UNIVERSE: FROM ELECTROMAGNETIC TO GRAVITATIONAL SPECTRUM

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By

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Abstract

As the title suggest the "Universe :from Electromagnetic spectrum to Gravitational spectrum", there is a transition from electromagnetic to gravitational wave .It is so in the case of black hole.Earlier the black holes were detected by observing the matter falling into the black hole. As matter falls in, it forms a disk around the black hole that become very hot and release energy in the form of light like X-rays and now there is change after the LIGO event. The gravitational waves produced by collision of binary black hole can locate the position and mass of the black hole. In the first section we have given a brief history that how name black hole came into existence.There were a lot of theories given by different scientists about the existence of Black holes . In the following section the formation is given; how a black hole is formed in nature; what are the mechanisms related to the formation of black hole. The structure is described. The next section is the interesting part of the topic; which is, detection of black hole. For a long time the black hole has been discovered by electromagnetic waves ,by the waves formed by x-ray and accretion disks are formed and hence can be detected in binary. But now after the LIGO event occurred there is a change from electromagnetic wave to gravitational waves which are formed during the merging of two black holes. We have collected the data from different sites for the black holes candidates which have already being discovered by scientist by different satellites like Chandra x ray , Uhuru and many more. A plot of mass and distance of the stellar and intermediate black hole has been drawn to show the distribution.A plot of all the black holes including stellar and intermediate black holes and those detected by LIGO is drawn to locate their position in corresponding to mass.

Chapter 1

INTRODUCTION

1.1 Introduction

Every time we look above the sky we see a large number of dots like structure scattered in random pattern. There is no doubt every one of us had ever thought about the existence or the formation of the universe at least once in our lifetime. Many questions arise what are these structures? How this universe was formed? This mystery about the formation of our universe had let many scientists to explore about the different facts of the universe. Now we know many things about the universe, from Aristotle's argument for the round shape of the earth and Kepler's theory of elliptical orbits to newton's gravitational law.With the time, there came different theories like big bang theory, expanding universe, dark energy and dark matter.As our knowledge of the Universe increased, it was soon realized that our Sun was a also a star, closest to our planet earth. It is close enough to be very bright due to the effect of the inverse square law.

The scientific use of the telescope brought many stars into view for the first time, and astronomers now believe there are some 10^{22} stars in the observable Universe. Stars have a wide range of masses, and their luminosity varies by many orders of magnitude. As stars increase in mass their lifetimes become dramatically shorter. Stars like our Sun live for about 10 Billion years before they exhaust their primary source of fuel, the simplest element, hydrogen. After this occurs they swell up dramatically becoming red giants before losing their outer layers and resembling a planetary nebula. Once the outer layers peel off, the star becomes known as a white dwarf. White dwarfs are still referred to as stars. Stars originally more massive than ab out 6-8 times the mass of the Sun can burn elements more massive than Hydrogen, and ultimately create cores that collapse catastrophically, creating neutron stars or black holes in a supernova explosion. Neutron stars and black holes are frequently referred to as stars, even though they are frequently invisible at optical wavelengths.[1]Thus,we see how the evolution take place in exploring the universe. The most important contribution to this was made by great mathematician,Albert Einstein who with his

good mathematical skills gave the famous theory on the curvature of spacetime known as Einstein's general theory of relativity in 1915. His theory changed the view of many scientists of that time.After his theory many mathematician worked and calculated methods to solve the equation given by him.This was a brief introduction about the universe and stars.But in this report our main focus will be only on the black hole .

1.2 Black Hole

Black holes are one of the most mysterious celestial bodies of the universe. It is the place where gravitational force is so strong that even light cannot escape. For this to happen, according to newton's gravitational theory the escape velocity at the surface of black hole should be greater than velocity of light. Escape velocity is defined as the minimum velocity required by a object to escape from the gravitational field of a body. for a body of mass m and to escape from the gravitational field of mass M , the escape velocity v_{esc} is given by

$$\frac{1}{2}v_{esc}^2 = \frac{GM}{R} \tag{1.1}$$

For a black hole, escape velocity is greater than the speed of light ($3 * 10^8$ m/s)i.e.

$$\frac{2GM}{c^2R} > 1 \tag{1.2}$$

According to Einstein's theory of relativity nothing can travel with the speed larger than the speed of light.Hence nothing can escape the gravitational force of a black hole.[2]If we see any body falling into the black hole it will be stretched out.The closer you go to the black hole the stronger the gravitational force you feel.Clocks run really slow near black holes.[3] Astrophysical black holes are macroscopic bodies with masses ranging from several $M_\odot$ to 10^6 - $10^{9.5}M_\odot$, where $1M_\odot = 1.99 * 10^30$ kg i.e.the mass of the Sun. Each black hole is characterized by just three parameter: mass,spin parameter,and charge.[4]These are the consequences of gravitational collapse.Everything that falls into black hole loses its identity only their mass charge and momentum are matters.[5] Black holes can be classified by their two properties of rotation and charge:

1. Schwarzschild Black Hole, otherwise known as a "static black hole", does not rotate and has no electric charge. It is characterized solely by its mass.

2. Kerr Black Hole is a more realistic scenario. This is a rotating black hole with no electrical charge.

3. Charged Black Hole can be of two types.
   (a) A charged, non-rotating black hole is known as a Reissner-Nordstrom black hole,
   (b) a charged, rotating black hole is called a Kerr-Newman black hole.

There is one more way in which the black hole can be classified i.e. classification on the basis of mass:

1. Stellar Mass Black Holes have masses between about 4 and 15 solar masses and result from the core-collapse of a massive star at the end of its life.
2. Intermediate Mass Black Holes of perhaps a few thousand solar masses may also exist. Sketchy evidence suggests that they may be found in some clusters of stars, and may eventually grow into supermassive black holes.
3. Supermassive Black Holes weigh between $10^6 and 10^9$ solar masses and are found at the centers of most large galaxies.

These are discuss in detail in chapter 4. Under the classical theory of general relativity, once a black hole is created, it will last forever since nothing can escape it. However, if quantum mechanics is also considered, it turns out that all black holes will eventually evaporate as they slowly leak Hawking radiation. This means that the lifetime of a black hole is dependent on its mass, with smaller black holes evaporating faster than larger ones. For example, a black hole of 1 solar mass takes 10^{67} years to evaporate (much longer than the current age of the Universe), while a black hole of only 10^{11} kg will evaporate within 3 billion years.[6] In next section we will describe how black hole came into existence.

1.3 History

Now,in twenty first century ,we have a lot information about the black holes ,their formation , properties and much more.It is believed that black hole was invented in the twentieth century after the Einstein gave his theory on general relativity,but it is not true. It has been there for 200 years.The concept of black hole was just a theoretical concept for decades.John Michell,in 1783 was the first to explain the concept of black hole.He concluded that the stars which were so massive and compact would have so strong gravitational pull that even light cannot escape.[7]Light cannot reach us from them because it will be dragged by its own gravity but one can feel the gravitational force around them. so he called them dark stars.He concluded that there is a relation between size of body and mass of body.If a body is made compact in size but mass remains the same,its escape velocity is increased .for example we know the escape velocity of the earth is 11 km/s, but if the size of earth is squeezed to half the escape velocity will be doubled i.e.22 km/s [8] After thirteen years laplace ,a french scientist

came up with same theory but independent of michell,After this there came the wave nature of light so these ideas were abandoned.[7] In 1915 Albert Einstein came up with his famous theory of general relativity,which predicted that light rays can be bend by gravity. This gave a sufficient proof for the existence of the black hole.Earlier,Einstein himself could not believed that such concept of black hole existed.According to relativity,a star will distort the space-time near it.If a massive star whose nuclear fuel has burnt cools and shrinks below a critical size, it will make a bottomless hole in space-time, that light can't get out of it.[9] This is how the concept of black hole came.thus it produce theoretical basis for black hole. One year later, Einstein had formulated his theory ,Karl Schwarzschild ,studied Einstein's new theory on general relativity and did the exact mathematical calculations for the Einstein's field equations of curvature of space time outside any spherical star which is not rotating.He showed that, for a spherical non-rotating mass that is associated with a particular distance from its center, at which it would collapse into a gravitational singularity, which is called as the Schwarzschild Radius.[10] If all the mass of an object were to be compressed within that sphere such that the escape velocity from the surface of the sphere would equal the speed of light,then the radius to which it is compressed is known as schwarzschild radius. If a star collapse to or below this radius, light can not escape from that star and It will not be visible directly,hence form a BLACK HOLE. The Schwarzschild radius is given by

