Black Holes

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If asked about black holes, a person would most likely give an account of how Hollywood portrays them. Television and movies have shown black holes as being a tunnel to a parallel universe or another dimension, or even a cosmic body that sucks in everything around it into a hole that leads to certain doom. While these ideas of black holes may seem plausible, these concepts are merely fictional attempts to grab an audience's attention. What black holes really are, makes them a fascinating mystery to scientists around the world. Much has been learned about these mysterious cosmic bodies and the path that led to these discoveries has also led to many breakthroughs and ideas that have greatly changed our way of thinking. Albert Einstein's theory of general relativity and Karl Schwarzschild's solutions to Einstein's field equations have laid the foundation for the explanation and depiction of the final stages of gravitational collapse, and the bodies now known as black holes.

Theoretical Discovery

In 1915, Albert Einstein developed his general theory of relativity when he had shown that gravity does in fact influence the motion of light through space. He developed a set of equations that are called the Einstein field equations. These equations specify how the geometry of space and time is influenced by whatever matter is present. As early as 1916, the astrophysicist Karl Schwarzschild found the first non-trivial exact solution to the Einstein field equations. He gave the solution for the gravitational field of a point mass and a non-rotating spherical mass which showed that a black hole could theoretically exist (General). But before black holes where proven to theoretically exist, the idea of a body so massive that not even light could escape its gravitational pull had already existed. Geologist John Michell first wrote about these bodies in a letter written to Henry Cavendish in 1783. The idea of black holes was again suggested in 1796 by mathematician Pierre-Simon Laplace in his book *Exposition du système du Monde*. But these ideas of black holes were for the most part ignored throughout the nineteenth century due to the belief that light was a massless wave that couldn't be influenced by gravity. This was the case until Albert Einstein came along and developed his general theory of relativity (Black Hole). In 1967, physicist John Wheeler first coined the term *black hole* to refer to a collapsed star. Before then, the terms *frozen star* and *collapsar* were often used (Pickover 8).

Formation of a Black Hole

Black holes are defined as a region in space in which its gravitational field is so strong that nothing, not even light, can escape its pull. Black holes are primarily formed by the death of a star or the gravitational collapse of a heavy object (Black Hole). Stars, which are born of gravity and eventually destroyed by gravity, are created from the atoms of dust and gas that swirl throughout space. Throughout the years, usually over billions of years, the atoms will gradually clump together into dense clouds that eventually collapse under their own gravity. But this collapse does not continue until a black hole is formed. Instead, other forces counteract gravity making the dust and gas in the cloud grow steadily hotter until a nuclear furnace switches on with the end result being a star. In the more massive stars, particularly stars more than 10 times more massive than the Sun, the nuclear fuel that keeps a star burning is used at an immense rate. When a massive star has exhausted all of its hydrogen, it has extremely high temperatures and pressures. The stars core then tries to fuse iron. But when it tries to do this, the star will try to contract its core to supply the energy it needs. As it does this, the contracting matter bounces off the core and, powered by a flood of neutrinos, the star's outer layers will be blasted into space. This creates a huge explosion known as a supernova (Picture below). If the remnant left after the supernova weighs more than three Suns, the superdense neutrons will be incapable of holding the remains up against the force of gravity (Couper 12). Due to no outward forces opposing this gravitational force, the remnant will collapse in on itself. Eventually, it will collapse to the point of zero volume and infinite density, creating a singularity. As the density increases, the light rays are bent and wrapped around the remnant until the infinite density is reached where no light is allowed to escape, creating a black hole (Black Holes). In principal, though not as common as gravitational collapse, black holes can also be formed by high energy collisions that create sufficient density (Black Hole).

