Research & Report

Black Holes

Contents

Introduction 3
What is a Black hole? 4
Formation of Black Holes 4
Features of Black Holes 6
Discovering Black Holes 8
Where are they? 9
What would happen if an object falls into a black hole? 9
Theory of general relativity.. 10
Hawking Radiation 11
Evaluation & Conclusion 12
Bibliography/Reference 13
Appendix 14

Introduction

For my research and report coursework topic I chose black hole as I've done a research on black holes for a presentation in the past so it would be fairly straightforward to do, and my current knowledge about black holes would help me to complete this coursework a lot easier. Moreover, I was always interested in astronomy, which includes black holes therefore doing a research and report coursework would enable me to expand ideas and knowledge. The fact that people are able to observe and analyse black holes in the boundless space also stimulated me to choose this topic because I was always curious about how people can analyse when black holes are millions of light-years away from where we live and unable to see. Also I wish to find out more about why there are so many theories associated with black holes and how the astronomers ended up making theories of their own, which are different to each other.

I will be doing my researches on different areas of black holes. Firstly, I will find out how black holes were created in the first place, what they are consisted of and the size plus number of black holes in the universe, which will allow me to make a good start with basic explanations about black holes. Then I'll do some calculations for escape velocity to prove that the light cannot escape the black holes and make this coursework more reliable. Secondly, I will push this topic into more complicated areas of physics by bringing up the effect of black holes, ways of analysing and discovering black holes when even lights cannot escape because surely if light don't exist near the black holes they wouldn't be observable. Furthermore, theories associated with black holes will be introduced later on this coursework to collect general ideas of what would happen if we were to fall into the black hole. These will be interesting to analyse as black holes are only known theoretically and because not many people are aware of what black holes are capable of.

In addition, I will be using different sources to gather a variety of information about black holes such as Internet, articles from magazines and books so that I don't just entirely rely on one source and the purpose of it is to make this coursework more interesting and reliable.

What is a Black hole?

A Black hole is known as a region of space with an extremely powerful gravitational field that even light, which travels at immense speed, cannot possibly escape once it passes a boundary so called, ‘event horizon’. But how on Earth was such space created in the first place? The formation of a black hole can be explained by the death of a star at the current level of astronomical knowledge and theories, which will be explained later on.

The first object to be recognised as a black hole was the x-ray binary star Cygnus X-1 proposed by Stephen Hawking in 1971. At first the mass of this object was known to be too high to be a neutron star therefore he considered it to be a black hole, which he had been doing his research on.

Formation of Black Holes

Firstly, the theory of the gravitational collapse of a star starts from the point when the following process comes to an end. The conversion of hydrogen into helium works as a generator for a star and this process creates heat, which then creates its own energy to create pressure in order to withstand its own gravity. This is on the assumption that the star is at least three times bigger than the Sun. However, when the hydrogen runs out, the star will no longer be able to produce helium for its own pressure to support itself against its own gravity and therefore it starts to shrink. When a star eventually stops generating its own energy, the collapse transforms the matter in the star’s core into a denser state, which forms one of the types of compact star, a white dwarf or a neutron star but if stars could shrink even more it would become a black hole. During this process the escape velocity, which simply means a minimum speed required in order to escape certain gravitational field strength of a star or planet, greatly increases. In other words, the star shrinks and gravitational field at the surface becomes stronger at the same time. We use kinetic energy in order to calculate the escape velocity because the positive kinetic energy is required to increase the negative gravitational potential energy to zero. So if we rearrange the first equation to have *v* as a subject, we get a new equation:

$$\tfrac{1}{2}mv^2 = \frac{GMm}{r} \qquad \therefore \qquad v = \sqrt{\frac{2GM}{r}}$$