$$r_s = \frac{2GM}{c^2} \tag{1.3}$$

where G is the gravitational constant, M is the object mass and c is the speed of light. Any object smaller than this radius is black hole. For small masses like human beings schwarzchild radius is of order 10^{-23} cm, for sun it is approximate 3 km. In 1926 Sir Arthur Eddington worked on radiation pressure and showed that internal thermal pressure of a star was necessary to prevent its collapse due to gravity. He explained the so-called Eddington limit of a star as the point where the gravitational force inwards equals the outwards radiation force ,supposing hydro static equilibrium and spherical symmetry.We will explain this in detail later. In 1930 ,an Indian scholar named Subrahmanyan Chandrasekhar did his calculations. At the time, scientists assumed that when fuel of the star is used up, it would become a white dwarf star. Chandrasekhar showed by his mathematics that a white dwarf whose mass is more than one and half times the mass of the sun could not exist, but would undergo a collapse into a small object with infinite density, from which nothing could escape, not even light. It was the first mathematical proof that black holes existed. This limit on the mass of the star below which a star is no more white dwarf is called CHANDRASEKHAR LIMIT.He calculated that a non-rotating body of electron-degenerate whose mass is above 1.44 solar masses (the Chandrasekhar limit) would collapse[11,7] In 1963 , a mathematician Roy Kerr with his calculation showed that massive stars drag the spacetime around them. He gave the exact solution of the Einstein's equation. He represented the untold number of massive black holes that are present in the universe. Finally in 1967 John

Wheeler coined the term BLACK HOLE in a public lecture.[20] John Wheeler uses the words black hole in a public lecture. Unocially,the phrase has been used earlier by others. Black hole uniqueness theorems make people believe that black holes cannot form,because time reversal in variance of Nature's laws would then imply that only perfectly symmetric initial states could collapse gravitationally.

1.4 Formation of Black Hole

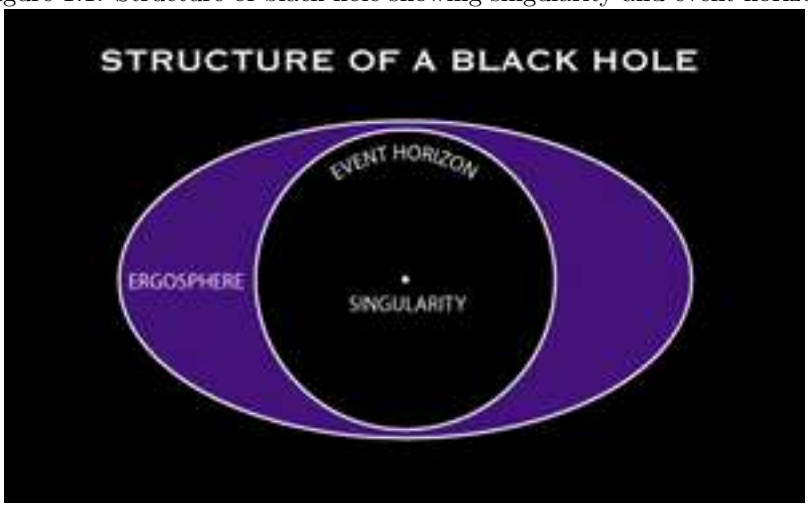
The process of formation of black hole is a little complicated one.We know that the black holes are consequences of the gravitational collapse,so to have better understanding of the formation of black hole we first need to know the life cycle of star. The life cycle of a star is a interplay between contracting force of gravitation and expansion of gases by heating.[12]A star consists of a large amount of gas, mostly hydrogen. Its life cycle begin with the collapsing of this gas itself due to its gravitational attraction. As a result it contracts, the atoms of the gas collide with each other at a more frequent rate and at very high velocities that results in heating up of gas. Finally the gas becomes so hot that when the hydrogen atoms collide they don't bounce off each other but instead merge with each other to form helium atoms. The heat released in this reaction is like a controlled hydrogen bomb.This is the main reason for the shining of the stars. This additional heat produced increases the pressure of the gas which is balanced by the gravitational attraction,hence the equilibrium condition is achieved and the gas stops contracting. The makes the star stable.The radiation from the nuclear reactions are balanced by the gravitational force. Eventually,the hydrogen from star is exhausted and there is no nuclear fuels left.[7] This is because the more massive the star is, the more heat it needs to balance its gravitational attraction. And the hotter the gas is ,there is more loss of radiation, the faster it will use up its fuel. When the fuel is exhausted,it will start to cool off and contraction continues. There are two possibilities now either the star reaches equilibrium against the force of gravity or never reaches equilibrium and gravitational collapse continue. When the star contracts, the matter particles get closer to each other. But,according to the Pauli exclusion principle no two particles can be in same quantum state. This creates a pressure known as electron Fermi pressure which makes the star expand so as to maintain itself at a constant radius by a balance between the attraction of gravity and the repulsion that arises from the exclusion principle,same as earlier in its life the gravity was balanced by the heat radiation. [12] Chandrasekhar calculated that a star of more than about one and a half times the mass of the sun can not support itself against its own gravity. This is known as the Chandrasekhar limit. While, the stars having mass less than this limit come n equilibrium and final state is WHITE DWARF. White dwarf is supported by electron Fermi pressure by exclusive principle. The stars with mass few times the mass of the sun which are not included in white dwarf are supported by neutron or proton Fermi pressure.These kind of stars are called NEUTRON STAR. For the second possibility i.e. The stars which

never reach a equilibrium condition and continue to gravitational collapse leads to BLACK HOLE. these are much massive than the mass of the sun. These can not be supported by degeneracy pressure and collapse to a black hole.

1.5 Structure of Black Hole

Irrespective of masses and sizes of different black holes ,their structures are all similar.[13] A black hole mainly consists of two parts;singularity and event horizon. In theory, any mass can be compressed sufficiently to form a black hole. The only requirement is that its physical size is less than the Schwarzschild radius. Figure 1.1 shows the structure of black hole.

Figure 1.1: Structure of black hole showing singularity and event horizon



1.5.1 Singularity

A singularity is hidden within a black hole at its center.The entire mass of black hole is concentrated at an infinitely small and dense point called a singularity.[13]It is a place where density and gravity become infinite and all the laws of physics start operating.All the physics laws breakdown at singularity. When the matter is compressed to such an extent that no other force of nature can balance it, then singularity is formed in black hole. Spacetime are crushed out of existence there. The escape velocity of the black hole decreases,as we move away from the singularity.Escape velocity is defined as the speed at which an object must move to escape from the gravitational force of some other object. For our planet Earth, the escape velocity is almost 11 km/ sec.At a certain distance from the singularity ,it becomes equal to the speed of light i.e. 3km per second.This distance is known as Schwarzschild radius.It depends on the

mass of object.for example:For a body having mass as Sun, the radius is about 3km. Current theory says that,If we observe an object falling into a black hole and approaching to the singularity at the center, it will seem stretched out due to the increase in gravitational attraction on different parts of it. By relativity theory, If a person view this from outside the black hole,they would see the object moving very slow as it approaches the black hole until it stops at the event horizon, never actually falling into a black hole. The existence of a singularity is assumed as the proof that the general theory of relativity has broken down , which is almost expected as it takes place in conditions where quantum become important.[14]

1.5.2 Event-Horizon

A black hole is bounded by a surface known as the "event horizon",in which we can't see anything.[16]It is a well defined surface from which nothing can escape, because as mentioned above the escape velocity would equal or exceed the speed of light which can not be possible physically. All the matter present inside the event horizon will eventually collapse into a single point,due to gravitational attraction. Hence, the mass of the black hole is then piled into this point,making it singular: the mass density is infinite. The event horizon is like a one-way membrane, where it is not possible to move against the flow or, to look for a different way, within the event horizon. Space itself is falling into the black hole with the speed greater than the speed of light. It is known as the "point of no return" for everything that approaches the black hole. If any object - from a spaceship to a particle of light - crosses the horizon, it cannot get back out. That object is trapped inside the black hole.[15] The mass of the object entering the black hole increases.And as the mass increases, the size of the event horizon also increases, So if you feed a black hole, it becomes fatter!For a non-rotating black hole, the radius of the event horizon is known as the Schwarzschild radius, and marks the point at which the escape velocity from the black hole equals the speed of light. In theory, any mass can be compressed sufficiently to form a black hole. The only requirement is that its physical size is less than the Schwarzschild radius. The rotating black hole is surrounded by a region in which the black hole drags space towards itself, this is called ERGOSPHERE.If the black hole is rotating ,then gravitational effects get more complicated otherwise if the black hole is not rotating,gravitational effects are straight forward.It actually drags the fabric of spacetime along with it and this effect is called frame dragging. [13] Hence,we can imagine the black hole as a singularity, hidden behind an event horizon It is called hidden, because no information about the singularity can pass through the event horizon. The escape velocity around the black hole is given as[1]

1. at event horizon : v_{esc} = c
2. outside event horizon: Escape velocity $v_{esc}$is less than speed of the light i.e. v_{esc} <c.Hence object is able to escape.

