Module # 3 – Component # 4

Quasars & Black Holes

Objectives

To understand how Quasars & Black Holes affect the universe.

Expected Outcomes

To be able to

- explain how Quasars and Black Holes are related
- describe a Quasar
- describe a Black Hole
- understand how they are formed
- describe the role of binary stars
- understand how gravity affects everything
- describe an AGN
- describe neutron stars
- explain the role of gravity
- describe how pulsars are formed

Pre – Test

1) **(True / False)** Quasars are far out!

2) **(True / False)** Black Holes cannot be seen.

Gravity

Quasars and Black holes are so **'new'** that the **'stories'** associated with them are **only two centuries old**. In 1874 Rev. John Michell wrote a paper in *Philosophical Transactions* based on Newtonian physics about the gravity of a massive object 600 times the size of the Sun. He hypothesized that "***all light emitted from such a body would be made to return towards it, by its own proper gravity!***" However such a body might betray its presence by the effects its pull would have on a neighbouring object. *"Yet, if any other luminous bodies should happen to revolve about them we might still perhaps from the motions of these revolving bodies infer the existence of the central ones with some degree of probability. This might afford a clue to some of the apparent irregularities of the revolving bodies, which would not be easily explicable on any other hypothesis"*. A decade later Pierre Simon Laplace stated that *"the most massive objects in the universe might be undetectable by their direct radiation, but observed by the effect that they have on material around them".*

Nearly two hundred years passed before astronomers discovered objects (neutron stars and black holes) with gravity as strong as Michell and Laplace hypothesized.

Gravity is a truly universal force and everything in the universe is influenced by its affect. More than three hundred years ago Isaac Newton realised that the same force which made an apple and a canon ball fall to the ground kept the Moon in its orbit around the Earth. The motions of the Sun, planets and other objects in the Solar System are all held together by their mutual gravitational attraction.

Where the gravitational fields are as strong as those conjectured by Michel and Laplace, Newtonian gravity and laws of motion break down. When objects are accelerated to the speed of light Einstein's theories are required to explain their motions. The "Special Theory of Relativity" formulated in 1905 postulated the fundamental relationship between mass and energy popularly known as $E=MC^2$. Just over a decade later his "General Theory" on gravity although less well known to public was a 'quantum leap' in the history of science and mathematics. Einstein proposed that **masses do not exert a gravitational pull but rather distort space within and around them**. The fate of the universe therefore depends on the curvature of space induced by everything in it. Objects moving through space follow the straightest possible path (**space-time**) but when space is 'distorted' their paths are curved and accelerated (known as gravitational lensing). Arthur Eddington observed this effect during a 1919 solar eclipse when the anomalies in Mercury's orbit were revealed by light rays passing close to the Sun, that were deflected by the amount predicted in Einstein's theories.

Neutron Stars

The Sun contains a thousand times more mass than Jupiter. If it were 'cold' gravity would compress it to a million times the density of a solid, and it would be the equivalent of a 'white dwarf' about the same size as Earth but 330 000 times more massive with a gravitational field a million times larger. The Sun however is not cold but extremely hot due to gravitational contraction causing the hydrogen atoms to heat up and fuse together into helium with the resultant emission of heat and light. This results in a temperature of 15 million degrees at the centre, which prevents the Sun from collapsing under its own gravity and keeps it in equilibrium.

Gravity does not always win, and the Sun when it becomes a white dwarf after a 10 billion year life span it will exist for a long time thereafter. **White dwarfs** can remain in gravitational equilibrium almost indefinitely due to **degeneracy pressure.** This is caused by an effect known as the **Pauli exclusion principle** which states that "**two identical particles cannot have the same position and momentum**" and is applicable to atoms and their protons, electrons and neutrons. When most of the 'particle' motion in a gas is the result of this resistance to compression the gas is called **degenerate**. There is however an upper limit to the mass of a white dwarf and in 1930 a young theorist named Subrahmanyan Chandrasekhar realised that a they could not be greater than 1.4 Solar masses, because at higher densities the degeneracy could not balance the gravitational collapse. This is known as the **"Chandrasekhar Limit"** and above this level the atoms would collapse in upon themselves in about one second, causing a massive explosion in the form of a supernova leaving a **neutron star**. In 1930 neutron stars had not been scientifically proven and many eminent scientists denied the theory.