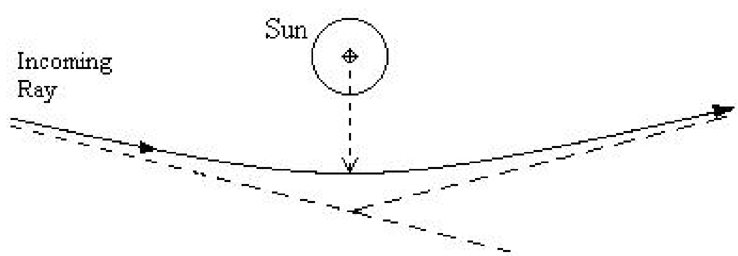
In this equation, *m* is mass of the object escaping the gravitational potential energy, *v* is velocity, *G* is a gravitational constant, *M* is the mass of the star and *r* is the distance between the centre of both the object and the star. So when *r* becomes smaller with others staying the same the value of *v* will increase. Because this imaginary star has shrunk a lot from its original size that is few times bigger than the Sun it eventually turns into a black hole and the escape velocity goes well over the speed of light, which is $3 \times 10^8 ms^{-1}$.

$$V = \left[\frac{2 \times (6.67 \times 10^{-11}) \times (100 \times 1.98 \times 10^{30})}{30{,}000} \right]^{1/2}$$

$$\therefore \quad V = 9.4 \times 10^{8}\text{ms}^{-1}$$

For example, if we assume that the mass of the black hole is approximately a 100 solar masses with a radius of about 30 kilometres and when we calculate it, we would have an escape velocity of $9.4 \times 10^{8}\text{ms}^{-1}$, which shows that this value is higher than the speed of light. This is on the assumption that we are measuring the escape velocity of a stellar-mass black hole, which would normally have 100 solar masses with the radius of 30km. In addition, in astronomy, the solar mass is the standard way of expressing mass, as what we are dealing with here are few times bigger than the mass of the Sun, therefore, it is a more reasonable measurement. So if the mass of the Sun is equal to one solar mass then 100 solar masses means the mass that is 100 times bigger than the Sun.

According to the theory of general relativity, space is not flat but distorted or curved by the matter and energy in it and we can observe this curvature in the bending of the light or radio waves that travel near the sun on their way to Earth (From Web link, Black Holes 5). In the case of light passing near the sun, the bending is very small. However, if the sun were to shrink until its radius is very small, the bending would be a lot greater that light leaving the sun would not get away but instead it would be dragged back by the sun's gravitational field and this explains us why only black holes can bend the light, forcing it to travel inwards towards the centre.



(The diagram above shows the effect of gravity on light that's travelling near the Sun. The ray would bend slightly towards the Sun as it gets closer to it but the Sun won't be able to attract the light completely. Instead the light travels on not as a straight line but creating a curve, leaving the Sun's gravity at the same angle as it entered the initially)

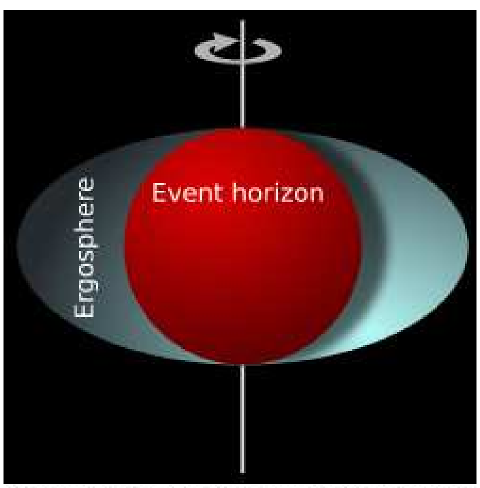
Features of Black Holes

There are two types of black holes, non-rotating and rotating black holes. Generally, black holes form from the gravitational collapse of a massive spinning star and because nearly all the black holes are believed to be rotating, I'm going to focus more on the features of rotating black holes. Although they generally have different features, both rotating and non-rotating black holes do share some features such as the inability of light to escape the event horizon and accretion disks, which will be explained later on.

One of the main features of black holes is event horizon. It is defined as the boundary of the region from which not even light can escape. This is of course not a solid surface and does not obstruct or slow down matter of radiation, which is travelling towards the region within the event horizon, and astronomers predict the rotating black holes to have two of these event horizons.

