WESTMINSTER SCHOOL

RESEARCH BRIEFING

OCR G496(B)

# A Brief History of Black Holes

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June 23, 2014

# Contents

# 1 Definition

When stars with enough mass reach the end of their life cycle they can collapse into black holes. A black hole is a collection of mass with such a strong gravitational force that nothing, not even light, can escape once captured within its *event horizon*. The addition of further mass to the black hole goes to increase its gravitational force which in turn attracts more mass, creating a vicious cycle.

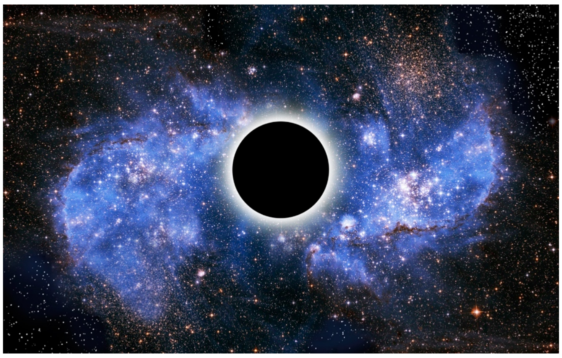

Figure 1: Artist's conception of an event horizon. [1]

An event horizon is described as a unidirectional membrane in spacetime across which information, matter and energy can only travel in one direction; it is the point of no return. This event horizon, or Schwarzschild Radius as it is also known, can be calculated mathematically with the equation $r_s = \frac{2Gm}{c^2}$ (for a star the mass of our sun the Schwarzchild Radius would be 3km, compared to its true radius of 700,000km[2]). Due to gravitational time dilation an object approaching the horizon would appear to slow down to external observers however from the perspective of the object itself time would not appear altered.

Black holes emit Hawking Radiation, also known as black hole evaporation. As a black hole radiates it loses energy and therefore also mass due to Einstein's equation relating energy and mass ($E = mc^2$). The rate of evaporation is inversely proportional to the mass of the black hole and so the smaller the black hole the faster the rate of evaporation, or decay, meaning that all Black Holes are predicted to ultimately vanish.

# 2 Discovery

## 2.1 Dark Stars

The precursors to black holes were Dark Stars, and as they were theorised long before Einstein's ideas of relativity their effects on time are completely ignored. Under Newtonian physics the equation for the gravitational force attracting two masses can be modeled by $F = G\frac{m_1 m_2}{r^2}$; this means that a massive object with a sufficiently small radius can have a gravitational force so strong that its escape velocity $[v_e = \sqrt{\frac{2GM}{r}}]$ exceeds the speed of light. John Michell first theorised these 'Dark Stars' in his writing to Henry Cavendish of the Royal Society in 1783:

> "If the semi-diameter of a sphere of the same density as the Sun were to exceed that of the Sun in the proportion of 500 to 1, a body falling from an infinite height towards it would have acquired at its surface greater velocity than that of light, and consequently supposing light to be attracted by the same force in proportion to its vis inertiae, with other bodies, all light emitted from such a body would be made to return towards it by its own proper gravity." [3]

Dark Stars differ from Black Holes in that it is not true to say absolutely nothing can escape a Dark Star. For instance any particle with a continued means of propulsion would eventually leave the Star provided the propulsive force was greater than the force of gravity ($g$) experienced by the particle; this leads to what is known as *Indirect Radiation.* Some particles temporarily escape the star's surface and interact with each other before being pulled back in, while free these particles can interact with one another and occasionally a particle can gain enough kinetic energy to escape completely.

John Michell went as far as to predict the effect of gravity on the wavelength of the light emitted. He claimed that light escaping a Dark Star would have less energy and therefore be shifted down the spectrum to a lower energy colour. Michell then cited Newton's claim that blue light was at the lower end of the energy spectrum; meaning that although Michell had anticipated Gravitational Shift well over one hundred years before Einstein's writings on the topic, he had the direction of the shift in reverse.