Massive stars are powered towards the end of their lives by a further sequence of nuclear reactions. As hydrogen to helium 'burning' is exhausted helium is fused into carbon, carbon into oxygen etc until they reach the element iron. At this point nuclear reactions cannot release energy from iron, as additional energy is required to fuse the heavier elements. If a massive star has an iron core larger than the Chandrasekhar Limit the core collapses, atoms are broken up and the star releases an amount of energy equal to **10 times the energy that the star emitted during its lifetime within the last second of its life!** The density is now so great that the protons and electrons are fused together to form neutrons which 'normally' only last about 10 minutes but in the super dense state form a neutron star. The degeneracy of the neutron now keeps the star from collapsing further.

As the skeletal remains of a massive star that exhausted it's nuclear fuel and subsequently ejected its outer shell in a supernova explosion, the remaining core, still possessing about a Sun's worth of mass, collapses to a sphere no larger than Albuquerque, about 7 miles in diameter.

One such event created what is known as the 'Crab Nebula' in Taurus the Bull, which was observed by the Chinese in 1054AD, and the remains of this supernova have expanded into the nebula that is observed today.

NASA scientists reported in April 2002 that they have observed a rare thermonuclear explosion on a neutron star that brightened it for so long that they could detect its motion as it moved towards and away from us on its orbit around a companion star. This enabled them to measure the star's orbital velocity using the Doppler effect in the same way a state trooper nabs speeding motorists.

This three-hour "superburst" also revealed the neutron star's spin frequency, confirming two key theories about neutron stars: that they can evolve into faster-spinning pulsars, and that the flickering of X-rays frequently seen in short bursts, called burst oscillations, are a direct measurement of spin frequency.

Scientists at NASA's Goddard Space Flight Center in Greenbelt, Md. noted, "This burst allowed us to do some interstellar police work," said Craig Markwardt of this neutron star, named 4U 1636-53. "Because the burst was so powerful -- a trillion times greater than the total U.S. energy consumption last year -- we could study the neutron star for much longer than usual. Its fast spin, well beyond the speed limit of most neutron stars, is strong evidence that these objects evolve into faster-spinning pulsars."

Neutron stars in "low mass" binary star systems such as the one observed here (where the companion has less mass than the Sun) have been suspected as the sites where slowly spinning neutron stars are spun-up to millisecond spin periods. A neutron star has a powerful gravitational field, and it can accrete gas from its companion. Matter spirals toward the neutron star in the form of an accretion disk, a journey visible in X-ray radiation. In doing so, it transfers its orbital energy to the neutron star, making it spin faster and faster. 4U 1636-53 is now spinning 582 times per second. The theory is that such a neutron star may eventually cannibalise its companion, becoming an isolated millisecond pulsar.

Pulsars

A pulsar is a neutron star that emits steady pulses of radiation with each spin.

Neutron stars are extraordinary objects and a **teaspoonful full weighs a billion tons,** as much as all the cars, trucks and buses on Earth. Its extraordinary density is equivalent to that of the nucleus of an atom with all the typical space between the atoms and their nuclei removed. An atom’s nucleus is composed of positively charged protons and neutrons, particles so small that 100 billion trillion of them would fit on the head of a pin!

