TEACHER NOTES – ASTRONOMY IN THE NEWS #07
GRAVITATIONAL WAVES FROM NEUTRON STARS-BLACK HOLE MERGERS

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: Neutron Star – Black Hole Mergers

As described above, the detection of gravitational waves is very difficult due to the sensitivity required, making detections very rare. Since LIGO was updated and went online as Advanced LIGO in 2015, only 10 detections of events have been made. These detections were predominantly black hole mergers, with one merger of neutron stars.

However, two detections in January 2020 were made of neutron star – black hole mergers. They are predicted to be this type of merger due to the masses of the two bodies involved. In each event, the mass of the primary body was within the permittable mass range for black holes but too high for neutron stars. The secondary body in each case was within the mass range permitted for neutron stars. The masses of the bodies are found in the table below, with all units solar masses:

Event	Primary Mass	Secondary Mass	Distance
GW200105	8.9 (Errors: +1.2, -1.5)	1.9 (Errors: +0.3, -0.2)	280 Mpc
GW200115	5.7 (Errors: +1.8, -2.1)	1.5 (Errors: +0.7, -0.3)	310 Mpc

Using these masses and these events, an incidence rate can be predicted which is 45 per Gpc^{-3} per year. By assuming other potential low-significance detections at gravitational wave detectors, a rate of 130 per Gpc^{-3} per year was calculated. The black hole and neutron star merger is the most likely scenario. There is no direct electromagnetic counterpart observed, which is not unexpected, however, could still be a black hole – black hole merger.

These observed rates are consistent with the modelled rate of 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, but this time leaves a neutron star behind due to its lower mass. The neutron star and black hole begin to spin faster and merge, producing gravitational waves. This leaves the black hole which has consumed the neutron star. This scenario has an incidence rate of 0.1-100 per Gpc^{-3} per year. Less likely scenarios for formation are collisions in globular clusters or open clusters.

The articles that this resource are built off can be found here:

https://www.bbc.co.uk/news/science-environment-57639520

https://www.theguardian.com/science/2021/jun/29/gravitational-waves-from-star-eating-black-holes-detected-on-earth

The research article can be found here. I am not sure how long this will remain free:

https://iopscience.iop.org/article/10.3847/2041-8213/ac082e/pdf

However, a permanent version from a pre-print server can be found here:

https://arxiv.org/abs/2106.15163

IMAGES:

1. (Top left) Cartoon demonstrating the different life cycles of stars depending on their initial mass. The top row is for stars less massive than 8 solar masses, whilst the bottom row is for stars with an initial mass of 8 solar masses or greater. A further differentiation is made with the most massive stars at 40 solar masses, where below that the supernova leaves a neutron star, whilst greater than that, a black hole remains. This demonstrates how two binary stars could form these two dense objects.
2. (Bottom left) Models that predict the incidence rate of neutron star – black hole mergers. The x-axis is the predicted rate, whilst the y-axis is the probability. The green line is the rate inferred from the two observed events, whilst the black line is the inferred rate from all low-significance triggers of the LIGO and VIRGO detectors.
3. (Right) Depiction of the evolution of a binary system that produces a black hole and a neutron star.

Slide 4 – Activity: Modelling Gravitational Waves

The activity this week is an experiment to try to demonstrate how gravitational waves are detected, and formed in the first place. I appreciate that they are quite difficult to visualise so a physical exercise may help the students understand.

The equipment needed is listed on both the slide and the website below, where you will also find the instructions for the experiment.

https://www.jpl.nasa.gov/edu/teach/activity/dropping-in-with-gravitational-waves/

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	2, 59, 65, 174
OCR Physics A	1.1.2 (a), 1.2.1, 4.4.1 (b), 4.4.2 (a), 4.4.3 (d), 5.5.1 (e,f)
OCR Physics B	1.1.2 (a), 1.2.1, 4.1 (b)
AQA Physics	3.3.1.1, 3.3.2.1, 3.9.2.6