## 2.2 Relativity

At the beginning of the $20^{th}$ century Albert Einstein first published the theory of Special Relativity in his 1905 paper "On the Electrodynamics of Moving Bodies' and ten years later he finalised his theory of General Relativity, publishing the Einstein Field Equations.

### 2.2.1 General Relativity

While Einstein's theory of Special Relativity is centred around the premise that light in a vacuum travels at the "speed limit of the universe" at 300,000km/s, the theory of General Relativity focuses on Einstein's Equivalence Principle claiming that inertial and gravitational mass are equivalent as demonstrated in Fig. 2.

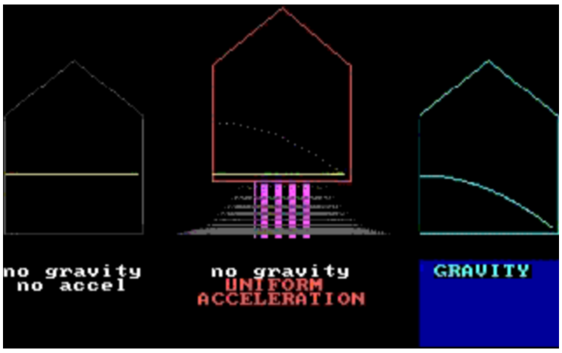

Figure 2: Equivalence between Inertial Mass and Gravitational Mass [4]

Einstein extended Galileo's Principle of Relativity claiming that the equivalence of these two types of mass was more than a coincidence, but a fundamental principle of the universe. Up until the $20^{th}$ century the universe was believed to have four dimensions: the three dimensions of space that we experience and a fourth dimension of time that flows universally at a rate of one second per second. Einstein challenged this stating that space and time were in fact interwoven in what he referred to as *spacetime*. Spacetime is curved by the existence of matter or energy and since Euclidean methods of geometry are simply incapable of representing four dimensional spacetime it must be expressed using the Riemann Tensor.

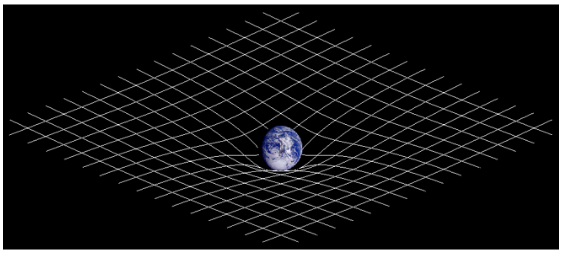

Figure 3: Representation of the effect of mass on Spacetime. [5]

The scientific community was not quick to accept that massive objects could affect the flow of time (Gravitational Time Dilation) as it clashed with all previous classical thought and ventured too close to what seemed to be science fiction. However a key piece of evidence for Einstein was the Precession of Mercury's Orbit, a problem that Newtonian physics had previously been unable to solve. When General Relativity was applied to the motion of Mercury the stronger gravitational pull observed as Mercury approached the sun was fully predicted, Einstein saw this as the crucial test for his theory.

Furthermore matter curving spacetime also explains why massless particles such as photons could still be affected by gravity. Light escaping from a gravitational field must lose energy and therefore is shifted to a lower frequency. This is referred to as Gravitational Redshift as it shifts visible light towards the red end of the electromagnetic spectrum and can be seen in light escaping strong gravitational fields or in light from galaxies moving away from the observer.

The Einstein Field Equations describe the effect of matter on spacetime and the gravitational force this creates. Karl Schwarzchild found a solution to these for masses with zero angular momentum and no electric charge, using the equation presented in the introduction of this briefing to work out the schwarzchild radius of the mass. Any mass with a radius smaller than this must be a a black hole as it would curve spacetime so much that light could not possibly escape; Schwarzchild's solution acts as a good estimate for slow spinning objects such as the earth and our sun. Other solutions emerged for rotating and electrically charged black holes including the Kerr-Newman metric and eventually the No-hair theorem was formed. The No-hair theorem states that Black Holes can only be differentiated by three parameters: angular momentum, electric charge, and mass.