There are also two photon spheres that surround the black holes and these are balls of photons that orbit around the black holes as a result of the gravity pulling in the photons. Because this spherical region have enough gravity to bend the photons towards the region, when light approaches near the black holes the photons of light are forced to travel in orbits. These photon spheres are known to be located further from the centre of the black hole than the event horizon and ergosphere. However, in the case of the black holes rotating, these photon spheres are dragged along with it. So the photon sphere that is closer to the black hole is moving in the same direction as the rotation, whereas the photon sphere further away is moving against it. Therefore, the greater the rotation speed of a black hole the greater distance between two photon spheres.

The region outside the event horizon but inside the photon sphere where the rotational velocity is the speed of light is called ergosphere as shown in the diagram below. It's the region that if any particles fall within the ergosphere, they are forced to rotate faster thereby gain energy. Because the particles have not yet reached the event horizon therefore they still have chance to escape the black hole. This is where Penrose process kicks in with the fact that the rotating black holes emit energetic particles at the cost of its own total energy. It is a process theorised by Roger Penrose who predicts that energy can be extracted from rotating black holes. The process occurs inside the ergosphere where if an object falls, it splits into two. In other words, if particle A falls into the region it will split into particle B and C. Only particle B will have chance to escape the ergosphere with greater mass energy, the extracted black hole's rotational energy, than particle A while particle C falls into the black hole. In this way, the rotational energy of black hole that is extracted by the particle is lost when it escapes the ergosphere and as a result the black hole will lose its rotational speed. Therefore, from this prediction, the black hole will eventually lose momentum,



(This image describes two important boundaries of a rotating black hole, the inner boundary called event horizon and the outer boundary called ergosphere, from Web link 1) becoming rotationally stationary at some point. This idea will be developed and explained later on.

In addition, due to the gravitational pull, the gas nearest the event horizon form a disk called accretion disk and because the gravity so strong, is compressed into a high density. Then enormous amount of energy is generated from the pressure and friction within the disk, and as a result a massive amount of heat is generated, which causes the emission of x-rays to occur from the disk around the black holes. Moreover, when a spherical non-rotating body of a critical radius known as 'Schwarzschild radius', collapse under its own gravitation under general relativity, theory suggests it will collapse to a single point. The theory also predicts that a rotating black hole will have a ring singularity, which lies at the centre that is zero width and thickness. In other words, the centre of a rotating black hole is a circle rather than a point. However, the ring singularity only applies to rotating black holes as they have angular momentum and because a point cannot support angular momentum in the theory of general relativity, this ring singularity is zero thickness but non-zero radius.

Schwarzschild was mentioned above in relation to the formation of ring singularity. It is defined as the radius for a given mass where, if that mass could be compressed to fit within that radius, nothing could stop it from continuing to collapse into a gravitational singularity. Therefore, an object smaller than its Schwarzschild radius is a black hole. Furthermore, the surface at the Schwarzschild radius acts as an event horizon in a non-rotating body.

The Schwarzschild radius is proportional to mass, with a proportionality constant involving the gravitational constant and the speed of light. The formula for the Schwarzschild radius can be found by setting the escape velocity, which we have seen earlier, to the speed of light. So if I rearrange the equation to make *r*, which is the radius, as a subject, I get the following equation for Schwarzschild radius:

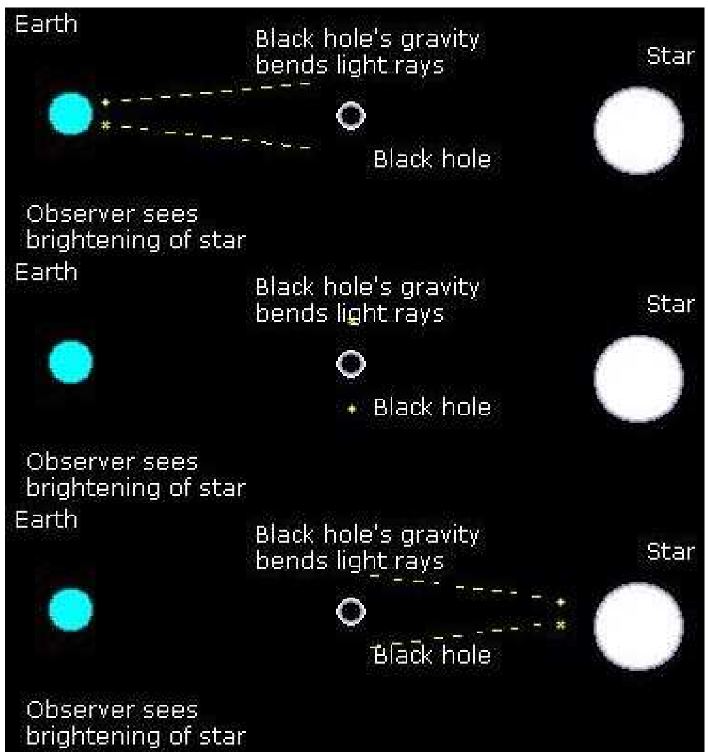
$$v = \sqrt{\frac{2GM}{r}} \longrightarrow r = \frac{2Gm}{c^2}$$

Everything is the same as the previous calculation of escape velocity, where *r* is radius, *G* is the gravitational constant, *m* is mass of the object and *c* is the speed of light. The reason why the radius and mass are proportional is because *G* and *c* are constant therefore in the new equation an increase in *m* would cause *r* to increase too. So I thought it would be interesting to measure the Schwarzschild radius of Earth. In other words, how small does it have to be in order to turn into a black hole?
G is (6.67×10^{-11}), *m* is (5.9×10^{24}) kg and *c* is (3×10^{8}) ms^{-1}. If I put these into the equation I get (8.745×10^{-3}) m, if I convert metres into millimetres and round up I get about 9mm of Schwarzschild radius. Therefore, the size required for the Earth to become a black hole is the radius of 9mm.

Discovering Black Holes

So how do we know whether black holes exist or not when Einstein's theory of general relativity proposes that the most densest and massive objects conceivable, such as black holes, have gravity that is so strong that nothing, not even light, can escape? Also even if we could know that they exist, how do we find out?

As I explained earlier, massive amount of heat containing x-rays are generated from the pressure and friction within the accretion disks that surround black holes. These emitted x-rays are then picked up by the x-ray telescopes that orbit around just outside the Earth's atmosphere. This is one of the methods that astronomers use in order to detect and analyse black holes. The other method to detect black holes is called gravity lensing. It occurs when a massive object such as a black hole, passes between a star and the Earth. The black hole acts as a lens when its gravity bends the star's light rays and focuses them on the Earth. From an observer's view on the Earth, the star would appear to brighten and this is shown on the following diagram.



(The image above shows how the black hole can affect the light ray, from Web link 6)

Black holes can also be detected by measuring how much mass there is in a certain region of space. Black holes have large, dark masses concentrated in small volumes. If a region has large amounts of this dark mass, then one can suspect the presence of a black hole.

However, most accretion disks and the emitted x-rays are not clear proof that a black hole is present because other dense objects such as white dwarfs or neutron stars also have accretion disks that generate x-rays and behave the same ways as those around black holes therefore a dense object that generates x-rays does not necessarily represent the black hole but it gives astronomers an idea of where it might be worth looking for a black hole.

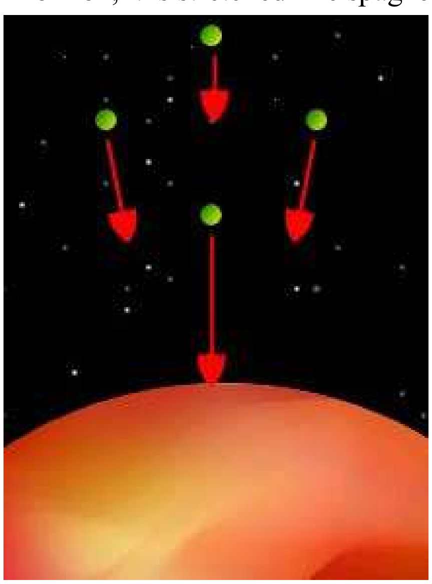
Where are they?

