newsletter

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An Introduction to Black Holes

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A black hole is region of space where the gravitational pull is so strong that light is unable to escape. Since no light can escape, we are not able to observe black holes directly.

Figure 1: John Wheeler (1911–2008), Wikipedia Commons

The physicist, John Wheeler (Fig. 1) is often credited with being the first to coin the term 'black hole' in 1969, however the concept dates back much further to the Rev. John Michell (Fig. 2) who hypothesised the existence of a 'dark star' in 1783. It took until the 1960s for the idea of black holes to gain any observational support but they are now firmly established in our cosmic inventory.

Figure 2: Rev. John Michell (1724–1793), courtesy of go51johnmitchell.weebly.com/biography.html

From 'Dark Star' to 'Black Hole'

In the late 1700s, natural philosophers were debating whether the nature of light was a particle or a wave. When considering light as a wave it was difficult to envisage how light could feel the force of gravity. However, if light was made up of particles, it was easier to imagine how gravity might effect particles in the same way that gravity dictates the motion of the planets or of a 'Newtonian' apple falling from a tree.

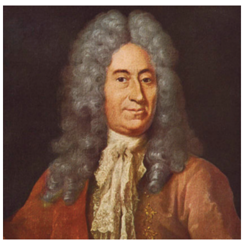

Figure 3: Ole Rømer (1644 – 1710), Wikipedia Commons

The discovery by Ole Roemer (Fig. 3) that light travels at a finite speed lead to the notion that gravity could potentially slow down light. John Michell put forward the idea of the possible existence of stars that had a gravitational pull so great that light itself would be slowed down to the extent that it would not be able even to be emitted. The celebrated mathematician Pierre-Simon Laplace (Fig. 4) independently made the same prediction as Michell around a similar time. Michell further proposed that these 'dark stars' might be numerous across the night sky but, since they emitted no light, their positions would appear to correspond to apparently empty regions of space.

Figure 4: Pierre Simon Laplace, (1749–1827), called the 'French Newton', Wikipedia Commons

Following this initial suggestion of a black hole by Michell and Laplace, the concept was not picked up by scientists at the time. It seemed possible to explain all the properties of light using the wave description and so the particle theory for light fell out of fashion and the idea of 'dark stars' was probably lost as a result. Although it seemed plausible that gravity could impact light, Newtonian physics was not able to explain it.

This required Einstein's (Fig. 5) theory of general relativity, put forward in 1915, which described cosmic bodies living within the fabric of a curved space and time, such that the planets, stars and galaxies tell space and time how to curve, which dictates how objects then move through space.

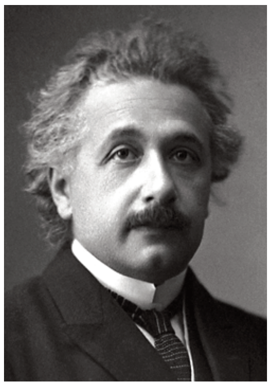

Figure 5: Albert Einstein (1979–1955) portrait after receiving the 1921 Nobel Prize in Physics

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Figure 6: Karl Schwarzschild (1873–1916) Wikipedia Commons

The astronomer Karl Schwarzschild (Fig. 6) used Einstein's equations to show that, if matter was compressed to a point, which is now referred to as a 'singularity', nothing would be able to escape the region of space around it. The extent of this region is known as the 'event horizon' and defines the region of space where it is no longer possible to observe anything that is going on inside this region.

Formation of a Black Hole

A star begins its life as a huge ball of hydrogen gas. As the gravitational pull squeezes the gas closer together it heats up until a nuclear fusion reaction begins in the core causing the star to start shining. This process converts the hydrogen into helium and continues until the hydrogen in the core is almost depleted. The core of the star then begins to contract and heats up further, causing the helium to burn to carbon.

The radiation pressure generated by the nuclear fusion reaction inside the star causes it to expand until it balances the gravitation pull holding the star together. This process of contraction and expansion is repeated while heavier and heavier elements are created in the core of the star. The evolution and eventual fate of the star is determined by how much mass the star contains and, for the most massive stars, this process will continue until the element iron is formed. No heavier elements can be produced beyond iron, as the nuclear burning of iron does not produce enough energy for the process to continue.

Once a star has run out of fuel, it begins to collapse under gravity. From our understanding of sub-atomic physics, we know that particles can be squeezed together only so much. Thus, when a star starts to contract at the end of its life, this contraction will, at some point, stop as the outward pressure from the particles counteracts the inward gravitational pull.