3. inside event horizon: escape velocityv_{esc} exceeds the speed of light c i.e.v_{esc} >c and the object is trapped forever.

Chapter 2

Detection

There were a lot of theories about black hole given by various physicist at different time,But they could not find convincing proof that black hole really exist. Everyone has to face criticism for giving some new theory about black hole. The obvious reason was its observance ,as no light could escape ,and invisible to human eye and telescopes.Hence scientist could not confirm their existence. As light can escape from the surface, it becomes almost impossible to observe an black hole. It has not been directly observed by anyone till now,though one can feel the gravitational attraction around them . They cannot be found by the traditional way of observing with telescopes.The scientist began to find indirect ways,in order to detect them.The most important discovery that led to the detection of black holes was the discovery of X RAYS. X rays (cann't be seen with naked eyes) are the part of electromagnetic spectrum.These radiations are very energetic and more penetrating than visible light. It is invisible form of electromagnetic radiation.[17] Out of the four interactions which are known to us gravity and electromagnetic are long range interactions.We know electromagnetic interaction is strong than gravitational interactions ,but large scale structure of the universe cannot be determined by them. As most of the structure are neural or charge is preserved in the galaxies, on the other hand astronomical objects generate a large amount of gravitational fields. A charged particle emits the electromagnetic radiation when it falls into a neutral Schwarzschild black-hole. If angular momentum of fall is zero,Then the electromagnetic radiation emitted by the N number of electron is much larger than the gravitation radiation emitted by the same.It is about one thousand times greater than the gravitational radiation. If the particles are spiraling in circular orbit we get the same energy whether charged particle and uncharged, but the time taken by charged particle is comparatively less. Hence there is new radiation mechanism represented by orbiting or linearly falling into black hole. The time taken for spiral uncharged particles which emit gravitational radiation is found to be more.[18] The most promising ways to detect black holes are: 1. by pulses of gravitational radiation. 2.electromagnetic radiation in the form of x ray and gamma rays.[5]

2.1 Electromagnetic Radiation

The discovery of X rays proved to be the most important for the detection of black holes. These are the invisible form of radiation which are much more penetrating than light.Astronomers can detect the black holes by measuring, radio waves and x-rays which are emitted by the the objects or matter in the accretion disc of a black hole.Else,they can measure the light emitted by the star which is orbiting a black hole,Hence the speed can be calculated through the doppler effect on the wavelength of the radiation emitted.If we know this, then, by the laws of gravity and by determining its mass we can conclude whether the star is really orbiting a black hole or not . With the discovery of x rays astronomer began to explore the universe .They were unaware of the x ray astronomy.The confirmation that the sun produces x rays came in 1948. with the continuous attempts, in 1962 a rocket was launched to moon,it unexpectedly detect a powerful X-ray sources which were beyond the solar system. Later rocket launches confirmed that there exist a source in the constellation Scorpius . It was named as Scorpius X-1, or Sco X-1 . Thus the process continued and one more x ray satellite was launched in december 1970 named Uhuru, and many even more sensitive probes were launched later, proving that there are a lot of x ray sources in the universe. Then, John Gribbin explained about binary star system, that the two objects, one a normal star and the other is a dense star may be be neutron star or black hole, are orbiting each other, held by mutual gravitational embrace. Gas from the large star will move away by tidal effects and get attracted to the small star. The gas spirals down around the small star,and it will form rotating disk of material, providing heat within the disk. The smaller dense star radiates at X-ray wavelengths,as it is surrounded by very hot gas falling from the larger star. A few scientists suspect that another kind of dense object might be the then hypothetical black hole. And finally, one strong X-ray source that was detected in the 1960's proved to be a promising black hole candidate.It was located in the Cygnus Constellation, it was named as Cygnus X-l, or Cyg X-1. Both Sco X-l which was detected earlier and Cyg X-1 are part of a binary star system. But difference was in the case of Sco X-l, we could see the object orbiting the normal star and the Cyg X-1 system does not emit any visible light at all. One more proof that it was black hole was the rate at which the bursts of X rays were coming. It occured at such a high rate approximately thousand bursts per second which confirmed astronomers that the invisible object is infinitely tiny and compact. Another proof why scientists suspected that the Cyg X-1 is a black hole is its mass . The normal star in Cyg X -1 system has mass about thirty solar masses. Astronomers worked on the orbital characteristics and calculated the mass of the invisible companion star, which came out to be nine solar masses, Hence, it is too massive to be a neutron star, which concluded that the Cyg X-1 system consists a stellar black hole. The distance between the black hole and the other star less than the distance of planet Mercury from the Sun. Such extremely close distances for massive bodies permits the black hole's gravity to accrete gases from the outer layers of the companion. As a result of which these gases get spiral in

toward the more denser object, and eventually forming a huge, rapidly spinning and hot accretion disk around the outside of the black hole's event horizon. After a period of time, the gases are pulled towards the horizon, where the black hole's gravity tears the gases atoms apart. This process releases strong bursts of X rays. With the time, the X rays emitted by this process travel outward, gradually reach the Earth and showing scientists the position of the black hole.[17] We will discuss the process of detection of black hole by this process in details in next chapter.

2.2 Gravitational Radiation

We know ,if the charged particles accelerate in the electromagnetic field , they produce the electromagnetic radiation,similarly, masses accelerating in the gravitational field produce gravitational radiation.Hence gravitational radiation are analogous to electromagnetic radiation. The terms gravitational waves and gravitational radiation are interchangeable in the same way electromagnetic radiation and electromagnetic waves are. As gravity is considered as a curvature of Spacetime in General Relativity,the Gravitational Waves are called ripples in the fabric of space and time.Just as a normal wave produces compression and rarefaction ,a gravitational wave stretches and shrinks alternatively as it moves through the space.[19] To emit graviational waves an object must be accelerating relative to another source, and if rotating, the mass distribution must change with time. So , it does not mean objects like perfect spheres that are rotating will emit gravitational waves,on the other hand things like binary stars emits. When a particle spirals into the black hole and move towards lower orbits due to loss of energy,then gravitational radiations are emitted from that particle.During this process,when the loss in energy of particle is such that it reaches the lowest stable orbit,we can capture the particle directly with no further radiation emits.For schwarzschild black hole,lowest stable orbit is very far from center,a very less amount of mass is emit as gravitational radiation. [5] For a long time there was no evidence for the gravitational wave, as it was not detected .But in 2015 LIGO has detected the gravitational waves produced by collisions of a binary black hole system. Laser interferometer observatories have been constructed that have detect the gravitational waves from possible sources like collision of black holes and hence by measurements and calculations we can locate the find the location of the black hole .Gravitational waves help us to understand various processes that occurring in the outer space, for example the collisions of pairs of black holes. The first detection has proved (a) the existence of binary black holes (b) the existence of black holes with masses about 30 solar mass.[21] Figure 2.1 shows gravitational spectrum.how at different frequencies we have different methods to detect black hole . There are two ways by which black holes can be discovered by observing gravitational waves.One is by observing from the space itself ,the space observations are made by LISA and other is done by observing from the Earth by LIGO. A brief description of both is given in next section.