Characteristics and Features

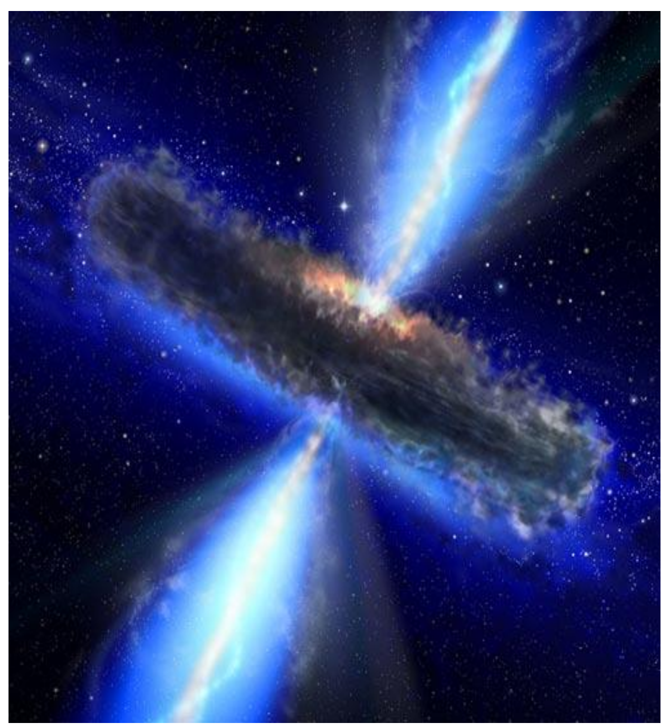
A black hole has many defining features. The first, and probably the most defining feature of a black hole, is the appearance of an event horizon. The event horizon is a boundary in spacetime. Spacetime is a mathematical model that combines time and space into a single continuum. Beyond this boundary, events cannot affect an outside observer. General relativity says that the presence of a mass will deform spacetime to where all paths lead toward the mass. At a black hole's event horizon, the deformation of spacetime becomes so strong that all paths will lead towards the center of the black hole. Once inside the horizon, it is impossible to move out or away from the black hole. In 1916, Karl Schwarzschild gave a solution to the Einstein field equations for a non-rotating, spherical body. In this solution, there contained a radius for an event horizon that came to be known as the *Schwarzschild radius*. An object's Schwarzschild radius is proportional to its mass. The equation of a Schwarzschild radius is,

$$r_s = 2Gm/c^2$$

with G being the gravitational constant and c being the speed of light. Any object can become a black hole if it collapses down to its Schwarzschild radius. The Schwarzschild radius for the earth is about 9 mm and the Schwarzschild radius for the sun is about 3 km (Schwarzschild). The second feature of a black hole is its singularity. At the center of a black hole is the singularity where its mass is compressed into a region with zero volume and infinite density. Here, the gravitational pull is the strongest and the spacetime has infinite curvature (Black Hole). The singularity is surrounded by the event horizon. Beyond the event horizon, lays a region of space called the ergosphere. The ergosphere is a region with the characteristics of a cosmic whirlpool in that when matter crosses into the ergosphere, it is not only dragged inward towards the singularity, but it also moves in a circle around the singularity.

<u>Classification of Black Holes</u>

Black holes can be classified by either their anatomies or by their mass. There are four main black hole anatomies. The first possible anatomy is the *Schwarzschild black hole*. This is a static, non-rotating, non-charged black hole. This is the simplest black hole and was named after Karl Schwarzschild when he found an exact solution to the Einstein field equations. These black holes consist of just a singularity surrounded by an event horizon. The second anatomy is the *black hole*. This is non-rotating but charged black hole. This black hole anatomy consists of two event horizons called the Inner event horizon and the Outer event horizon. The third possible anatomy is the *Kerr black hole*. This is a rotating, non-charged black hole. In a *Kerr black hole*, the singularity is elongated into a ring shape and is surrounded by an Inner and Outer even horizon. The singularity of this type of black hole is also surrounded by an ergosphere (Couper 20). The last black hole anatomy is the *Kerr-Newman black hole*. This is a charged, rotating black hole (Pickover 52). Black holes can also be classified by their mass. A *Supermassive* (Picture) black hole contains hundreds of thousands to billions of solar masses. These are believed to exist at the center of most galaxies, including the Milky Way. An *Intermediate* black hole contains thousands of solar masses. A *Stellar-mass*



black hole usually has a mass of about 1.4 to 20 solar masses. The final mass group is the *Micro* black holes. These black holes usually have masses much less than that of a star (Black Hole).