Supermassive black holes, a black hole with a mass of an order of magnitude between 10^5 and 10^{10}, are predicted to be at the centre of every large galaxy according to the American Astronomical Society. In addition, Hubble Space Telescope produced observations in 2002 indicating that there are number of both intermediate-mass black holes and stellar-mass black holes that exist in the Milky Way as well as in the other universe.

What would happen if an object falls into a black hole?

What would happen if a probe were launched towards a black hole? To the observers watching safely from a far distance, the infalling probe's clock slows down; radio signals from the probe come at increasingly longer wavelengths due to the gravitational red-shift. The probe approaches closer and closer to the horizon, but the distant observer never see it cross over into the hole. Time seems to come to a half for the probe, and the red-shift of its radio beacon goes to infinity, as measured by the faraway astronomers. At some point the last, highly red-shifted signal from the probe is heard, and then nothing more. The probe disappears forever. This is what would happen in a non-rotating black hole but what would it be like to fall or to watch an object falling into a rotating black hole then? If an explorer fell straight down toward the equator of a black hole from a great distance, it would feel to the falling observer that his path was straight and he was not rotating, but a far-off observer would see him spiralling inward as he neared the horizon and would feel excessively large forces before passing the event horizon. To him, on the other hand, it would seem that the distant stars would begin to rotate. Like a leaf sucked into a vortex at the bottom of a waterfall, the explorer would be dragged into a spiral path by the flow of space-time and finally absorbed.

In addition, another theory was proposed by Steven Hawking, called Speghettification. This is the idea that if an object passes within a black hole's event horizon, it is stretched like spaghetti due to the gravitational pull. If we consider four objects falling into a black hole as shown on the left hand side, each object will start accelerating towards the centre of the black hole once they reach the event horizon. Because these objects are falling into one spot at the centre of the black hole that is very small, the objects located on the left and right will squash together. On the other hand, the bottom object will fall faster than any other object since it is closest to the black hole and the force of gravity decrease with the distance. As a result, the bottom and the top object are pulled further apart as it gets closer to the centre. Eventually these four objects will form a narrow diamond shape and as they get even closer to the centre of the black hole, the shape will become even narrower forming spaghetti like shape before reaching the singularity.

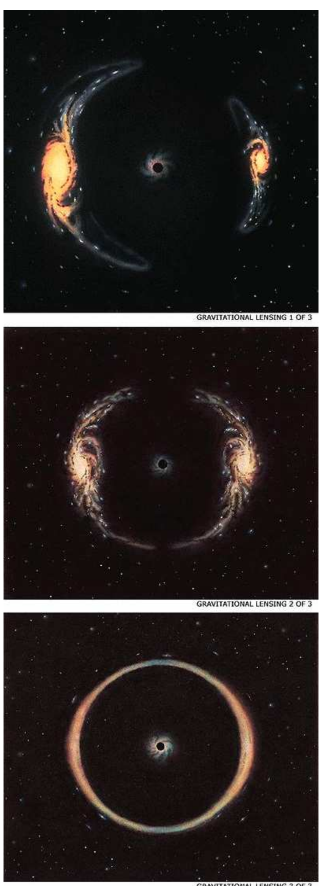


(The diagram above shows how objects can be stretched like spaghetti under a huge gravitation, from Web link 1)

Theory of general relativity

This is the theory developed by Albert Einstein in 1915, which unifies special relativity, Newton's law of universal gravitation and the insight that gravitational acceleration can be described by the curvature of space and time. There are a great number of areas associated with black holes that are related and well supported by the theory of general relativity.