This is how a 'white dwarf star' or a 'neutron star' is formed and is the fate of stars which have a mass of around three times that of our Sun.

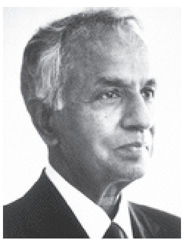

Figure 7: Subrahmanyan Chandrasekhar (1910 –1995), Wikipedia Commons

Subrahmanyan Chandrasekhar (Fig. 7), who went on to win a Nobel Prize for physics, questioned what would happen if a star was more massive than this. What he found was that the pressure from the already compressed particles would not be sufficient to support the star against its own gravity. At the time, this idea seemed completely 'off-the-wall'.

Figure 8: Robert Oppenheimer (1904 –1967), Wikipedia Commons

The American scientist, Robert Oppenheimer (Fig. 8) – famous for leading the Manhattan atomic bomb project in World War II – investigated this further and in 1939 showed that as the gravitational pull of a star increases, the path on which light travels becomes so distorted that nothing can finally escape, not even light. This region of space from which light cannot escape is now known as a black hole.

What happens inside a black hole?

The event horizon, which defines the edge of this region, is the point of no return; any object that is travelling towards this black hole will not be able to escape once it has crossed over into this region. As an object approaches the event horizon, the end of the object which is nearer to the black hole feels a stronger gravitational force than the other end. As a result, the object is pulled apart or 'spaghettified'.

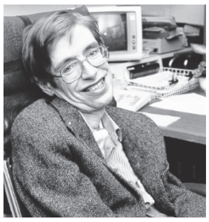

Figure 9: Stephen Hawking (1942 – 2018) Wikipedia Commons

Figure 10: Sir Roger Penrose (born 1931) holding his Nobel Prize, Wikipedia Commons

In the late 1960s, Stephen Hawking (Fig. 9) and Roger Penrose (Fig. 10) showed, from considerations of general relativity, that within the black hole there must be a singularity of infinite density and curvature (of space and time). At this point, the laws of science break down. Observers outside the black hole would, however, be oblivious to this as they would not be able to see beyond the event horizon. This event horizon essentially acts as a cloak of invisibility around the singularity.

Another prediction from general relativity is that, as cosmic bodies move through space and time, they send out ripples or 'gravitational waves' which carry energy away from the object. For example, as planets orbit around the Sun in our solar system, they send out gravitational waves. As a result, their orbits are ever so slightly reduced due to the loss of energy. This effect is so small that fortunately we do not have to worry! However, a gradually reducing orbit has been seen in pairs of stars that are orbiting each other and, as a result, spiral in towards one another.

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Properties of Black Holes

Given that only a stellar mass of a few tens of times that of the sun is required to form a black hole, it was not clear whether other stellar properties made a difference to the black hole that finally resulted.

Figure 11: Werner Israel (1931–2022), courtesy researchgate.com

Werner Israel (Fig. 11) showed that, according to general relativity, for a non-rotating black hole, only the mass of the star that was present beforehand mattered. All non-rotating black holes were shown to be spherical in shape and their size determined by their mass alone, all the other characteristics of the star were lost once it became a black hole.

This result was the solution to Einstein's equations that Karl Schwarzschild had found decades earlier. A star need not be perfectly spherical to form a black hole as the gravitational waves emitted when star collapses would make it spherical in its final black hole state.

Figure 12: Roy Kerr (born 1934), Courtesy ICRA.Net-ISFAHAN Astronomy Meeting

For the case where the initial star is rotating, Roy Kerr (Fig. 12) discovered solutions to Einstein's equations which showed that, for rotating black holes, the final black hole rotates at a constant rate, and that their size and shape is determined by their mass and rate of rotation. Rotation means that the black hole is no longer perfectly spherical and bulges around its equator; the faster a black hole rotates the bigger the bulge becomes.

These two scenarios define the two types of black hole: a 'Schwarzschild black hole' which is non-rotating and a 'Kerr black hole' which rotates.

Low mass black holes

Low mass black holes could intriguingly also exist (because they would be well below the mass limit required for stellar mass black holes to be formed). These would have a mass of as little as that of a planet. This type of black hole could form if matter was compacted to an incredibly high density due to large external pressure. Such high temperatures and high-pressure conditions existed in the very early universe and so these black holes are referred to as 'primordial black holes'. Being able to find these primordial black holes could inform astronomers about conditions just after the Big Bang.

