Proceedings of the 3rd International Conference on Computing Innovation and Applied Physics
DOI: 10.54254/2753-8818/9/20240789

The formation and evolution of black holes

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Abstract. The concept of Black Holes was first introduced as a prediction by Eistein's Theory of General Relativity and later solved by the Schwarzschild Solution in 1915. A point of mass to great that the bend in space time as a result doesn't allow even light to escape its gravitational pull within the Event Horizon, a point of infinite density and a point at which the laws of time break down. Formation of Black Holes are of interest in many fields of not only Astrophysics but the Physics as a whole. For example it can tell us about the structure and rotation of galaxies which in turn reveals properties of Dark Matter while features such as Hawking Radiation help to further link the world of quantum mechanics to Eistein's Theory of General Relativity. Stellar Black Holes are the remains of enormous stars which has collapsed after running out of fuel for nuclear fusion to continue. These objects can be found throughout the galaxy but most importantly at the center of each galaxy lies a Supermassive Black Hole such as Sagittarius A* at the centre of the Milky Way which has a massive of 4.6 million solar masses, the process by which these Supermassive Black Holes form remain unknown till this day. Black Holes have been notoriously hard to detect due to the fact that they cannot be seen and only through the analysis of orbits of objects around it can its properties like mass be determined. Their mystical nature is exactly why Black Holes draw so much interest within the Astrophysics community today. The formation of such large celestial objects has been debated among Physicists for decades and this paper aims to review current understandings and existing research on the formation of Black Holes to provide an overview on the collapse of stars and the processes with which the core may evolve into a black hole.

Keywords: Black Hole, Event Horizon, General Relativity Theory, Schwarzschild Radius, Dark Matter.

1. Introduction

The study on the workings of the Universe began with Newtonian Classical Physics and Newton's laws of motion. These laws helped explain things from the motions of objects on Earth and in space to even Gravity itself but had the fundamental flaw of assuming that time and space is uniform for all observers. This flaw was revealed by the orbit of Mercury, which was slightly rotating but couldn't be explained by calculations using Classical Physics. Although the problem was put aside initially as simply error within the equipment, this observation troubled Astronomers for many generations. However, when Eistein introduced his Theory of Special and General Relativity in the early 20th century, our understanding of how the Universe functions was reshaped. Time and Space were no longer uniform but could be bent by mass, energy and velocity and formed a web called Space-Time which makes up the fabric of this Universe. Eistein's General Relativity helped explain the slightly rotating orbit of Mercury as the bending of Space-Time by the Sun's mass affected the gravitational interactions of other planets with Mercury which resulted in the slight rotation. Eistein's new theory gave us a new way of explaining the Universe but it also predicted the existence of Black Holes which are points of such large mass that the bend in Space-Time wouldn't even allow light to escape within the Event Horizon. Under current research, the formation of Black Holes are mainly from two different methods. The first is when the core of a star with a huge amount of mass collapse directly into a black hole near the end of its life and the second is when Proto-Neutron Stars form into Black Holes due to stellar remnants fall back after a Supernova. The structure of this paper is as such: Section 2 will explain the basic quantum mechanics behind the collapse of stars and what separates white dwarfs, neutron stars and black holes. Section 3 will explain what occurs as a star nears the end of its life, how supernovae occur and the different types of supernovae that could result in a Black Hole as well as how metallicity affects the likelihood of a star collapsing into one. Section 4 of this paper will outline some of the simpler predictions that General Relativity makes on Black Holes as well as some famous examples of Black Holes and their features. Section 5 of this paper will be an overview of the entire process of a star forming into a black hole.