Firstly, on page 9, we talked about what would happen if an object were to fall into a black hole theoretically. If a person fell towards a black hole the time would seem to have slowed down to him as he approaches closer to the black hole. This is because the gravity has immediate influence on the passage of time. For example, if two observers A and B are at a great distance at rest, with observer A closer to the source of gravity. Then for light sent from A to B, B will measure a lower frequency than A and the light sent towards A will be blue-shifted and the light sent towards B will be red-shifted. Also A's clock would tick slower than B's clock. Therefore, the rate at which A and B age would be different and the effect is not restricted to clocks. The idea is that light or other forms of electromagnetic radiation of a certain wavelength originating from a source placed in a region of stronger gravitational field will be found to be of longer wavelength when received in a region of weaker gravitational field. This is due to the photons losing its energy from passing through a gravitational field and in this case its colour reddens. According to the theory proposed by Einstein, the consequence of this gravitational shift was gravitational time dilation. Also it was proved and demonstrated by noting that atomic clocks at differing altitudes will eventually show different times. Although in this experiment the difference of two clocks was extremely small, the theory predicts that the higher the local distortion of space-time due to gravity, the slower time passes and hence causes time dilation therefore, the time difference would be greater at greater gravity.



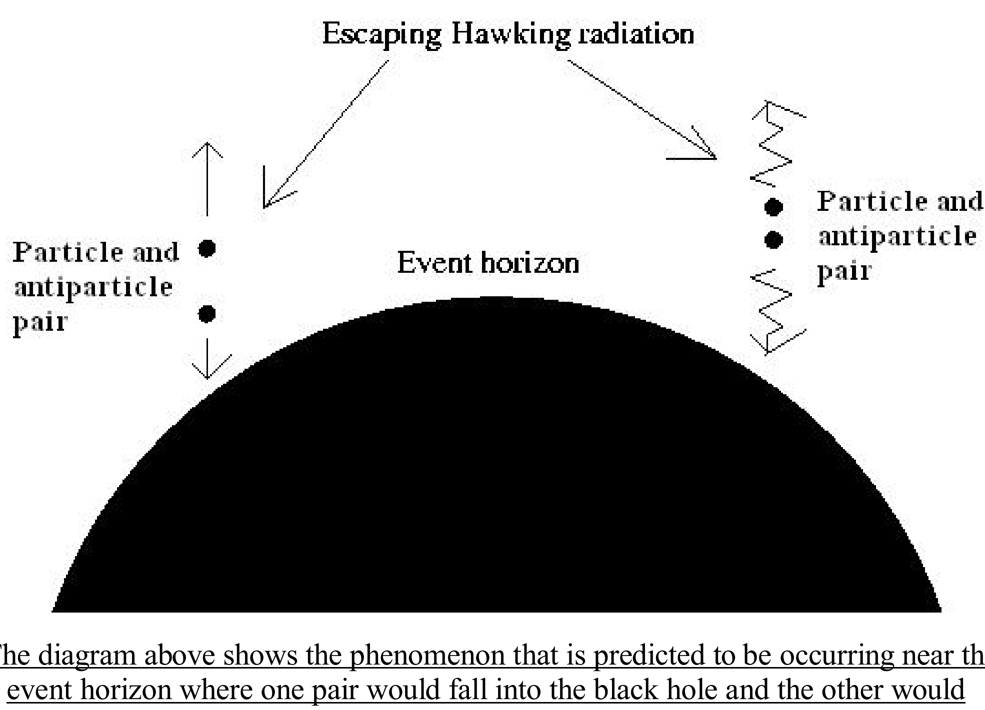
Secondly, the distortion in relation to gravitational lensing can occur from the deflection of light by gravity. On page 8 we discussed about how we observe or detect black holes by gravitational lensing method. However, it is possible to for the observer to see multiple distorted images of the target during this process, shown in the diagram to the left. Moreover, it can also result in two images, a bright ring known as an Einstein ring, or a partial rings called arcs. If the source, massive lensing object, and the observer lie in a straight line, the source will appear as a ring behind the massive object.

