TEACHER NOTES – ASTRONOMY IN THE NEWS #33

NATURE OF BLACK HOLES

Slide 2 – Background Science: Black Holes and the Fundamental Interactions

Black holes are at the frontier of our knowledge of physics, especially the physics inside of a black hole. They form via the explosion of very massive stars (greater than 40 solar masses) via supernova, which leaves behind a black hole. Supermassive black holes are also found in the centre of galaxies, but the formation mechanism of those is unclear, although mergers or the destruction of supermassive stars (in the early Universe) are possible explanations.

Any theory must explain both quantum mechanics (the physics that describes atomic and subatomic interactions) as well as general relativity, which explains gravity and spacetime. Currently, both of these theories break down. To combine these theories, physicists need to look back to the Big Bang, where it is thought all forces and interactions were combined into one.

There are four fundamental interactions in nature: gravity, electromagnetic force, strong and weak forces. Gravity is the force of attraction we see both on Earth and in the motions of astronomical systems. The electromagnetic force which concerns the electric and magnetic fields. The two subatomic forces, strong and weak are responsible for constraining the nucleus and radioactivity, respectively. It is thought that these forces were combined at the Big Bang, and as the Universe cooled, they separated. Gravity was the first to separate, with the strong force following, with finally a split of the electroweak force into electromagnetism and the weak force.

Producing a theory for combining these forces into a theory of everything is a very active area of research, and essentially requires finding a way to explain gravity as the other three forces. The electromagnetic and weak force were combined as the electroweak force, whilst the Grand Unification Theory combines the strong force with the electroweak force. However, combining gravity is more difficult. The basic explanation of a force is that two particles (called fermions) interact, they exchange force carrying particles (bosons) and then the two fermions move away. The bosons for the electromagnetic, strong and weak forces (photons, gluons, W and Z bosons, respectively) have all been observed experimentally. However, the gravity boson, named a graviton, is currently only a theoretical particle (and is likely to remain that way due to the extremely low probability of detecting one).

IMAGES:

1. (Left) A flow chart of the four fundamental interactions and their separation as the Universe cooled. The forces began unified, with the first departure gravity at 10^{32} K, with the strong force splitting away at 10^{27} K, and the electromagnetic and weak forces splitting at 10^{15} K.

2. (Top right) The first direct imaging of a black hole from the Event Horizon Telescope, a collection of radio telescopes across the globe. This shows the accretion disk on which matter accretes onto the black hole. This image is at a wavelength of 1.3mm and shows the polarisation around the supermassive black hole in the centre of the galaxy, M87. This polarisation is linked to the magnetic fields that surround the black hole.
3. (Bottom right) 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 30-40 solar masses, where below that the supernova leaves a neutron star, whilst greater than that, a black hole remains.

Slide 3: Hairy Black Holes?

Stephen Hawking first introduced the idea that quantum gravity and quantum mechanics are not compatible at the edge of a black hole. The theory of general relativity states that once material enters a black hole, then no information about this material can escape. This is the “basic” understanding of a black hole, that nothing can escape, not even light (thus information). However, this is forbidden under quantum mechanics.

However, the authors of this new paper have developed a new mathematical solution to this problem. By assuming quantum gravity, and the existence of the graviton, a new effect is calculated. They assume that two black holes of the same size, can have different gravitational fields. These different gravitational fields are caused by the accreting material leaving an imprint in the spacetime surrounding the black hole, or to be more precise, the behaviour of the gravitons to be dependent on the internal structure of the black hole. These imprints are nicknamed “quantum hairs” since they leave hair-like strands in the quantum gravity space and it was always thought that black holes were defined only by their mass and spin (hence bald).

The importance of this theory is that it describes black holes, as well as not requiring the rewriting of quantum mechanics (as other explanations do, such as string theory), as well as potentially giving the first step towards unifying gravity with the other three forces.

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

https://www.bbc.co.uk/news/science-environment-60708711

https://www.theguardian.com/science/2022/mar/17/quantum-hair-could-resolve-stephen-hawking-black-hole-paradox-say-scientists

A free, permanent version of the research article can be found here:

https://arxiv.org/abs/2112.05171

I do have a warning though, that this is a very mathematical paper, not something I’ll be checking line for line!

IMAGES:

1. An artist's impression of material accreting onto a black hole. The pathways that the material takes could be akin to the "quantum hairs" that are left behind during this process.

Slide 4 – Activity: Is an untestable theory science?

This week's activity is a philosophical discussion about what science is. We are taught that a theory is something that can be tested experimentally with repeated observations. However, many theories, especially surrounding some areas of particle physics are untestable. For example, gravitons will not be directly detected since the cross-section of interaction is extremely low. To highlight this, a detector the size of Jupiter with 100% efficiency in orbit around a neutron star would only detect one graviton every ten years. Another untestable theory, currently, is that of string theory. Therefore, are these theories science or are they just philosophy?

GCSE Specifications:

Specification	Knowledge Point
Pearson Edexcel Astronomy	13.8, 14.10, 14.11

A-Level Physics Specifications:

Specification	Knowledge Point
Pearson Edexcel Physics	138, 140, 179
OCR Physics A	4.5.1(b), 5.5.1(e)
AQA Physics	3.2.1.4, 3.9.2.6