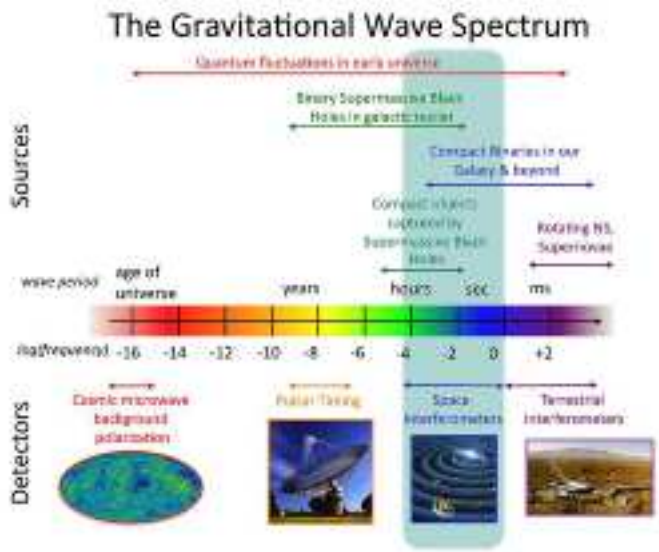


Figure 2.1: Gravitational Spectrum image source:ligo.org

2.2.1 LISA

As we know there are two ways to detect black hole one by observing by the space itself and one direct observation.The space observations are made by LISA. LISA(Laser interferometry space antenna) observations investigate the black holes over a large range of redshift. LISA discovered the black hole that seeds out to redshifts of order 20, and determine their masses and spins,by gravity alone. LISA studies the evolution of the black holes by tracking their merging history during dawn and high noon. For this to happen, it is important to effectively measure their characteristics like mass, spin and redshift over a wide range. The black holes lying between the range of mass $10^4 M_\odot$ and $10^7 M_\odot$ (from Intermediate to supermassive black holes) are detected by LISA. The Gravitational Universe will make it possible to survey the large number of all massive black hole binaries throughout the universe. This expose an large unseen population of bodies which potentially carry valuable information about the black hole population as a whole. It surveys the sky deeply and widely .As the nature of the gravitational wave detectors do not depend on particular direction,the wide range of black hole red shifts and masses is explored which is complementary to the space explored by electromagnetic observations. Even the black holes which are not active,can be detected by LISA. Due to its unbiased and thorough survey, it is possible to find the link that connects the growing seed and rich population of active supermassive black holes. Only the gravitational wave observations are able to distinguish between the different massive Black hole formation and evolution scenarios.[22]

2.2.2 LIGO

LIGO, Laser Interferometer gravitational wave observatory is the world's largest observatory for gravitational wave detection .The physical properties of light and of space itself are used to detect gravitational waves .This concept was first proposed in the early 1960's and the 1970's. The first unsuccessful attempts to detect gravitational waves in the 1960s tried to measure how they make aluminum cylinders ring like a very soft bell. There are a lot of interferometers which were completed by the early 2000s. These include TAMA300 in Japan, LIGO in the United States ,GEO600 in Germany, and Virgo in Italy. these detectors in combinations made observations between 2002 and 2011, but could not detect any gravitational wave sources. So, in 2015 the LIGO detectors upgraded and began to operate as Advanced LIGO.It is the first most sensitive global network of advanced detectors. This interferometer consists of two "arms" which are4km long suspended at right angles to each other, within which a laser beam is lit and is reflected by mirrors at each end. As a gravitational wave passes by alternative stretching and squashing of space, the arms of the interferometer also began to lengthen and shrink alternatively, one become longer while the other shorter and then vice-versa. Due to change in the arm length of the interferometers, the time taken by laser beams to travel through the arms is different which implies that the two beams are out of phase with each other.Hence the pattern produce by this is known as interference This is the reason these detectors are called interferometer. The difference in the length of both the arms is in proportion to the strength of the gravitational wave that is passing by the space.this is known as the gravitational-wave strain, and this is quite small number. For a typical gravitational wave which we detect,the expected strain is about 1/10,000th the width of a proton! Therefore the LIGO's interferometers are made so sensitive that even a extremely small amount can be measured. For successful detection of a gravitational wave event the LIGO detectors should be very sensitive and must have the ability to isolate real signals from instrument noises like small disturbances, environmental effects or by the instruments themselves. To achieve a greater sensitivity there is need of upgradation of almost every aspect of the Initial LIGO design. These upgrades includes:

1. increasing the power of the laser beam ,which reduces the high frequency noise.

2. The test masses used should be large and heavier and silica fused, so that the mirrors must not move.

3. The test masses to be suspended should be fused silica fibers,this reduces the thermal noise.

4. The test masses which are to suspend must be a four-stage pendulum,so that their isolation is improved. [21]

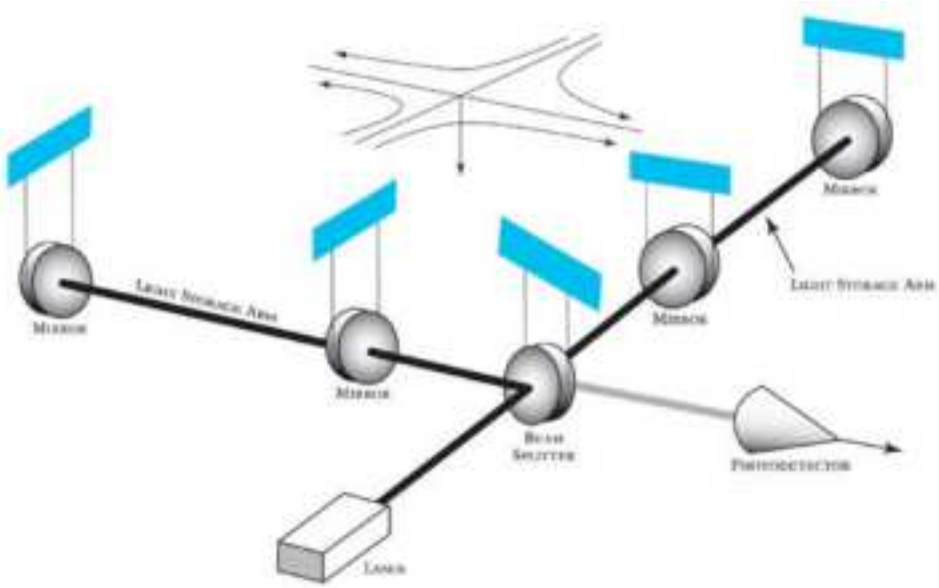


Figure 2.2: Working of LIGO image source: www.ligo.org

Working of LIGO

Figure 2.2 shows how the ligo works. Here is the basic set-up: It includes two mirrors, a photo detector, a light source (LASER)and a beam splitter: Light is sent into the detector from the (laser) light source to the beam splitter which, true to its name, sends half of the light on to the mirror1 and the other half through to the mirror2. At Mirror1 and Mirror2, respectively, the light is reflected back to the beam splitter. There, the light arriving from Mirror1 (or Mirror2) is split again, with half going towards the photodetector , the other half back in the direction of the light source(LASER). We will ignore the latter half and pretend, for the sake of our simplified explanation, that all the light reaching B from Mirror1 or Mirror2 goes on to the light detector . This setup, by the way, is called a Michelson Interferometer. We will see below why it is a good setup for gravitational wave detectors. We will assume that the mirrors and the beam splitter, shown as being suspended, react to the gravitational wave in the same way freely floating particles would react. The key effects are between the mirrors and the beam splitter in what are called the two arms of the detector. Arm length is 4 kilometer in advanced LIGO detectors. In comparison, light source and light detector are very close to the beamsplitter; changes of the distances between these three do not signify. The light source(LASER) emit light pulses. The light goes into the horizontal and the vertical arm, respectively. In reality, there is no distinction, just light apportioned at the beamsplitter. Light running towards Mirror1 will be offset a little to the left, light coming back from Mirror1 to the right. Same goes for Mirror2. When a gravitational wave passes through

the interferometer, the spacetime in the local area is altered. Depending on the source of the wave and its polarization, this results in an effective change in length of one or both of the cavities. The effective length change between the beams will cause the light currently in the cavity to become very slightly out of phase (antiphase) with the incoming light. The cavity will therefore periodically get very slightly out of coherence and the beams, which are tuned to destructively interfere at the detector, will have a very slight periodically varying detuning. This results in a measurable signal. After an equivalent of approximately 280 trips down the 4 km length to the far mirrors and back again, the two separate beams leave the arms and recombine at the beam splitter. The beams returning from two arms are kept out of phase so that when the arms are both in coherence and interference (as when there is no gravitational wave passing through), their light waves subtract, and no light should arrive at the photodiode. When a gravitational wave passes through the interferometer, the distances along the arms of the interferometer are shortened and lengthened, causing the beams to become slightly less out of antiphase. This results in the beams coming in phase, creating a resonance, hence, some light arrives at the photodiode, indicating a signal. Light that does not contain a signal is returned to the interferometer using a power recycling mirror, thus increasing the power of the light in the arms. These signals are then simulated by the computers.[23] Till now two black holes candidates have been detected by this advanced LIGO.