(The image on the left is the artistic view of three different phenomenon of gravitational lensing caused by a black hole that exists between Earth and the matter observing. First two are the multiple images due to the deflection and the third one shows a complete Einstein Ring, from Google image search – Einstein Ring)

Hawking Radiation

Although the existence of Hawking radiation has never been observed, there is some dispute over whether Hawking radiation actually exists or not. It is a thermal radiation predicted to be emitted by black holes due to quantum effects. Steven Hawking suggests that because black holes can lose mass from this hawking radiation emission, black holes which loser more matter than they gain through other means can evaporate, shrink and eventually vanish. He also stated that even though the radiation is emitted from beyond event horizon, this radiation does not come directly from the black hole itself, but rather is a result of virtual particles being boosted by the black hole's gravitation into becoming real particles. If a particle-antiparticle pair appears close to the event horizon, one of the pair falls into the black hole whilst the other escapes. We have talked about this on the previous page on how black holes can lose its rotational energy therefore there is connection between the theory of general relativity and hawking radiation. It is this process that would appear to be emitting a particle.

However, if Hawking's idea is correct then only the very smallest black holes are likely to evaporate. For example, a black hole with the mass of our moon would gain as much energy from cosmic microwave background radiation, which is a form of electromagnetic radiation that fills the universe, and larger black holes will gain more energy than they emit. In reality though, the smallest black holes, which can be created naturally is about five times the mass of our sun. Therefore, even though the cosmic microwave background radiation eventually becomes weak enough so that the black hole emit more Hawking radiations than the energy of the background radiation being absorbed by the black hole causing evaporation, the process would take a very long time to complete.



(The diagram above shows the phenomenon that is predicted to be occurring near the event horizon where one pair would fall into the black hole and the other would escape, a possible cause of evaporation)

Evaluation & Conclusion

Over the last few weeks, I have come across with numerous ideas and theories associated with black holes, which I found quite hard but challenging. Just before I started writing this report, first I planned out on how and what areas of physics I can include and sorts of areas I was going to look at. The planning was crucial in completing this report, as this is not an easy topic and the areas of physics I needed to look at were very broad. Therefore, I thought it was necessary to plan out first of what to do a research on so that I don't overwrite or write too little about black holes. Moreover, this research and report required analytical mind, as there are a lot of theories that sometimes do not work each other and can be controversial. I needed to spend a lot of time reading and searching for information about black holes and had to be sure that I find the most reliable sources that are up to date because most ideas are only theoretical therefore old information may be unreliable. Almost all the information and theories that I have come across were new and complex, which I struggled at some point. But it was all these new interesting ideas about black holes that not many people know of, which stimulated me to carry on and produce this research and report coursework.

Although I understood most of the theories and ideas on black holes there are still some predictions that I don't appreciate fully. I included Spaghettification, the idea that when an object falls into a black hole it is stretched like spaghetti, and thought the theory might not necessarily apply to all the objects but only to a certain size of the objects that are big enough to be affected in terms of the proportionality of gravitation and distance. In other words, I think an astronaut wouldn't necessarily be stretched because he is not big enough. Furthermore, it was hard writing this report because there were time and word limits to write a topic that is full of theories with very broad ideas, and for this reason I had to move on without any question or including my own ideas. Also some predictions would be easy to follow but never be able to understand in depth in terms of how the astronomer developed his idea or why it is believable. In addition, there were uncertainties about the description of the singularity for black holes because quantum mechanics is as well supported as general relativity and it does not allow objects to have zero size. But even though there isn't any well supported theory that combines these two, I decided to follow on general relativity because general relativity is a bigger scale theory that most articles follow. Apart from these problems I found everything else was fairly straightforward.

On the other hand, there were several alternative ideas associated with black holes without the existence of singularity proposed such as the Gravastar, but they were thought to be artificial and no observable differences from black holes, and therefore denied. There were also a number of ideas based on quantum mechanics that black holes do not exist but are dark energy stars instead, again they were denied with little support.

I already had basic ideas of black holes beforehand but after all the research and reading, I gained a lot more knowledge without myself realising. Moreover, I was pleased to have choice in choosing my own title to produce research and report, which I thought was good because I worked more enthusiastically than what I normally do. Although some people might think this is completely needless knowledge in our lives, but personally I felt doing this research and report coursework was beneficial because at some point in the future we will be expanding our ways into space.