2. White dwarf, neutron star and black hole

Quantum mechanics lies at the heart of the formation of white dwarfs, neutron stars and black holes and is also what separates them from each other. Quantum mechanics is the study of subatomic particles and their behaviours when interacting with each other. Two main principles define the study into the collapse of stars, the first being the Pauli exclusion principle and the second Heisenberg Uncertainty Principle. Austrian Physicist Wolfgang Pauli proposed that no two electrons can be in the same state in 1925 after observing patterns of light emissions from atoms and this plays into the Electron and Neutron Degeneracy Pressure which is vital in the formation of white dwarfs and neutron stars and is what keeps them from collapsing in on themselves. Heisenberg Uncertainty Principle, proposed in 1927 by Werner Heisenberg, describes how the position and momentum of a subatomic particle cannot be both determined at the same time and that with the determination of one would come with the uncertainty of the other. This is the driving force for the Degeneracy Pressure which prevents neutron stars and white dwarfs from collapsing in on itself. The separation between white dwarfs, neutron stars and black holes is detailed further in Mirabel (2017b) [1].

2.1. *Pauli Exclusion Principle*

This principle states that no two fermions, which includes electrons, protons and neutrons, can be in the same quantum state or configuration at any single point in time. This principle does not apply to particles like Bosons. In practice this principle says that two electrons cannot occupy the same space at any singular point in time and comes into play when the core of stars collapse and atoms are crushed together forcing electrons into close proximity of each other.

2.2. *Heisenberg Uncertainty Principle*

The principle states that the product of the measured momentum and the measured momentum is greater than or equal to Planck constant divided by 4π. This in other words describes that the more determined a subatomic particle's momentum is the less determined the position is and the minimum is h/4π. As the atoms of a star's collapsed core are crushed together, the position of the atoms become determined which then in turn gives the particles a huge momentum as stated by this principle. This increased momentum creates a pressure between the atoms or particles that prevents the core from collapsing indefinitely under its own gravity.

$$\Delta X \Delta P \geq \frac{h}{4\pi} \tag{1}$$

ΔX is Position, ΔP is Momentum, h is Planck constant.

DOI: 10.54254/2753-8818/9/20240789

2.3. Electron and Neutron Degeneracy Pressure

In the event of stellar collapse of mass less than 1.4 solar masses, the star would collapse into a white dwarf with the core held up by Electron degeneracy pressure. As the atoms of carbon and oxygen of the core are being compressed together due to the star's gravity, the electrons are given a huge momentum as their positions are very well-known as stated by Heisenberg's Uncertainty Principle. Since the electrons cannot occupy the same position as stated by Pauli Exclusion Principle, this creates an outward pressure which counteracts the gravitational collapse of the white dwarf. However as the white dwarf approaches 1.4 solar masses, the electrons are pushed closer and closer together and as Heisenberg Uncertainty Principle states, since the positions get more determined, the momentum and therefore velocity of the particle increases. At 1.4 solar masses also known as the Chandrasekhar Limit (Pinochet & Van Sint Jan, 2016b) [2], the velocity of the electron reaches the speed of light and since the speed of light is the largest speed possible in the universe, electron degeneracy pressure can no longer hold a star of mass above 1.4 Solar Masses and the white dwarf collapses to form a neutron star.
Equation for Electron Degeneracy Pressure:

$$P = \frac{\pi^2 \hbar^2}{5M\mathrm{eMH}^{\frac{5}{3}}} \left(\frac{3}{\pi}\right)^{\frac{2}{3}} \left(\frac{\rho}{\mathrm{\mu e}}\right)^{\frac{5}{3}} \tag{2}$$

$\hbar$ is $\frac{\text{Plank's Constant (h)}}{2\pi}$, Me is Mass of electron, μe is ratio of electrons to protons, ρ i s Density, MH is Mass of Proton .

Similar to electron degeneracy pressure of a white dwarf, a neutron star is kept from collapse by neutron degeneracy pressure. Between masses of 1.4 to 3.0 solar masses, neutron stars can be held up by the pressure created from the huge momentum given to the neutrons as stated by Heisenberg's Uncertainty Principle and the fact that two neutrons are unable to have the same quantum state as given by Pauli Exclusion Principle. Above 3.0 solar masses, the neutrons reach the speed of light and can no longer provide enough pressure to counter the gravitational collapse and much like the white dwarf, collapses in to form a Black Hole.