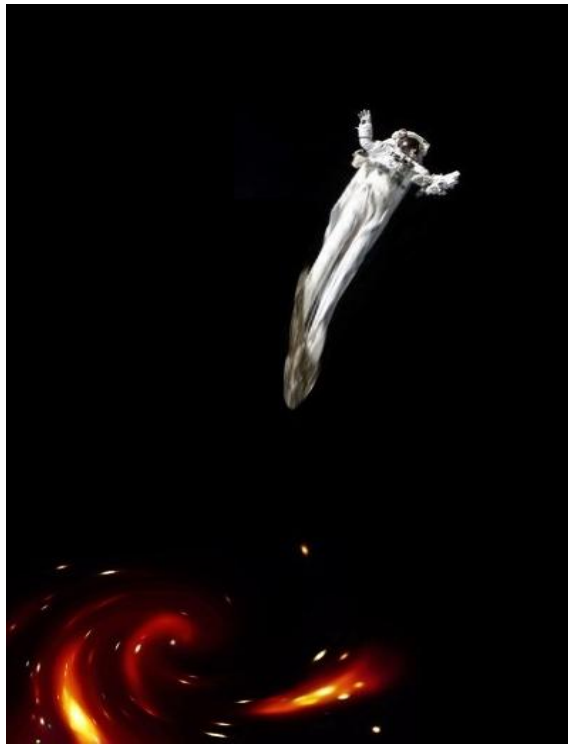
Gravitational Lensing

A gravitational lens is formed when light from a distant light source is bent around a massive object. As predicted by general relativity, this process is known as gravitational lensing. General relativity says a mass will warp spacetime in such a way to create gravitational fields that will be able to bend light. In theory, if an observer were to fall past the event horizon, a black hole will produce a gravitational lens that will squeeze the observer's view of the universe into a bright circular disk that becomes smaller as the observer approaches the singularity (Pickover 29).

Falling In

If a person were to fall into a black hole, Einstein's general relativity would say that the person falling in would experience different effects than what an observer who is watching would see. First, as the person gets closer to the event horizon, the person will begin to stretch. This stretching is called spaghettification (Picture). It is due to the fact that the gravitational force on the person's body closest to the singularity is stronger than the gravitational force that affects the person's body that is farthest away from the singularity. As this happens, time will seem to pass normally for the person falling in.

But, from the perspective of the observer, time seems to slow down for the person falling in. The black hole's gravity is so strong that it is distorting space and time. As the person gets closer to the event horizon, that person will begin to turn red because light will lose energy as it tries to fight the force of gravity. Eventually, the person will be almost invisible to the observer because the light has become dim and red from the loss of energy. Due to time dilation, the observer will never see the person cross the event horizon. Because time appears to run slower and slower for the person falling in from the observers point of view, the person will appear to hover outside the event horizon for an infinite amount of time (Couper 26).

