by Einstein in his theory of General Relativity and were first discovered in 2015.

Spacetime is a mathematical model which describes the four-dimensions of space and time (x, y, z, t). A body in spacetime produces a well, or curvature, in the spacetime. The more massive an object is, the greater the curvature is. Once a body is accelerated, it causes waves in the spacetime, these are the gravitational waves.

To describe the detection, the distance between two objects increases and decreases as the gravitational wave passes over that patch of spacetime at the frequency of the wave. The amplitude of these increases is inversely proportional to the square of the distance, and as such, the amplitudes of these strains is less than 1 part per 10^{20}. As an example, the first detection of gravitational waves changed the size of the 4km-long detector by less than a quarter of the width of a proton.

Sources of gravitational waves are any systems that cause gravitational acceleration, such as two non-identical bodies orbiting each other (such as a neutron star and black hole), supernovae, or collisions between large bodies such as black holes and neutron stars. The observable frequencies of gravitational waves correspond to rotating neutron stars, collisions between black holes and/or neutron stars, and supernovae. Gravitational waves are postulated to exist at all frequencies, as with electromagnetic radiation. There may be longer wavelength, lower frequency gravitational waves (which are undetectable) associated with the cosmic microwave background. The advantage to gravitational wave astronomy is that they can detect objects and interactions (such as black hole collisions and prior to the CMB) that are undetectable with electromagnetic telescopes.

The gravitational wave detectors, LIGO (USA) and VIRGO (Italy), use the same technique to detect the presence of gravitational waves. They are interferometers, and are looking for very small deviations in wave patterns. A laser beam is split by a mirror, and sent down two identical tubes (4km in LIGO, 3km in VIRGO). At the end of these tubes is a mirror which returns the laser beam to a detector. If there is no gravitational wave, the two beams arrive aligned, and the two waves cancel each other out. However, if a gravitational wave passes over the interferometer, one tube will be lengthened, whilst one is shortened. This causes the two waves to arrive at different times, and the resulting pattern can be compared to models to determine the nature of the source of the gravitational wave.

IMAGES:

1. (Top left) Cartoon image of two neutron stars orbiting each other. This demonstrates the waves on the spacetime, which is depicted by the "grid" on which they are drawn.
2. (Top right) A depiction of spacetime and how objects with different masses cause different curvatures in spacetime. The more massive the object, in this case the yellow sphere is the most massive, the greater the curvature caused.
3. (Bottom) This image is in two parts and demonstrates how the wave patterns of the laser combine with no detection and with the detection of a gravitational wave. On the left is how the LIGO and VIRGO detectors operate without the distortion, whilst the distortion causes the interference pattern on the right-hand side.

Slide 3: GW Sources

The number of gravitational wave detections has increased rapidly since the first two observing runs. The first two runs totalled 11 detections, however now the number stands at 90. Of the 90 total detections, 82 are black hole-black hole mergers, whilst 4 are black hole-neutron star mergers, 2 are two neutron stars, and the final 2 are undetermined. Of the 35 highlighted in the article below, 32 are black hole mergers, whilst 2 are probably neutron star mergers, whilst the final one is undetermined. The undetermined merger is most likely a black hole-neutron star as the secondary mass is too low to be a black hole (but at the same time, too high to be a neutron star).

The most likely formation method which is either in a binary system or a young stellar cluster. Two massive stars form in a binary system, or close-by in a young stellar cluster. The more massive star of the system goes supernova, and leaves a black hole behind. The second star then continues with its evolution, and becomes a red supergiant. As it expands, it encompasses the black hole in its envelope. The star then produces a supernovae, and either leaves a neutron star or black hole behind. The two compact objects begin to spin faster and merge, producing gravitational waves. This leaves a larger black hole which has consumed the other object.

The article that this resource is built off can be found here:

Record number of new gravitational wave offers game-changing window into Universe

There is no research paper attached to this release, but please go to the LIGO and VIRGO websites as there are press releases corresponding to these detections:

https://www.ligo.caltech.edu/

https://www.virgo-gw.eu/

IMAGES:

1. An infographic of the detections from the LIGO, VIRGO and KAGRA detections. The three semesters of observations are shown in different colours. The turquoise shows run 1, light blue is run 2, whilst the remaining observations are from runs 3a and 3b. The key in the bottom left explains what each observation is. A black circle represents a black hole, whilst a blue circle is a neutron star and a mixed circle is an uncertain object. The mass, in solar units, is shown below them. The combined mass of the final object is shown as the larger circle, which is always a black hole.

Slide 4 – Activity: How “significant” are detections?

In the slide, I give the students the numbers quoted above, where the strains from the gravitational wave produce changes in 1 part per 10^{-20}. I also give the students the length of a LIGO arm, at 4km. I ask them how much would of an observed change would this be, and what does this size compare to.

The answers to this are 4×10^{-17} m. The size of a proton is approximately 10^{-16} m, whereas the upper limit for the size of an electron is 10^{-18} m.

GCSE Specifications:

Specification	Knowledge Point
Pearson Edexcel Astronomy	14.10, 14.11
Pearson Edexcel Physics	4.1, 4.3, 5.7, 5.11, 7.19
Pearson Edexcel Combined Sciences	4.1, 4.3, 5.7, 5.11
OCR Physics B	1.1.3, 1.3.5, 4.1.2
OCR Combined Science B	1.1.3, 1.3.5
AQA Physics	4.6.1.2, 4.6.2.1, 4.8.1.2
AQA Combined Trilogy	6.6.1.2, 6.6.2.1

A-Level Physics Specifications:

Specification	Knowledge Point
Pearson Edexcel Physics	59, 65, 174
OCR Physics A	4.4.1 (b), 4.4.2 (a), 4.4.3 (d), 5.5.1 (e,f)
OCR Physics B	4.1 (b)
AQA Physics	3.3.1.1, 3.3.2.1, 3.9.2.6