1. On 11 February 2016, the LIGO and Virgo collaborations announced the first observation of gravitational waves. The signal was named GW150914.The waveform showed up on 14 September 2015, within just two days of when the Advanced LIGO detectors started collecting data after their upgrade.It matched the predictions of general relativity for the inward spiral and merger of a pair of black holes and subsequent 'ringdown' of the resulting single black hole. The observations demonstrated the existence of binary stellar-mass black hole systems and the first observation of a binary black hole merger.The black hole merger has mass 62 solar mass and was formed by two black holes of masses 36 and 29 solar masses at a distance of 1.3 billion light years.

2. On 15 June 2016, LIGO announced the detection of a second gravitational wave event, recorded on 26 December 2015, at 3:38 UTC. Analysis of the observed signal indicated that the event was caused by the merger of two black holes with masses of 14.2 and 7.5 solar masses, at a distance of 1.4 billion light years.The mass of resultant black hole was 20.8 solar mass. The signal was named GW151226.[21]

2.3 Gravitational Redshift

In astrophysics, gravitational redshift or Einstein shift is the process by which electromagnetic radiation originating from a source that is in a gravitational field is reduced in frequency, or redshifted, when observed in a region at a higher

gravitational potential. This is a direct result of gravitational time dilation (if one is outside of an isolated gravitational source, the rate at which time passes increases as one moves away from that source). As frequency is inverse of time (specifically, time required for completing one wave oscillation), frequency of the electromagnetic radiation is reduced in an area of higher gravitational potential. There is a corresponding reduction in energy when electromagnetic radiation is red-shifted due to the electromagnetic radiation propagating in opposition to the gravitational gradient. There also exists a corresponding blueshift when electromagnetic radiation propagates from an area of higher gravitational potential to an area of lower gravitational potential.[24] Einsteins theory of general relativity predicts that the wavelength of electromagnetic radiation will lengthen as it climbs out of a gravitational well. Photons must expend energy to escape, but at the same time must always travel at the speed of light, so this energy must be lost through a change of frequency rather than a change in speed. If the energy of the photon decreases, the frequency also decreases. This corresponds to an increase in the wavelength of the photon, or a shift to the red end of the electromagnetic spectrum hence the name is: gravitational redshift. This effect was confirmed in laboratory experiments conducted in the 1960s. The converse is also true. The observed wavelength of a photon falling into a gravitational well will be shortened, or gravitationally blueshifted, as it gains energy. As an example, take the white dwarf star Sirius B, with a gravitational field 100,000 times as strong as the Earths. Although it sounds extreme, this is still considered a relatively weak field, and the gravitational redshift can be approximated by:

$$z = \frac{GM}{rc^2} \tag{2.1}$$

where z is the gravitational redshift, G is Newtons gravitational constant, M is the mass of the object, r is the photons starting distance from M, and c is the speed of light. In this case, the gravitational redshift suffered by a photon emitted from the stars surface is a tiny 3 10^{-4}. In other words, wavelengths are shifted by less than one part in 30,000.[25] For radiation emitted in a strong gravitational field, such as from the surface of a neutron star or close to the event horizon of a black hole, the gravitational redshift can be very large and is given by:

$$1+ z = \frac{1}{\sqrt{1-\frac{2GM}{rc^2}}} \tag{2.2}$$

Chapter 3

X -ray Binaries

X-ray binaries are defined as short-period (lasting from hours to days) interacting binaries which contains two stars orbiting each other. In these binaries one component is an normal star and other is compact star which can be either white dwarf or neutron star or black hole. Usually the compact star is more denser. The normal star transfers material onto its compact companion .This transfer of material take place in the form of ACCRETION DISK around the compact star. The strong gravitational field allows the matter to spiral,and eventually falling onto the surface of companion star[26].Two third of the star population is a member of these binary system. These are formed when a massive star dies i.e. the fuel is exhausted and it collapse under the gravitational force and produce a supernova explosion.The remnant of this explosion is the compact star.The material that orbits around the disk lose energy in many dissipation processes.The inner regions of the disk get hotter and hotter by the energy released during these processes, The temperature get high to such extent that it produce X rays, converting gravitational potential energy of the matter to X ray luminosity.[12] The X-ray luminosities which are generated in this accretion process are very high greater than $10^3$8erg s^1,which infers that it can not be a white dwarf. One more factor which determines the nature of compact star is mass.It is possible to calculate mass,by simple application of Keplers laws. [26] If the mass is greater than one and half time the mass of the sun then it can not be white dwarf. If mass is more than 3 times the mass of the sun ,it is no longer neutron star. These x-ray binaries can be observe by x-ray telescopes which orbits around the earth. These can be classified into two categories on the basis of the mass of the losing star.

1. HIGH MASS X-RAY BINARIES(HMXB): If the mass of the losing star i.e. normal star is greater than the mass of compact companion .The binary is referred to as high mass x-ray binary.

2. LOW MASS X-RAY BINARIES(LMXB): If the mass of the losing star i.e. normal star is less than the mass of compact companion .The binary is referred to as high mass x-ray binary.

There are two approaches which can be used to study these binaries. The first include the study of the physical state of objects . In this we make the use of the observations or physical methods to determine the physical processes so as to characterize the observed objects,for example mass orbital periods of stars and binaries, the properties of accretion disk and white dwarfs and properties of stars such as their mass-loss rate. In the second includes the study of the formation and evolution of these objects.In this approach we take the results of the previous approach as a initial point which help us to understand the further evolution and formation of these stars in the binaries and This approach is very successful in the explanation of the formation of different objects, e.g. X-ray binaries , double neutron stars and double white dwarfs .

3.1 Accretion

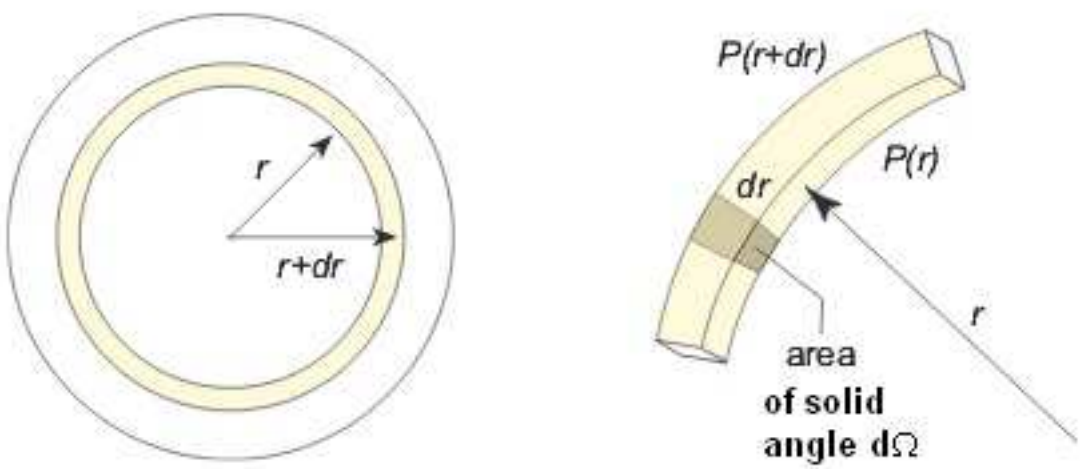
As mentioned earlier, when the fuel of the star is exhausted ,there are two possibilities neutron star and black hole. The outer region of these is described by Schwarzschild geometry. To explore this geometry we need to observe the motion of matter .The matter present close to them i. e. from companion star can fall onto these compact objects. Thus creating a binary pair, which loses orbital energy by radiations formed due to gravity. As there are two star in a binary the secondary star orbits the compact object and when the gas comes off the star, it, also orbits the compact object. There is friction created and particles rub against each other and a lot of heat radiations are produced. Hence the size of orbit began to decrease and it decreases to such an extent that companion star get attracted to the compact star. The gravitational force of compact star is so strong that it attracts matter from the companion star. The gravitational energy is converted to radiation by accretion. The matter which is falling has some angular momentum and due to this conservation of angular momentum matter is prevented from falling directly. Hence a disk is formed around the star known as ACCRETION DISK.[12,31] There will be heating of the gas and energy will dissipate. Hence due to conservation of angular momentum particles slow down and eventually spirals the compact star creating a disk around the surface of star. The disc expands much more than the initial radius and angular momentum is carried further to the edge. The matter spirals inwards in circular motion till it reaches the inner most orbit. The distance between the black hole and the other normal star very less. Such close distances for massive bodies permits the black hole's gravity to accrete gases from the outer layers of the companion. As a result of which these gases get spiral in toward the more denser object, and eventually forming a huge, rapidly spinning and hot accretion disk around the outside of the black hole's event horizon. After a period of time, the gases are pulled towards the horizon, where the black hole's gravity tears the gases atoms apart. This process releases strong bursts of x - rays. With the time, the x - rays emitted by this process travel outward, gradually reach the Earth and showing scientists the position of the black hole. By neglecting the energy transferred by viscosity, the rate can calculated at which accreting

is done. There must be loss of gravitational potential energy .[27]