Observing the invisible in binary systems

By the late 1960's, the mathematical description and theoretical prediction for the existence of black holes was well established; however there was no observational data to support this. The question was how could this evidence be collected if black holes do not emit light directly? The key was recognised back in the 1700s, in John Michell's original work, where he noted that a black hole (his 'dark star') would still exert a gravitational force on nearby objects.

Pairs of stars orbiting each other, referred to as 'binary systems', that were locked together by gravity had been regularly observed. Single stars that appeared to be orbiting around some unseen object, had also been observed, hinting at the presence of a black hole (the unseen object). This was not concrete evidence however as the unseen object might not be a black hole, just a very faint star.

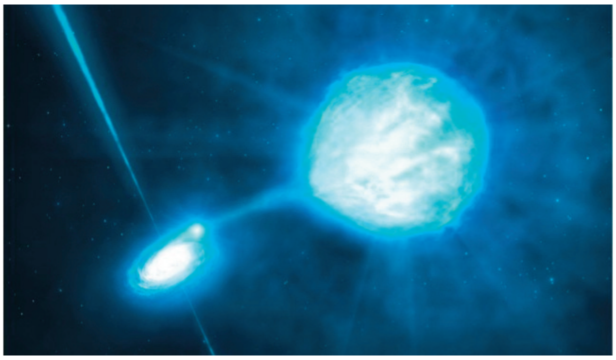

Figure 13:
Artist's impression of a stellar-mass black hole (on the left) accreting material from its companion star as they orbit one another in a binary. Credit: ESO/L. Calçada/M.Kornmesser

In a binary system, if the two objects are close enough to each other, the outer atmosphere of one or both stars can be gravitationally distorted and, in some instances, material can be exchanged from one to another (Fig. 13). Considering the case of a black hole (or other compact object like a neutron star or a white dwarf) in a binary system with a star, gas from the star can fall onto the black hole, releasing gravitational potential energy by emitting X-rays. As the material is transferred from the star, it forms into an accretion disk around the black hole. Friction inside the disc causes it to heat up with the inner region closest to the black hole being heated more than the outer parts. As the material falls towards the black hole and loses gravitational potential energy, part of this energy is released by jets of particles that are directed perpendicular to the accretion disk.

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The galactic X-ray source known as Cygnus X-1, was discovered in 1964 and was the first observation of a black-hole-star binary system. Since X-rays cannot penetrate through the Earth's atmosphere, early observations of X-rays from space were made using sub-orbital rockets. Nowadays, astronomers have many space-based X-ray telescopes. By measuring the orbit of the star, astronomers were able to conclude that the object the star was circling must be a black hole as nothing else would be massive enough. Since the discovery of Cygnus X-1, there have been several other similar systems found within our galaxies providing more support that black holes do exist.

Supermassive Black Holes known as Quasars

Similar observations have been made for the case of supermassive black holes, which are known as 'quasars'. These are extremely luminous objects that were first detected from observations made with radio telescopes. When they were first discovered, there was a great mystery as to what could possibly be producing this emission, since they appeared so bright and yet so far away. It has since been concluded that only a supermassive black hole could be the source of these observations. The mechanism is like the above description of X-ray emission from stellar black holes, with material falling in towards the black hole creating an accretion disc around the black hole.

As the matter spirals in, the black hole rotates in the same direction, which creates a magnetic field, similar in form to the magnetic field around the Earth. As this material gets closer to the black hole, the energy contained within the particles increases and they are then ejected out along the axis of rotation by the magnetic field creating jets of high energy particles. These jets have now been seen for many galaxies.

It is still not clear, however, how 'supermassive black holes', which have a mass of millions to billions of times that of our Sun, are formed. Some have suggested that the collapse of massive clouds of gas during the formation of a galaxy could produce a supermassive black hole or, alternatively, that stellar mass black holes could accrete so much matter that they grow to become supermassive black holes.

A further possibility is that black holes, which are sufficiently close to one another, merge to form a supermassive black hole.

These are still an open questions and an active area of research.

The photographing, for the first time, of a black hole

One of the most exciting developments in recent times was the first ever photograph of a black hole in 2019. The black hole was at the centre of a relatively nearby galaxy called M87 (Fig. 14). It was a historic first for astronomers that was only made possible due to the advanced technology used along with modern computational facilities. It was accomplished by using a network of telescopes which together form the Event Horizon Telescope (EHT).