In 1968 a young graduate student named Jocelyn Bell at Cambridge University’s Mullard Radio Astronomy Observatory and her thesis advisor Anthony Hewish were surveying the sky with a new radio telescope when they found a source emitting regular pulses of energy every 1.3 seconds. Soon these **pulsating stars** (pulsars) were found in other parts of the sky and the one at the centre of the Crab Nebula flashed ‘on and off’ **30 times a second.**

Anything larger than a neutron star could not pulse or spin at this prodigious rate and the first observational evidence for a star predicted by Chandrasekhar was found. Their discovery also solved the problem of the Crab Nebula’s glow, which is emitted by electrons or positrons moving at close to the speed of light in a magnetic field (**known as synchrotron radiation**). These tiny stars are acting like a particle accelerator continuously generating electrons that produce blue light. The magnetic fields of these strange stars are trillions of times stronger than the Earth’s field (a fridge magnet is between a 100 to a 1000 stronger than the Earth’s field but a billion times weaker than a pulsar is). **However the gravity of a neutron star is about a trillion times that of the earth and its escape velocity would be about half the speed of light.**

Black Holes

From a relativistic point of view a gravitational field is characterized by the ratio of the escape velocity to the speed of light ($E=MC^2$). When the relationship is very small as it is close to the Sun, Newtonian theory will apply, but as it approaches 1.0 General Theory predicts bizarre effects. The ratio near a black hole is close to 1.0 and both the curvature of space and 'relative time' are severely distorted (Time appears to slow down in the presence of the gravity of a large mass). Light emitted close to such a large mass would display a 'gravitational redshift', and a black hole is an extreme mass. Karl Schwarzschild gave the first modern theoretical description of a black hole in 1916, and calculated the distortions of space inside a spherical body of a given mass. He stated that "If the mass of the 'body' remains the same but the radius is reduced to a certain size the body would no longer be visible from the outside". The boundary between the visible and invisible is called the "Event Horizon", and lies at a radius of 3 times M kilometres (where M is the mass of the black hole measured in solar masses). The Sun would therefore become a black hole if it were compressed into a sphere of a radius 3 x 1 (a 6km diameter ball!).

A black hole with the same mass as earth would be only 9mm in diameter.

All of this seemed to be pure theory until Oppenheimer and Snyder in 1939 suggested that the explosion of a massive dying star (supernova) might create a black hole. **Supernova explosions are fairly rare events** that occur only once or twice each century in the Galaxy. Although they are also rare in other galaxies the total number of galaxies is so vast that they should be observable more frequently than twice a century and the supernova in the Large Magellanic Cloud, named 1987A was widely recorded and observed.

Before the development of X-ray astronomy in 1960, the problem with observing black holes was similar to that of finding "a black cat in a coal cellar at midnight". Scientists realised however that a black hole moving through space would absorb matter from the interstellar medium (accretion). Soviet theorist Yakov Zeldovich and American Edwin Salpeter realised that a black hole accreting matter might be 'luminous', when the gases are compressed and heated. They suggested that the best place to look for black holes was close to binary star systems where one star accreted matter from another. The transferred gas would be heated to temperatures of 100 million degrees and would emit X-rays. By the 20th century physicists knew that heated gases radiated in a wide range of wavelengths and that extremely hot gases emit X-ray and even gamma ray radiation. Unlike visible light however X-rays cannot penetrate the Earth's atmosphere.

Other sources were soon found and X-rays from the Crab Nebula were confirmed when 'detectors' were put into satellites, and X-ray astronomy boomed. NASA's small Uhuru X-ray satellite launched in 1970, was a vehicle to test Richard Giacconis experiments. It proved highly successful and located numerous extra galactic X-ray sources, including **active galaxies** and its discovery of the binary sources including SCOX-1 confirmed the theories. Cygnus X-1 is the 1st and still the most likely black hole candidate. The Einstein Satellite launched in 1978 carried the 1st X-ray telescope and extended the observations of these enigmatic objects.

X-ray binary stars also transfer mass from a normal star to a neutron star or black hole by accretion. Mass transfer of stars has been recognised for some time but the 'Algol paradox' was always a problem, until it was realised that accretion could lead to the lesser component becoming more massive than the other. (The so called 'Algol paradox' is when the initial more massive star evolves to a red giant it overflows its Roche Lobes and spills matter onto its originally less massive component, so reversing their roles).