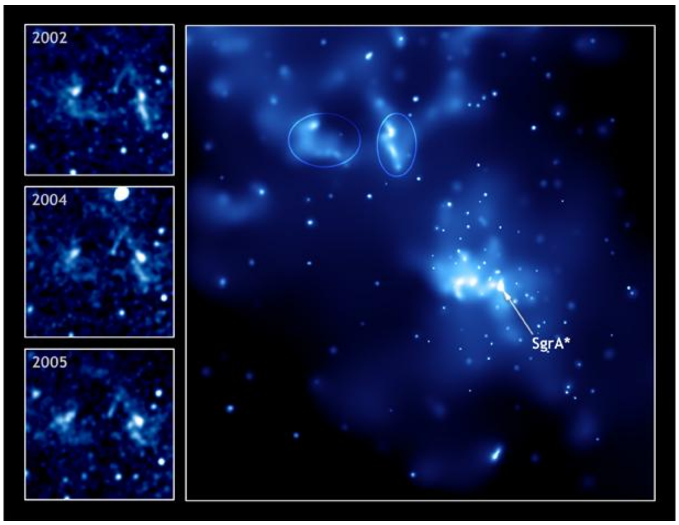


<u>Evaporation</u>

In 1974, Stephen Hawking predicted that black holes can evaporate or even explode. Inspired by an imaginative combination of general relativity and quantum theory, Hawking found that energy is emitted by the gravitational field around a black hole. His calculations showed that black holes emit particles that are created with bursts of energy borrowed from the gravitational field. This effect is known as Hawking Radiation. If Hawking's theory about black hole radiation is correct, then when a particle escapes from a black hole without releasing its borrowed energy, then the hole has lost this amount of energy from its gravitational field. According to Einstein's equation $E=mc^2$, if energy is lost, then mass is lost. As the hole shrinks, it will emit even more particles, and the black hole will eventually evaporate over time (Couper 34). The rate at which this evaporation or shrinking occurs is dependent on the mass of the black hole. Since black holes emit particles with energy, black holes must have a temperature. The temperature of a black hole is inversely proportional to its mass. Therefore, a smaller black hole with little mass will lose energy faster than a larger black hole because it will emit more radiation (Black Hole). As a black hole shrinks and the rate of which it emits particles increases, the temperature will also increase. When the temperature reaches a quadrillion degrees, the black hole will explode. This explosion takes place in less than a millionth of a second and has the energy of a billion hydrogen bombs (Couper 35). For example, a black hole with the weight of a car and a size of about 10^{-24} m will evaporate in only a nanosecond. But, it would have the brightness of more than 200 times that of the sun (Black Hole).

Black Holes throughout the Universe

Stephen Hawking believes there are more black holes than visible stars. This would be about a hundred thousand million black holes in our galaxy alone. Though this number is astounding, the actual proof that black holes exist has not been given because black holes are invisible. Scientist and astronomers can only collect data that infers the existence of black holes (Pickover 7). In 1970, American scientists launched a satellite, *Uhuru*, which was designed to find powerful X-ray sources. Among its discoveries was Cygnus X-1, an intense X-ray source in the constellation Cygnus. At the same position as Cygnus X-1 is a gigantic, hot blue star that is about 30 times more massive that the Sun. What scientist discovered was that this star was being swirled around by an invisible body, Cygnus X-1, about the size of 10 Suns (Couper 14). Matter that was torn off from the blue star formed a swirling disk in which the gravitational energy was being turned into heat and producing X-rays. Astronomers agree that Cygnus X-1is almost certainly a black hole and the first that was discovered. In 1995, more evidence for black holes emerged from ten radio telescopes known as the Very Long Baseline Array, or VLBA. The VLBA allowed scientist to look into the spiral galaxy NGC 4258. They measured the swirling motion of a gas disk orbiting the core and found it was going at a speed of 900 kilometers per second. From this, they found that the density of the core was greater than 100 million suns per cubic light year. This is a greater density than any galactic center measured up to that time. This calculation of the density of the core of NGC 4258 is a very strong case for the existence of a supermassive black hole in a galactic nucleus. Many astronomers now believe that black holes inhabit the center of most large galaxies (Pickover 6). At the center of our galaxy, the Milky Way, astronomers believe that there is a supermassive black hole in the region Sagittarius A*. Some other notable galaxies with supermassive black hole candidates include Andromeda Galaxy, M32, M87, NGC 3115, NGC 3377 and the Sombrero Galaxy. Some more recent discoveries of black hole candidates include the evidence



collected in 2002 by the Hubble Space Telescope. Scientists conclude that two global clusters, named M15 and G1, may have intermediate-mass black holes. In 2004, a team of scientists reported finding an intermediate-mass black hole with a mass of 1,300 solar masses only 3 light years away from Sagittarius A* (Picture) in the Milky Way Galaxy (Black Hole).

Always a Mystery

There will always be questions regarding the complicated topic of black holes. Though some questions have been answered through the work of brilliant minds such as Albert Einstein and Stephen Hawking, scientists will always work to find new discoveries and make new advances. With new and greater technology now available, scientists have endless possibilities to make these new discoveries. But with new discoveries, comes new and more complicated questions that will take many years to answer. The human race has only scratched the surface when it comes to the knowledge of how our universe works; making black holes one of the most mysterious and exciting elements in the universe.

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