Figure 14: The first image of a black hole using data collected by the EHT from 2017 to 2019. Credit: EHT Collaboration.

The Supermassive Black Hole at the Centre of our Galaxy

As early as the 1930s however, a source of radio emission was discovered in the constellation of Sagittarius close to where the centre of the Milky Way was believed to be; this radio source became known as Sagittarius A (Fig. 15).

Later observations in the 1980's found that this was a complex radio source consisting of several components including a very compact source that was called Sagittarius A*.

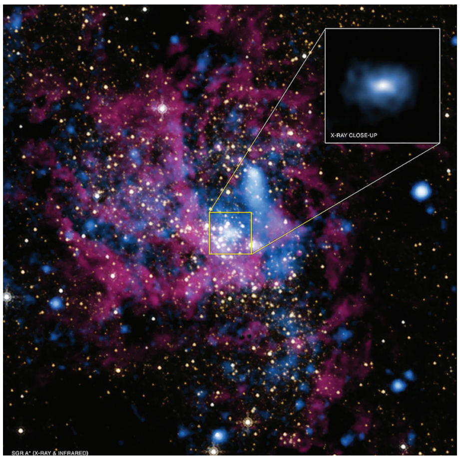

Figure 15: The centre of the milky way. This image is made from observations (in blue) of X-rays using the Chansra t elescope and infrared Data from the Hubble Space Telescope (shown in purple). The inset shows the X-ray emission from SAgittarius A*.

Credit: X-ray: NASA/UMass/D.Wang et al., IR: NASA/STScI.

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Stars and gas close to the centre of galaxies have been observed to have high orbital velocities which can most easily be explained by a massive object at the centre which is creating a strong gravitational field close by. Direct evidence for this being a supermassive black holes was inferred from looking at how material near the centre of galaxy is orbiting.

Figure 16: Andrea Ghez, (born 1965), with her Nobel Prize, Wikipedia Commons

Figure 17: Reindard Genzel (born 1952), Wikipedia Commons

Andrea Ghez (Fig. 16) and Reinhard Genzel (Fig. 17) were awarded the Nobel prize for physics in 2020 for their work on showing that Sagittarius A* is the supermassive black hole at the centre of our own galaxy, the Milky Way.

It is about four million times the mass of the Sun. This black hole has been recently photographed for the first time (Fig. 18).

It is believed that most galaxies have a supermassive black hole at their centre.

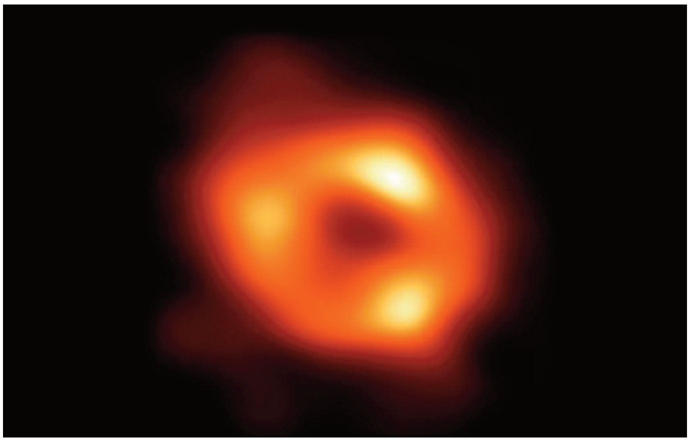

Figure 18: This is Sagittarius A* the Black Hole at the centre of our galaxy. It is second image ever to be taken of a black hole. Credit: EHT Collaboration

Can black holes radiate energy?

In the 1970s Stephen Hawking conjectured that black holes can radiate energy. This concept is now known as 'Hawking radiation'.

The concept behind Hawking radiation is that empty space is not empty of energy after all but contains what is called the 'vacuum energy'. Although, in a vacuum, there may be no particles present, there may still be gravitational and electromagnetic fields with their own energy. From Heisenberg's Uncertainty Principle there are quantum fluctuations in these fields. These fields can generate pairs of 'virtual particles', which appear together before annihilating each other, effectively zipping in and out of existence. These virtual particles cannot be detected with a particle detector in the same way as real particles; however, their existence can only be inferred from indirect effects such as changes in the energy of electron orbits in atoms.