3.2 Hydrostatic Equilibrium

For the majority of the life of a star, the gravitational force (due to the mass of the star) and the gas pressure (due to energy generation in the core of the star) balance, and the star is said to be in hydrostatic equilibrium. This balance is finely-tuned and self-regulating i.e. if the rate of energy generation in the core slows down, gravity wins out over pressure and the star begins to contract. This contraction increases the temperature and pressure of the stellar interior, which leads to higher energy generation rates and a return to equilibrium. Hence equilibrium is maintained.[28] Suppose in a spherically symmetric system with

Figure 3.1: Spherically symmetric star with density ρ and shell of thickness dr



density ,star is in quasistatic equilibrium.Consider a shell of thickness dr at radius r inside a star .Mass of shell is,

$$M(\mathbf{r}) = \int_0^r \rho 4\pi r^2 dr \tag{3.1}$$

Acceleration due to gravity on shell,

$$\text{g} = -\frac{GM(\mathbf{r})}{r^2}$$

$$(3.2)$$

Now,force acting on small element with area dA and thickness dr due to gravity,

$$F_g = \rho(\mathbf{r})dAdr \times g \tag{3.3}$$

$$F_g = - \frac{GM(\mathbf{r})\rho(\mathbf{r})dAdr}{r^2} \tag{3.4}$$

This pressure is applying in all dimensions ,but star is not collapsing under gravity,there is inside pressure which is holding star . This is due to pressure gradient.The force per unit area resulting from pressure difference between r and r+dr is

$$\mathrm{P}(\mathbf{r}) - \mathrm{P}(\mathbf{r+dr}) = \frac{\partial P}{\partial r}\ \mathrm{dr} \tag{3.5}$$

$$F_p = \mathrm{P}(\mathbf{r}) - \mathrm{P}(\mathbf{r+dr}) = - \frac{\partial P}{\partial r}\ \mathrm{dr} \tag{3.6}$$

Total force acting on unit surface area is

$$\mathrm{F} = F_g + F_p = - \underbrace{\frac{\partial P}{\partial r}dr}_{PressureGradient} - \underbrace{\frac{GM(\mathbf{r})\rho(\mathbf{r})dr}{r^2}}_{Gravity} \tag{3.7}$$

We know by newton's second law

$$\mathrm{F} = \mathrm{ma} = \underbrace{\rho dr}_{mass} \cdot \underbrace{\frac{\partial^2 r}{\partial t^2}}_{acceleration} \tag{3.8}$$

hence by comparing equation 3.7 and 3.8 we get

$$\rho \frac{\partial^2 r}{\partial t^2} = -\frac{\partial P}{\partial r} - \frac{GM(\mathbf{r})\rho(\mathbf{r})}{r^2} \tag{3.9}$$

According to hydrostatic equilibrium ,net force must be vanish. hence our equation reduced to

$$-\frac{\partial P}{\partial r} = \frac{GM(\mathbf{r})\rho(\mathbf{r})}{r^2} \tag{3.10}$$

Hence equation 3.10 gives thermostatic equilibrium.In this the pressure gradient produced by fusion and internal heat is exactly balance by gravitational forces.[29]

3.3 Eddingtton Limit

The Radiation emitting from the disk carries a radiation pressure. This pressure is exerted on the accreting matter.Gradually the radiation pressure become so high that even graviational pull cease and accretion stops.This radiation pressure force is proportional to luminosity.When this radiation pressure exceeds the gravity force the luminosity increases proportionally. The luminosity at which pressure exceeds the force of gravity is known as eddington luminosity.[27,31] Here we are going to derive the eddignton limit for the accretion.Consider a source of radiation . The mass of the object is m. Let us consider the accretion be on any small accreting element with mass dm is acted upon by two forces gravitational potential forece and radiation pressure. Gravitational potential force (F_g)

$$F_g = -\frac{GMdm}{r^2} \tag{3.11}$$

For a charged particle q and photon energy E ,force is directly proportional to number of charged particles, force per unit particle.

1. mass o the particle :

$$\text{dm} = m_p\ n_e\ .\text{dv} \tag{3.12}$$

2. Rate at which momentum is transferred,

$$\frac{dp}{dt} = \frac{1}{c}.\frac{dE}{dt} \tag{3.13}$$

3. Number of photons coming per unit time per unit area. Rate of energy is

$$\text{dn} = \frac{L}{4\pi r^2} \tag{3.14}$$

But this is effectively interacting with particle .So,energy absorbed per unit particle per unit time is given as

$$\frac{L\sigma_T}{4\pi r^2} \tag{3.15}$$

where σ_T is Thomson cross sectional area; Hence force imparted per particle

$$\text{f} = \frac{L\sigma_T}{4\pi r^2 c} \tag{3.16}$$

Radiation pressure (F_{rad}) is given as[30]

$$F_{rad} = \frac{2n_e dv \times L\sigma_T}{(4\pi r^2 c}$$

$$F_{rad} = \frac{L\sigma_T dm}{2\pi r^2 c m_p} \tag{3.17}$$

For accretion to occur $F_{rad} < F_g$

$$\frac{L\sigma_T dm}{2\pi r^2 c m_p} < \frac{GMdm}{r^2}$$

$$\text{L} < \frac{2\pi M m_p c}{\sigma_T} = L_{edd} \tag{3.18}$$

The limiting luminosity at which accretion occur is: $L_{Edd} = \frac{4\pi GMm_p c}{\sigma_T}$ =1.310^{47} erg/s, Since

$$\frac{2\pi cGM \times m_p}{\sigma_T} > \frac{GM\dot{\mathbf{M}}}{r^2}$$

$$\dot{\mathbf{M}} < \frac{2\pi c r_s \times m_p}{\sigma_T} \tag{3.19}$$

Where $\dot{\mathbf{M}}$ is called eddington rate,r_s is swarchzchild X-ray binaries typically have luminosity $L<<10^{38}$erg/s For low mass x ray binary (LMXRB):There is a flat distribution and maximum luminosity allowed is $10^{38} - 10^{39}$erg/s. For high mass x ray bianry (HMXRB): There is power law distribution and maximum luminosity allowed is:10^{40}erg/s[27]

3.4 Chandrashekhar Limit

Astronomers have found that if black holes represent a minimal amount of mass then only it can be formed from normal stellar objects. There is the limit on the mass , i.e. below this limit a star can not be a black hole. It is black hole as long as its mass is above some certain value. This limit is known as Chandrasekhar limit .The Chandrasekhar limit refers to the largest amount of mass one can make of a substance where only electron pressure resists the gravitational attraction. This limit given by chandrashekhar is about 1.44 solar masses.

Chapter 4

TYPES OF BLACK HOLES

Till now in this report we know history of black holes describing how it came into existence , its formation when the fuel of the star is exhausted, its structure which include event horizon and singularity. In this chapter we will discuss about the classification of black holes. On the basis of mass i.e. how massive a black hole is, these are classified into three categories. 1.Stellar black holes ; 2.intermediate black holes ; 3.supermassive black holes .