In a massive binary system the mass transfer would be extreme and X-ray binaries can form. As the stars evolve if the more massive star explodes and becomes a supernova the binary system would be destroyed and the stars would fly apart. If however the exploding star is the less massive component the binary remains intact and one component becomes a neutron star or a black hole.

Neutron stars and black holes are gravitational monsters. Infalling matter will release energy equivalent to 10% of their mass, the central object will become unstable and massive flares will be produced to equalize the energy (X-ray bursts). The theories also predict a point or **singularity** inside a black hole where gravity is infinitely strong!

Stephen Hawking realised in 1974 that black holes are not completely black, but radiate with a well-defined temperature. This discovery led to the proposal for **mini black holes**, which are especially interesting as to how gravity links them to the other natural forces. Black holes appear to be the cause of many of the phenomena present in the universe and the central singularity involves the same physics that occurred with the big bang. When black holes are finally 'seen' and their affect understood the origin of the universe may be at hand. A grand unified theory is still the most ambitious aim of many physicists.

Black holes represent the ultimate triumph of gravity over all other forces.

In April 2002 Jon Miller, a doctoral candidate at MIT's Center for Space Research, who led the observation and analysis of a black hole in the Milky Way, made the following announcement:
"As strange as it sounds, it is very likely that black holes spin, and this has consequences for the matter orbiting and falling into a black hole," said Miller. "The fabric of space itself can be dragged along by the spinning black hole, so matter zips around the black hole on something analogous to a moving walkway at an airport."

Scientists have long thought that black holes spin; just like stars and galaxies, yet they have been hard-pressed to find evidence. After all, a black hole is a singularity, a point of infinite density surrounded by a border known as an Event Horizon, from which no light can escape. When a black hole is spinning, matter (usually in the form of extremely hot plasma glowing predominantly in X-rays) can maintain a stable orbit six times more closely than it could around a non-spinning black hole.

One of the most unusual theories emerged in April 2002 from Researchers at the U.S. Department of Energy's Los Alamos National Laboratory and the University of South Carolina when they provided a hypothesis that "black holes" in space are not holes at all, but instead are more akin to bubbles.

The researchers' explanation redefines black holes not as "holes" in space where matter and light inexplicably disappear into another dimension, but rather as spherical voids surrounded by an extremely durable form of matter never before experienced which they have called Gravastars.

The Gravastar explanation for black holes helps provide answers to some of the daunting questions raised by traditional black-hole descriptions. As previously discussed black holes form in space when stars reach the end of their lives and collapse in on themselves. According to black hole theory, the matter from these dying stars occupies a tiny amount of space - a mere pinpoint or singularity - and creates a mind-boggling gravitational field so powerful that nothing can escape, not even light.

The scientists at Los Alamo believe that dying stars collapse to the "Event Horizon" - in essence the point of no return for objects entering the gravitational field of a black hole. At this point, the matter in the dying star transforms to a new state of matter that forms a Gravastar. Although unconventional, the Gravastar explanation for a black hole does solve at least one serious quandary created by black hole theory. Under a black-hole scenario, the amount of entropy created in a black hole would become nearly infinite. Physicists have struggled for years to account for the huge entropy of black holes, and largely have failed. Unlike their black hole counterparts, Gravastars would have very low entropy.

Quasars

The intense concentration of blue light towards the centre of galaxies has been studied for some time. The light was too blue/ultraviolet and hot to come from ordinary stars and galaxies containing these central concentrations are known as AGN's or Active Galactic Nuclei (see M3H4 Galaxies). The most extreme examples of this phenomena are called Quasars (originally from quasi-stellar objects, because they looked like stars at a great distance).

Karl Seyfert recognised a class of galaxy with blue point-like centres that are now called Seyfert Galaxies. Study of a galaxy known as Cygnus A associated a radio source with a faint galaxy more than 300 times further away than the Andromeda Galaxy. The faint optical images of Cygnus A showed what appeared to be two colliding galaxies (See M3H4 galaxies).

Radio studies of Cygnus A reveal two radio lobes with the resultant synchrotron radiation. The source to power this radiation was enormous and according to Geoffrey Burbridge must exceed the complete annihilation of a million solar masses of material! This was the first indication that galactic nuclei can release energy on a vast scale.