3. Stellar lifecycle and supernovae

3.1. Stellar Fusion

Fusion takes place within stars to provide energy and to exert the radiational pressure which prevents its core from collapsing. The two main processes that takes place within main-sequence stars are the proton-proton chain and the CNO cycle for the fusion of hydrogen into helium.

Table 1. Steps of the proton-proton chain.

Proton-Proton Chain	Step 1:	$H^1 + H^1 \rightarrow H^2 + e^+ + \nu$	$H^2 + H^1 \rightarrow He^3 + \gamma$
	Step 2 (68.7%):	$He^3 + He^3 \rightarrow He^4 + H^1 + H^1$	
	Step 2 (31.0%):	$He^3 + He^4 \rightarrow Be^7 + \gamma$	$Be^7 + e^- \rightarrow Li^7 + \nu$
		$Li^7 + H^1 \rightarrow He^4 + He^4$	
	Step 2 (0.3%):	$Be^7 + H^1 \rightarrow B^8 + \gamma$	$B^8 \rightarrow Be^8 + e^+ + \nu$
		$Be^8 \rightarrow He^4 + He^4$	

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Table 2. Steps of the CNO Cycle.

CNO Cycle	Step 1:	$C^{12} + p \rightarrow N^{13} + \gamma$
	Step 2:	$N^{13} \rightarrow C^{13} + e^{+} + V$
	Step 3:	$C^{13} + p \rightarrow N^{14} + \gamma$
	Step 4:	$N^{14} + p \rightarrow O^{15} + \gamma$
	Step 5:	$O^{15} \rightarrow N^{15} + e^{+} + V$
	Step 6:	$N^{15} + p \rightarrow C^{12} + He^{4}$

P-P Chain usually occurs in cooler stars such as the Sun while the CNO cycle dominates in hotter and larger stars as the CNO cycle can occur at much faster speeds but require higher temperatures for the reaction to initiate.

3.2. Multi-Shell Burning

As a star's hydrogen reserves decrease but the core of helium hasn't reached the 100 million K required for helium fusion, the core of helium begins to contract. As the contraction occurs, the temperature increases due to the Ideal Gas Law $\boldsymbol{PV = nRT}$. This accelerates hydrogen fusion around the core and produces a shell of 'burning' hydrogen which then expands the star outwards into a Red Giant or a Super Giant Star due to the increased radiational pressure.

When the core reaches 100 million K helium fusion occurs and turns Helium Nuclei into Carbon nuclei This process repeats with Carbon fusing into oxygen then neon, magnesium, silicon and finally inert iron core much like the figure below depicts.

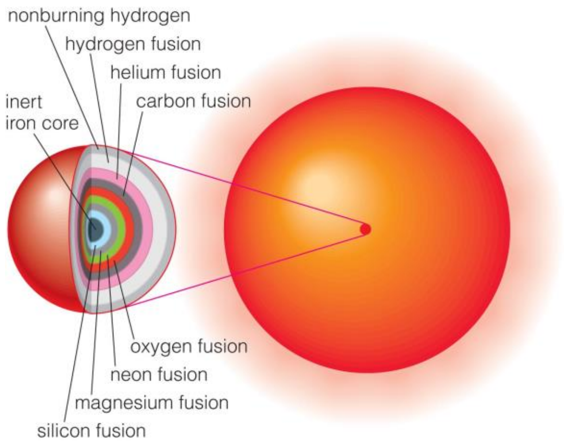

Figure 1. Depicting the different shells of fusion in the core of a collapsing star.

3.3. Supernovae

As explained previously, the inert core is prevented from collapse from Electron Degeneracy Pressure. However, when the core reaches 1.4 Solar Masses (Chandrasekhar Limit), the electron degeneracy pressure no longer holds and the core collapses. During collapse protons and electrons fuse to form the products neutrons and neutrinos and this creates huge amounts of energy and a shockwave which rips apart the star in a supernova. For mass below 1.4 solar masses, the star collapses into a white dwarf. For mass between 1.4 and 3 solar masses, star collapse into neutron stars and for mass above 3 solar masses stars collapse directly into a black hole. The core collapse of stars is further detailed in simulations done by Kuroda et al. (2022b) [3].