### 2.2.2 Evidence

In 1919 the British astrophysicist Sir Arthur Eddington led two expeditions to Brazil and Africa to observe how a Solar Eclipse would affect the position of the Hyades cluster stars behind the sun. While his measurements were far from precise they clearly showed a deflection and the result brought immense popularity and credibility to Einstein's work.

Figure 4: Representation of the effect of the Sun on starlight. [6]

# 3 Life Cycle of a Black Hole

**Birth**

Stars with a mass approximately 20 times greater than that of our sun [7] or greater have the possibility of forming a black hole at the end of their life cycles. As the star runs out of fuel for nuclear fusion the pressure force pushing out against its own gravity begins to weaken and so the core of the star begins to compress. The combination of the weakening outwards pressure force and the growing gravitational force leads to the rest of the star collapsing into the superdense core.

If the core left after any remaining gas is expelled via a supernova has sufficient mass it will continue to collapse under its own weight until it reaches a point where its volume is effectively zero, and therefore the density is infinite. This is referred to as the singularity and can be found at the centre of all Black Holes.

The radius around the singularity where spacetime is so deformed that not even light can escape is known as the event horizon of the newly formed black hole. Once matter or energy has passed through this point there is no way for it to escape.

## Growth

Once the black hole has a sufficiently great gravitational force it will absorb nearby stars and interstellar dust along with background radiation. Black holes situated in globular clusters and binary systems are more likely to have the opportunity to absorb other stars and more likely to eventually become supermassive black holes. Supermassive black holes can have masses up to millions of times that of our Sun and are expected to exist in the centers of most galaxies.

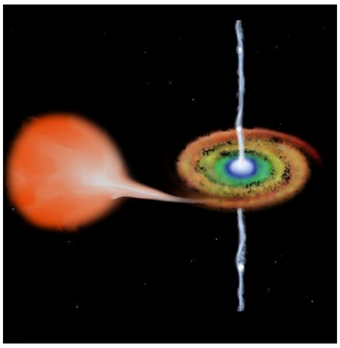

Figure 5: Representation of a black hole absorbing a star. [8]

As matter falls into the black hole (but before it crosses the event horizon) it forms an accretion disk, heated by its own friction and one of the brightest objects in the night sky. This disk gets so hot the matter within it can become plasma and therefore electrically charged. The combination of motion and electrical charge polarizes the black hole and this forces the electromagnetic radiation being emitted by the heat to leave by one of the two poles as shown in Fig. 5.

**Death**

In 1974, Stephen Hawking proved that black holes emit small amounts of radiation. This radiation, known as Hawking Radiation, is caused by quantum fluctuation (temporary change in the quantity of energy at a point in space) causing particle-antiparticle pairs to appear near the event horizon. To preserve energy the particle that entered the black hole must have a negative energy and the process would be equivalent to the black hole emitting a particle.

Hawking Radiation takes place at a rate inversely proportional to the mass of the black hole. This means that that small black holes emit much more radiation than their larger counterparts. For instance a black hole the size of a car would have a radius of $5 \times 10^{-25}$m and evaporate in a nanosecond [9]. Stephen Hawking predicts that this means all black holes will eventually evaporate into nothing, given enough time.

This feature of black holes means it's completely safe to artificially create them here on earth. In fact this is exactly what the scientists at CERN [10] are trying to do at the moment by smashing together to small particles at near light speed in the hopes of creating a large enough density for a micro-black hole to form.

## 4 Summation

The theory behind black holes has existed from classical Newtonian physics, to Einstein's theory of relativity, and survived introduction of Quantum mechanics; its resilience is unquestionable. Details in their definition may have updated to fit with our changing understanding of the nature of our universe but the core concept of a dead star that now absorbs everything around it, including light, remains the same.

Although problems with the current theory behind black holes are apparent, such as the Information Loss paradox, these should not be seen as weaknesses but as opportunities to improve our current understanding of our universe.

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