The famous radio source 3C 273 was the breakthrough required for the next step of linking black holes to Galactic nuclei. 3C 273 (no 273 in the third Cambridge Catalogue) was a faint star like object shining at 13th magnitude in 1963 when first seen. Maarten Schmidt using the 200-inch Hale telescope produced a spectrum of the object. Nothing seemed to make sense on the resultant spectrum as all the lines were in the wrong place. If however they were assured to be "red shifted" by 15 per cent they would all fit into their correct positions. For an object to be red shifted by that amount according to the Hubble Constant it should be 2 billion light years away but if it was at that distance it would still be equivalent to a very bright galaxy. A new class of objects had been found and many other puzzles fell into place. These objects called quasi-stellar objects or Quasars were 100 times more luminous than an entire galaxy!

"Yet it is possible that some bodies of a nature altogether new and whose discovery may tend in future to disclose the most important secrets in the system of the universe, may be concealed under the appearance of very minute single stars no way distinguishable from others of a less interesting character but by the test of careful and often repeated observations." John Herschel 1820, address to the Royal Astronomical Society.

Quasars are now believed to be the same luminous blue nuclei that Seyfert observed in AGN's. Their appearance as stars is that they outshine the rest of the galaxy of which they form the centre. When the universe was about two billion years old Quasars were more common than now. Research has shown that they reached maximum activity about the time when galaxies were three times closer than they are today.

Pushing further back toward the first generation of objects to form in the Universe, NASA's Chandra X-ray Observatory has in January 2002 observed the three most distant known quasars and found them to be prodigious producers of X-rays. This indicates that the super massive black holes powering them were already in place when the Universe was only about one billion years old.

The three quasars were recently discovered at optical wavelengths by the Sloan Digital Sky Survey and are 13 billion light years from Earth, making them the most distant known quasars. The X-rays Chandra detected were emitted when the Universe was only a billion years old, about 7 percent of the present age of the Universe.

Groups from Penn State University, Ohio State University and the University of Arizona agreed that the masses of the black holes producing the X-rays are huge, given their relative youth. By various estimates, the three quasars each weighed in at between one and 10 billion times the mass of the Sun. By comparison, the black hole at the center of the Milky Way is believed to contain the mass equivalent to only about 3 million Suns.

Standard Galactic Nuclei

The concentration of stars towards the centre of a galaxy is fairly easy to observe on photographs. The nucleus of the Milky Way is observed at visible wavelengths by dust and gas, but observations in the infrared range have revealed up to a **million stars per light year towards the centre**. In the Sun's neighbourhood the concentration is a minute 0.006 per light year and even the extraordinary density at the centre of the globular clusters is still a mere 60 000. Violent collisions between stars are therefore inevitable in galactic nuclei, and are predicted to occur once every

10 000 years in the nucleus of the Milky Way. Sometimes they may collide but become captured by another star and form what is known as a 'tidal capture binary'. If the tides are strong enough the two stars may coalesce into a single more massive star.

Supernova explosions would disrupt galactic centres even further and if the galactic nuclei were condensed and more massive of up to a billion solar masses, collisions would be unavoidable. Radio, infrared X-ray and gamma ray emission would be intense. At the centre of the Milky Way is an intense source known as Sagittarius A star (SAG A*) and for many years astronomers have debated whether it is a black hole of a million solar masses or just a dense concentration of stars. Evidence for black holes in the centre of other galaxies is growing and the link to Quasars is substantial.

One of the more extraordinary recent discoveries is that even normal galaxies appear to be powered by black holes at their centre. The Milky Way contains one, which is equivalent to 3 million Suns and the Andromeda Nebula's black hole is between 30 – 70 million Suns. From the size of the black hole at the centre of the Milky Way the galaxy could never have been a Quasar.

Active Galactic Nuclei

AGN's can be categorized as follows:

1. They can emit enormous amounts of energy – outshining ordinary galaxies by 100 times.

2. They are extremely compact – variations on brightness over short period limit their overall size due to the distance that light can travel in that period.