4.1 STELLAR BLACK HOLES

These are the smallest black holes which have been discovered. These black holes have masses a FEW times the mass of the Sun. Our galaxy milky way consists of million stellar black hole. Stellar black holes, with masses less than about 100 times that of the Sun, comprise one of the possible evolutionary endpoints of high mass stars. Once the core of the star has completely burned to iron, energy production stops and the core rapidly collapses resulting in a supernova explosion. If the core is greater than about 2-3 solar masses (the maximum mass of a neutron star), the pressure of neutrons is unable to stop the collapse and a stellar black hole is formed. These black holes are generally modelled as Kerr black holes, as it is expected that the original rotation of the massive star would be conserved during the collapse, and that black holes contain little electric charge. Since radiation cannot escape the extreme gravitational pull of a black hole once it crosses the event horizon, it is very difficult to discover one in isolation. Stellar black holes are therefore most easily found in X-ray binary systems, where gas from a companion star is being pulled into the black hole. X-rays are produced by this gas which is heated to tens of millions of Kelvin as it spirals towards the black hole via an accretion disk. Astronomers can also measure the mass of the black hole (typically between 3 and 20 solar masses for a stellar black hole) by observing its gravitational effect on the companion star.

There are currently around 20 X-ray binary systems that are thought to contain stellar black holes, though this number continues to climb as the sensitivity of instruments improves and more observations are made. The first black hole discovered was cygnus X-1. It was discovered in 1971 when a satellite called UHURU X ray satellite was launched. The mass of the 15 times the mass of the sun.[32] Table 4.1 shows list of stellar black holes candidates with their masses and distance from us and the constellation in which they are present.[33,34]

Sno.	Name	Distance(kiloparsec)	Mass(solar mass)	Constellation
1	4U1543-47	7.665	9	Lupus
2	GRO J0422+32	2.483	7	Perseus
3	GRS 1009-45	3.985	$8-9$	Vela
4	GS2000+25	2.698	$5-10$	Vulpecula
5	GU Muscae	5.058	7	Musca
6	IGRJ17497-2821	8.278	10	Sagittarius
7	GX339-4	8.278	$5.8-10$	Ara,the alter
8	H1705-25	8.278	$5-7$	Ophiuchus
9	MAXI J1659-152	8.584	$3-10$	Ophiuchus
10	XTE J1118+480	1.839	7	Ursa Major
11	XTE J1650-500	7.971	3.8	Ara
12	XTE J1859-226	$4.599-15.330$	5.4	Vulpecula
13	Cygnus X-1	$1.839-3.066$	15	cygnus
14	A0620-00	$0.858-1.042$	$3-13$	Monoceros
15	GROJ1655-40	$1.839-3.066$	7	SCORPIUS
16	LMC X-1	50.589	10.9	DORADO
17	LMC X-3	50.589	$5-13$	DORADO
18	XTEJ1550-564	5.212	$10-15$	Ara
19	v404 cygni	2.391	$10-15$	cygnus
20	V4641Sagittarii	$7.358-12.264$	$3-10$	sagittarius
21	GRS1915+105	2.483	14	Aquila

Table 4.1: List of Stellar Black Hole

4.2 INTERMEDIATE BLACK HOLES

These black holes are thousand times as massive as the Sun. Only few candidates are discovered for this category. These are the link between the stellar and supermassive black holes. Some of the black hole candidates are shown in table 4.2.One of the candidates is M15 with mass 1500-3000 times of the mass of the sun.[33] There is intense interest as to whether globular clusters contain black holes and, even more basic, whether intermediate-mass black holes even exist at all. Intermediate mass black holes play a critical role in understanding the evolutionary connection between stellar mass and supermassive black holes. However, to date the existence of these species of black holes remains ambiguous

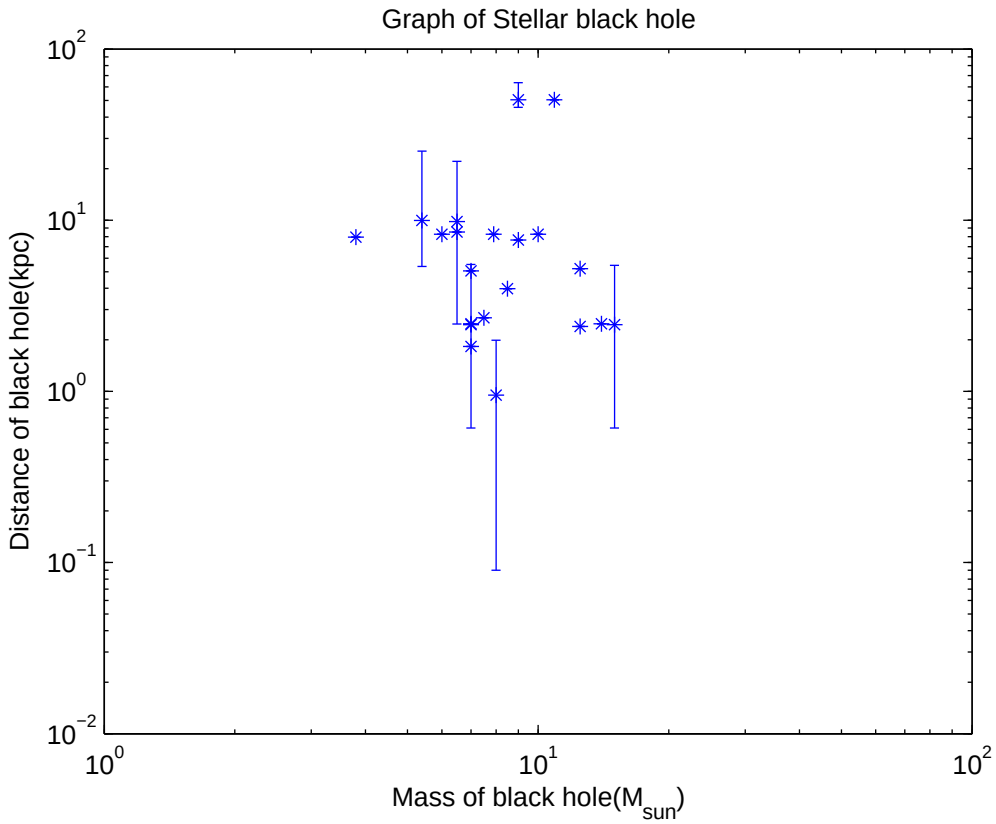


Figure 4.1: Graph of stellar black hole

and their formation process is therefore unknown. It has been long suspected that black holes with masses $10^2 - 10^4 M_\odot$should form and reside in dense stellar systems. Therefore, dedicated observational campaigns have targeted globular cluster for many decades searching for signatures of these elusive objects. All candidates found in these targeted searches appear radio dim and do not have the X-ray to radio flux ratio predicted by the fundamental plane for accreting black holes. Based on the lack of an electromagnetic counterpart upper limits of $2060 M_\odot and 470 M_\odot$ have been placed on the mass of a putative black hole in 47 Tucanae (NGC 104) from radio and X-ray observations respectively. When the dynamical state of the globular cluster is probed with pulsars. The existence of an intermediate mass black hole in the center of one of the densest clusters with no detectable electromagnetic counterpart suggests that the black hole is not accreting at a sufficient rate and therefore contrary to expectations is gas starved.This intermediate mass black hole might be a member of electromagnetically invisible population of black holes that are the elusive seeds leading to

the formation of supermassive black holes in galaxies. Some ultra-luminous X ray sources (ULXs) in nearby galaxies are suspected to be IMBHs, with masses of a hundred to a thousand solar masses. The ULXs are observed in star-forming regions (e.g., in starburst galaxy M82), and are seemingly associated with young star clusters which are also observed in these regions. However, only a dynamical mass measurement from the analysis of the optical spectrum of the companion star can unveil the presence of an IMBH as the compact accretor of the ULX. A few globular clusters have been claimed to contain IMBHs, based on measurements of the velocities of stars near their centers; the figure shows one candidate object. However none of the claimed detections has stood up to scrutiny. For instance, the data for M31 G1, the object shown in the figure, can be fit equally well without a massive central object.Additional evidence for the existence of IMBHs can be obtained from observation of gravitational radiation, emitted from a binary containing an IMBH and a compact remnant or another IMBH.[35] Table 4.2 shows list of some intermediate black holes with their mass and distances along with constellation in which they are present.Figure 4.2 shows how different intermediate black hole candidates which have been discovered are situated which are discussed in table 4.2