Virtual particles are created in particle/anti-particle pairs, such that one particle has positive energy and the other has negative energy (in relation to the vacuum energy) since energy cannot be created out of from nothing. Normally, these pairs of particles would rapidly annihilate each other. Close to a black hole though, it becomes possible that one of the negative energy particles crosses the event horizon (thus reducing the energy and mass of the black hole) while the remaining positive energy particle might travel away from the black hole and thus be emitted from the black hole. This emission is the Hawking radiation.

However the timescale for a stellar mass black hole to evaporate completely is expected to be much longer than the age of the Universe.

Primordial black holes, on the other hand, have a lot less mass than stellar black holes. As such, they have much smaller evaporation timescales and therefore it is possible that the smallest black holes could have already radiated themselves away through Hawking radiation. The primordial black holes with a slightly larger mass will not have had enough time to evaporate completely and could still be emitting radiation through X-rays and gamma rays. It is possible then to find these black holes from flashes of gamma rays during the final stages of their existence.

The astonishing concept by Hawking is that black holes do not live forever and, while a black hole may have appeared to be the full stop at the end of a star's life, it may continue its own slow evolution and eventual demise.

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When black holes collide

Pairs of black holes, which orbit in a binary system, have been shown to occur, with the Laser Interferometer Gravitational-Wave Observatory (LIGO) being the first to measure the case of two black holes merging. These black holes were estimated to have masses around 36 and 29 times the mass of the Sun.

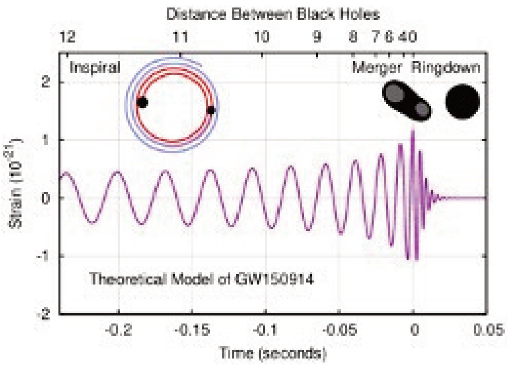

Figure 19: Diagram showing how the emission of gravitational waves correlates with the merging process. The purple line shows the strength of the gravitational waves as time goes by and the black holes get closer together. This peaks when they merge and then is rapidly damped down. *Credit: https://astrobites.org/2018/03/08/recoil-detectives-searching-for-black-hole-kicks-using-gravitational-waves/*

The merging event begins with the two black holes spiralling in towards each other. This initial phase takes a long time and during the process very weak gravitational waves are emitted. As the distance between the black holes becomes ever smaller, the speed at which they orbit increases, which, in its turn, increases gravitational wave emission. Eventually, they get close enough that they can merge; this is when the emission of gravitational waves is at its highest. Once the merger has occurred, a single black hole is left which will then 'ringdown', by emitting further gravitational waves (Fig. 19).

In the case of the first merger detected, a black hole that was around 62 times the mass of the Sun was created by the merging event. The sum of the two masses of the original black holes was 65 times the mass of the Sun so that 3 solar masses were is lost immediately as gravitational radiation. This measurement was the first-time gravitational waves were detected providing further support for Einstein's theory of General Relativity.

Conclusion

Current questions include, for example, how do black holes impact the evolution of the galaxy they inhabit (this is important for understanding galaxy formation). We still need to understand the implications of Hawking's conception of black hole evaporation. Measuring the gamma-ray background in order to study primordial black holes is also an active field of research.

From its beginnings as being only a mathematical concept to black holes becoming powerhouses at the centre of galaxies, much has been learnt about black holes over the last century.

It is now is undeniable that they play an important role in our wider understanding of the cosmos.

Prof. Neiman planting the Einstein tree in Maxwell's garden

Maxwell's garden with the Einstein tree by the stake on the right.

Planting of the Einstein tree in Maxwell's Garden

We very pleased that Professor Susan Neiman, Director of the Einstein Forum in Germany, could undertake the official planting of the Einstein tree in Maxwell's garden when she was in Edinburgh giving the prestigious 'Gifford Lecture'. Following the visit, in 2018, of our former Chairman to Einstein's former summerhouse near Berlin, the Einstein tree was presented by the Einstein Forum. This was particularly appropriate as the tree was grown from cuttings taken from an apple tree growing in the garden of Einstein's summerhouse in Germany. The story as to how it came about that this summerhouse was built for Einstein was told in Maxwell Newsletter No. 13.[1]

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The birthplace in 1831 of James Clerk Maxwell.

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1 https://clerkmaxwellfoundation.org/Newsletter_2019_Summer.pdf