TEACHER NOTES – ASTRONOMY IN THE NEWS #53
GRAVITATIONAL WAVES FROM SMBH MERGERS

Slide 2 – Background Science: Gravitational Waves and Pulsars

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.

Pulsars are the remnants of massive stars. Once massive stars end their lives via a supernova, stars with a progenitor mass between 8 and 20 solar masses leave behind a neutron star. It is this neutron star that causes a pulsar. The neutron star has the same angular momentum as the star but is now much smaller. As a result, it rotates at a rate between milliseconds and seconds. On Earth, we detect this as a beam of radiation, at radio waves as a very frequent pulse. In fact, they are so frequent they are more accurate timekeepers than an atomic clock. This radiation is caused by the rotation of a very strong magnetic field, and as a result, produces an electric field. This electric field strips protons and electrons from the surface of the neutron star, producing an electromagnetic beam from each pole.

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) A cartoon gif of the lighthouse effect that is observed on Earth from a pulsar as it rotates.

Slide 3: Gravitational Hum

As with electromagnetic radiation (EM), gravitational waves were postulated to exist at all wavelengths and frequencies. To detect longer-wavelength, lower-frequency gravitational waves (GW) directly would require larger and larger telescopes, as with electromagnetic radiation. With EM radiation, world-class optical telescopes have operated at the 2-10 m size range, whilst for longer-wavelength radio waves, 35-100 m telescopes are required. However, the size range required is ramped up for gravitational waves. As mentioned above, to detect the short-wavelength GWs, a 4km long detector is required for a deviation that is a quarter of the size of a proton. Therefore, it is not feasible to directly detect these long-wavelength GWs.

This is where the result from these articles comes in, the indirect detection of large-scale gravitational waves. This result was confirmed by multiple teams, but is not confirmed at a significance level that previous, direct gravitational wave detections were. Teams have observed a large sample of pulsars over a period of 12-15 years, and by timing these pulsars and tracking miniscule differences in the timing, a large-scale gravitational wave is detected. The timing of pulsars, which as mentioned above, is more accurate than some atomic clocks, should have an exact period, so any deviation from this timing is significant. The difference in timing is not due to a physical change in the period, it is caused by the distance that the emission needs to travel changing due to a stretching or compressing of spacetime. The cause of this is thought to be the imprint that 8 billion years of galaxy mergers have caused, or more specifically, the merger of the supermassive black holes that are at the centres of all galaxies. The cause is less certain though, and this is just the most likely cause. It is also possible that the gravitational imprint of the Big Bang is the cause. Both mechanisms would provide a similar level of gravitational wave. This wave, travelling at the speed of light, would take 30 years to pass through Earth. Using standard formulae, gives a wavelength of 2.83×10^{17} m! This is the equivalent to 10 parsecs.

The articles that this resource is built on can be found here:

https://www.bbc.co.uk/news/science-environment-66039810

https://www.theguardian.com/science/2023/jun/29/astronomers-detect-cosmic-bass-note-gravitational-waves

There are also a large number of associated research articles with this result. The free, permanent versions of these papers can be searched by using the article identifiers 2306.16213-2306.16230, inclusive:

https://arxiv.org/archive/astro-ph

IMAGES:

1. (Left) Cartoon of the schematic of the discovery method of these gravitational waves. The pulsar gives off emission, but the emission timing changes slightly due to the existence of a low-frequency gravitational wave.
2. (Right) Image of two colliding galaxies, in this case the Antennae galaxies, an example of the mergers that are thought to have caused these gravitational waves.

Slide 4 – Activity: Dame Jocelyn Bell Burnell

This week's activity is to research the life and career of Dame Jocelyn Bell Burnell, the discoverer of pulsars who was snubbed for the Nobel Prize celebrating said discoverer. Dame Bell Burnell is an example of a remarkable woman in STEM and is worthy of further celebration and recognition within the field.

GCSE Specifications:

Specification	Knowledge Point
Pearson Edexcel Astronomy	13.27