Sno.	Name	Distance(Megaparsec)	Mass(solar mass)*1000	constellation
1	M82X-1	3.37	1	Ursa Major
2	M15	0.010	$1.5 - 3$	Pegasus
3	M74	9.81	10	Pisces
4	G1	0.705	$14 - 23$	Andromeda galaxy(M31)
5	ESO243-49HLX-1	88.91	20	Phoenix
6	Omega Centauri	0.0052	40	Centaurus

Table 4.2: list of Intermediate black holes

4.3 SUPERMASSIVE BLACK HOLES

These black holes are much more massive than the intermediate black holes. These are found at the center of the galaxy. These are million times to billion times the mass of the sun. As the name suggests, supermassive black holes contain between a million and a billion times more mass than a typical stellar black hole. Although there are only a handful of confirmed supermassive black holes (most are too far away to be observed), they are thought to exist at the center of most large galaxies, including the centre of our own galaxy, the Milky Way. For many years, astronomers had only indirect evidence for supermassive black holes, the most compelling of which was the existence of quasars in remote active galaxies. Observations of the energy output and variability timescales of quasars revealed that they radiate over a trillion times as much energy as our Sun from a region about the size of the Solar System. The only mechanism capable

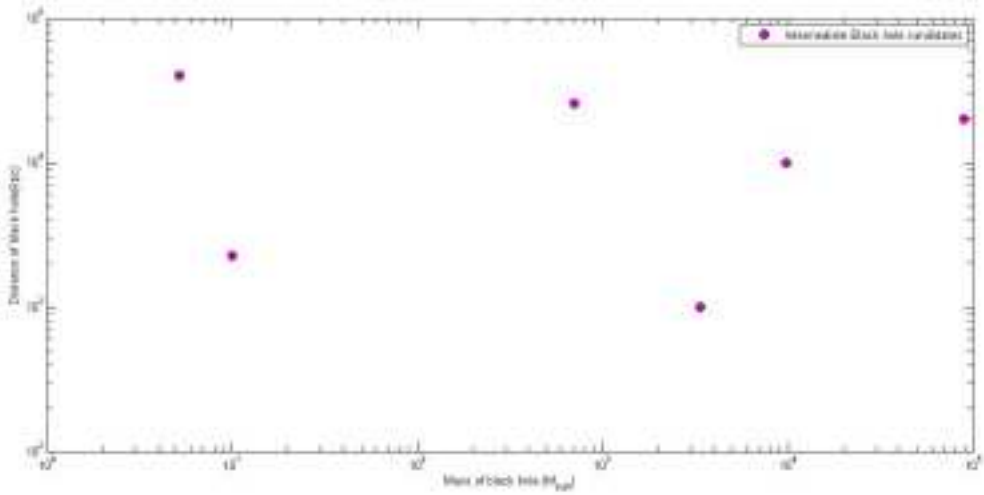


Figure 4.2: Intermediate black hole candidates

of producing such enormous amounts of energy is the conversion of gravitational energy into light by a massive black hole.[32] More recently, direct evidence for the existence of supermassive black holes has come from observations of material orbiting the centres of galaxies. The high orbital velocities of these stars and gas are easily explained if they are being accelerated by a massive object with a strong gravitational field that is contained within a small region of space i.e. a supermassive black hole. Astronomers are still not sure how these supermassive black holes form. Stellar black holes result from the collapse of massive stars, and some have suggested that supermassive black holes form out of the collapse of massive clouds of gas during the early stages of the formation of the galaxy. Another idea is that a stellar black hole consumes enormous amounts of material over millions of years, growing to supermassive black hole proportions. Yet another, is that a cluster of stellar black holes form and eventually merge into a supermassive black hole.

4.4 Results and Discussions

We have prepared a list of stellar and intermediate black holes which have been discovered and their masses and distances have been calculated .These all have been plotted in a single graph showed in the figure 4.3. In table 4.1 there is a list of 21 stellar black holes which have been discovered in x ray binaries by different observatories. As indicated in Table 4.1,all of the 18 Xray novae are lowmass Xray binaries (LMXBs), which typically contain a secondary with a mass of roughly $1M_{\odot}$ or less .The Black hole binaries $4U154347$ and V4641 have relatively massive secondaries:$2.7 \pm 1.0M_{\odot}$ and$2.9 \pm 0.2M_{\odot}$, respectively

. We classify them as LMXBs because their secondary masses are comparable to the mass of the secondary of Her X1 ($2.3 \pm 0.3 M_{\odot}$) which is a wellknown LMXB[34].A brief description of how these candidates were formed(accretion around the black hole) and discovered is given in next section.

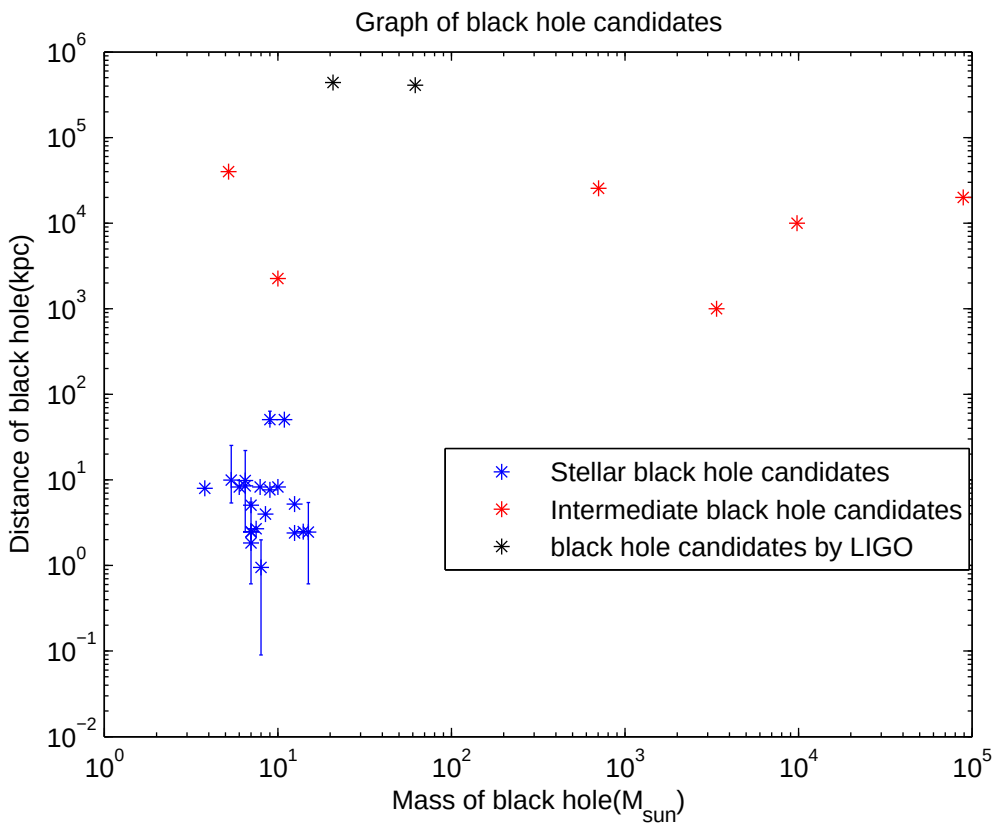


Figure 4.3: Graph of black hole candidates

4.5 Conclusion

The black holes are the consequence of a gravitational collapsing. Smaller stars whose mass is three times as that of the size of the Sun, will burn their fuel and become a white dwarf or a neutron star. While, when a large star collapses under gravity it forms a stellar black hole, which is extremely small in size, just a few kilometres across, still having heavy density that results in a large gravitational pull. Our own galaxy i.e. milky way contains a few hundred million stellar black holes. These can be detected by the two processes mentioned in the previous chapter i.e by electromagnetic waves and gravitational waves.

Almost all of the black hole candidates are discovered till date are observed by the x rays originating from the black hole in the binary system. In this binary there are two stars in which one transfer matter to the other in the form of accretion disc ,but there are certain limits in this accretion process which have been discussed above.The 21 such binaries of stellar black holes have been discussed . Intermediate black holes which are discovered can have different theory,because they could be formed as a product of stars colliding during a chain reaction. Consequently, several black holes can be created in the same region , as they start pulling in material they could collide which eventually form a supermassive black hole. These are controversial, though. Several candidates have been discovered, all of which are in the cores of star clusters. But unlike the supermassive black holes at the centers of galaxies, which are so heavy but compact that there is no other reasonable explanation, astronomers can offer other possibilities for the densities at the centers of star clusters.Intermediate black holes are hard to find.

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