3. The radiation they emit is unlike that produced by stars or gas – radiation is emitted over a wide range of wavelengths from the radio and infrared to the optical and through the ultraviolet, X-ray and Gamma ray spectrum.

4. They contain gas moving at high speed approaching the speed of light. The jets that are sometimes produced are ejected at enormous speeds.

Due to the enormous energy required to power these objects a black hole is the likely candidate for its source. Astronomers have now measured the red shifts of more than 10 000 quasars.

Massive black holes can generate high luminosity in two different ways, either by accretion or by harnessing their spin energy.

When the aspect of the jets emitted from AGN's is discussed the problem with a black hole being the power source is suspect. Black holes by their very nature absorb surrounding matter, so how can they emit matter especially at such high speeds (some at nearly the speed of light). Centaurus A in the Southern sky has two lobes typical of radio galaxies and these appear to be the ends of two high speed jets emitted from the galactic centre. Further research is still required to connect the jets and the AGN with black holes.

For the past six years, Dr Phil Uttley and Prof. Ian McHardy at the University of Southampton, together with other colleagues, have used NASA's Rossi X-ray Timing Explorer (RXTE) satellite to monitor the X-ray variations of several active galaxies. Their aim is to compare the slow variations in the X-ray output of active galaxies with the much more rapid variations of black hole X-ray binary systems known as BHXRB's. These are black holes that are a million times smaller than the monsters in galaxy centres and feed off gas from normal, 'companion' stars.

It has long been thought that, despite the huge difference in size, the innermost regions of active galaxies and BHXRB's are essentially the same. From a theoretical point of view this makes sense, because those regions are dominated by the black holes' enormous gravity, and do not care about the external environment which feeds them. Whether there is a normal companion star, like in an X-ray binary, or the gas-rich environment in the centre of a galaxy.

Gamma Ray Bursts

Black Holes should not however be confused with probably the most enigmatic of all objects, Gamma Ray bursts. In 1991 when NASA launched the Compton Gamma Ray Observatory everybody was surprised when the 1500 bursts detected came from random directions with no concentration towards the Milky Way. Coupled with their relative brightness's, the isotropic distribution indicates an extra galactic source, or the universe. This hypothesis severely challenges theory however as at cosmological distances the luminosity of each burst is about 10e17 times the Sun or 10 thousand times the rate of a Quasar for a few seconds. The most likely candidates at present are a pair of neutron stars or a neutron star and a black hole in a binary orbit.

Since the 1960s, scientists have used orbiting platforms to measure high-energy radiation (X-rays and gamma rays), finding a range of perplexing cosmic burps, buzzes, and pops. Researchers at the U.S. Department of Energy's Los Alamos National Laboratory now seem to have explained these strange noises by a variety of extreme mechanisms involving strange objects such as neutron stars, black holes, and quasars. The most energetic and powerful of these phenomena are gamma-ray bursts, which typically last less than a minute, and emit a large majority of their energy in the form of high-energy photons called gamma rays.

After recent discoveries of lingering X-ray, optical and radio afterglow emissions from the sites of these bursts, scientists now generally agree that they occur in some of the most distant galaxies known, but how they are produced remains a mystery.

Similarly mysterious are lower- energy X-ray transients that also typically last less than a minute, and have been observed for decades by several different instruments. It has long been hypothesized that these X-ray events and gamma ray bursts are related to the same phenomenon, but only now does evidence support the idea.

These findings lead the researchers to tentatively conclude that X-ray flashes are the low-energy relatives of gamma-ray bursts, created by similar mechanisms. However, because of the small number of flashes, and the weakness of their detected emissions, the preliminary findings need to be confirmed by more observations.

The subject of Black Holes and Quasars is always guaranteed to be controversial, with as many scientists for their existence as against. One thing is certain, if Black holes are not the cause for the bizarre and extreme behaviour of Quasars and AGN's then the objects that power them will be even more extraordinary.