Bibliography/Reference

Books

Black holes and baby universe and other essays - Stephen Hawking, published in 1993
: A book published by Stephen Hawking which includes the properties of black holes, how it was created in the first place and more importantly, the theories of falling into the black holes. The book was very easy to follow and was reliable since the author is one of the most well known scientists associated with black holes.

A Brief History of Time (From the Big Bang to Black Holes) - Stephen Hawking, published in 1988
: Again the author is the same as above but it deals with more complicated areas of black holes and was slightly harder to follow than the previous one.

Foundations of Modern Cosmology - John F. Hawley, Katherine A. Holcomb, published in 2005
: A solid explanation on general theory of relativity in relation to black holes and properties of black holes. Also the book includes information about Hawking radiation and Schwarzschild radius, which had helped me a lot in understanding what they are. Again it was very reliable because it contains calculations as well as explanations. Also this book was very useful as both theories and properties of black holes were covered as well as other important areas of black holes such as hawking radiations and the theories.

Advanced PHYSICS - Steve Adams, Jonathan Allday, published in 2000
: This book covers the calculations for escape velocity and Schwarzschild radius and was very useful in terms of understanding the question as it clearly shows step by step to calculate them. Although there were no explanations on how these equations were created, I thought it was a reliable source.

Articles

Inside science – NewScientist, Dark destroyers, 19 October 2002
: Although it was fairly brief, there was information on ring singularity and how a black hole's gravity distorts space and time. Also it contains accretion disks, escape velocity and spaghettification theory.

Web Links

Web link 1 – www.wikipedia.com
(This web page was last modified 22nd of September in 2007)
: Size, properties and types of black holes are included as well as the techniques to find black holes and its features with solid explanations on why light cannot possibly escape it. Although this web site provides a lot of information, I wouldn't say it's always reliable as this web site allows anyone to update it therefore some part of it can be debatable or unreliable.

Web link 2 - http://www.bbc.co.uk/science/space/deepspace/blackholes/index.shtml
(Modifiers and modified date not specified)
: A very brief web page that contains types of black holes and how x-rays are given off.

Web link 3 - http://cosmology.berkeley.edu/Education/BHfaq.html
(By Ted Bunn, This web page was last modified September 1995)
: This web page had helped me a lot in understanding the areas of physics and theories associated with it. Although this web page also includes other areas such as the evaporation of black hole, it generally covers a lot of theories.
Web link 4 - http://imagine.gsfc.nasa.gov/docs/science/know_l2/black_holes.html
(By Dr. Jim Lochner, Meredith Gibb & Phil Newman, This web page was last modified 6th of September 2006)
: The ways in finding out black holes from analysing the source given out by the black holes and some areas of physics are covered.
Web link 5 - http://www.virtualsciencefair.org
(Colin Fung)
: An in depth description of black holes. Contains information about what they are, their formation, and their types. Further, the site explains relativity and their connection to black holes.
Web link 6 - http://www.rdrop.com/users/green/school/index.htm
(By Mark O'Brien and John Chang, This web page was last modified 8th of June 1998)
: Information about how they are formed, how we can detect and properties of black holes are explained and described. It has a good explanation on gravity lensing.
Web link 7 - http://www.hawking.org.uk/text/public/warps.html
(Modifiers and modified date not specified)
: Theories in relation to black holes included, especially the hawking radiation theory with particles-antiparticles are explained well.

Appendix

- Ch. 11 Out into space – I've explained about the relationship between the kinetic energy and gravity. Higher kinetic energy is required to minimise the effect of gravity. This connects to calculating the escape velocity of black hole.
- Ch. 12 Our place in the Universe – I've mentioned the red-shift caused by gravitation which is related to the time differences between two observers, one falling into the black hole and the other at a safe distance. Also the black holes gaining some energy from the cosmic background radiation.
- Ch. 17 Probing deep into matter – Particle-antiparticles were mentioned with a possibility of black hole evaporation due to the loss of the gravitational energy by this phenomenon
- Ch. 18 Ionising radiation and risk – The creation of black holes due to the stars not being able to produce helium from hydrogen in order to sustain its atmospheric pressure