The type I of supernova describes when a white dwarf absorbs enough material from either a nearby star or forming a binary system with another white dwarf which results in their eventual collision and

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merge. Both cases result in the breaking down of electron degeneracy pressure which prevented the initial gravitational collapse. The collapse causes a shockwave outwards which heats the stellar material and causes the material to expand outwards at very high speeds leading to an explosion. This type of supernova tend to form either larger white dwarfs and neutron stars depending on how much material was ejected by the supernova explosion but don't tend to form Black Holes.

The type II of supernova refers to the collapse of stars as described by the multi-shell burning previously. Depending on the mass of the star and its metallicity, which will be further detailed, stars between masses of 1.4 and 3 solar masses tend to collapse to a neutron star while stars above 3 solar masses collapse into a black hole due to the overcoming of neutron degeneracy pressure. The iron core would collapse in less than a second and as the core reaches the density of a atom's nucleus further compressions are resisted and a shockwave is sent as the energy rebounds outwards. This sends out a shockwave through the star which heats the gas and makes it expand outwards at speeds of a significant percentage of the speed of light (around 5%). The release of neutrinos from the merging of photons and electrons helps the heating as some are absorbed at these high densities. This leads to a supernova of Type II. Black Holes could be formed directly from the collapse of the iron core, however high metallicity could result in larger amounts of fallback of the stellar remnants after a proto-neutron star has already formed which would lead to a delayed formation of a black hole when the total mass reaches the limit of 3 solar masses. (Vigna-Gómez, Schröder, Ramírez-Ruiz, et al., 2021) [4].

3.4. *Metallicity*

Metallicity is the proportion of atoms within the star that has a higher mass number than hydrogen and helium and has been shown to affect the likelihood of a star forming a black hole due to its effect on the radiative opacity of material within the star. Radiative opacity, calculated as the sum of Bound Bound, Bound Free, Free Free and Electron Scatter (Jean-Christophe Pain & Franck Gilleron 2009) [5] has a heavy correlation with nuclear charge and describes how easily photons are absorbed or scattered by the nuclei of atoms within the star. And as metallicity is a measurement of the proportion of heavier elements within the star itself, metallicity has a positive correlation with radiative opacity. Greater opacity has two major effects on the star 1) More mass loss due to Stellar Winds and 2) Greater convection within the star that leads to a smaller core. The effects of high metallicity in the hot atmospheres of galaxies as well as its effect on whether a massive star explodes in a supernova can be found in Mao et al. (2021b) [6].

As explained prior, higher metallicity leads to greater opacity which increases the proportion of photons, and therefore energy, absorbed by materials within the star. Stellar Winds, huge ejections of mass from the surface of stars, are powered by radiative pressure and since stars with higher metallicity absorb radiation better, those stars are going to have larger stellar winds as its material is more easily accelerated by radiation. As a result higher Metallicity leads to higher rate of mass loss (Vink & de Koter 2005) [7] due to the larger stellar winds.

Higher absorption of radiation within the star also increases its temperature as more heat is trapped. The effects of heating on early star clusters as a result of high metallicity as well as the relation to mass loss can be found in Trani et al. (2014b) [8]. This increases the rate of fusion within the star and as a result the radiative pressure increases causing the star to expand outwards. This also contributes to the rate of mass loss as gravity at the surface of the star, which has an inverse squared relationship with distance, decreases due to the increased radius leading to material being more easily lost as there's a smaller force acting on it.

As more heat is trapped in higher opacity stars, there's larger temperature differences between regions which leads to greater convection within the convective zone and mixing of materials within the star. This could lead to smaller cores within stars of higher metallicity as heavier elements synthesized in the core are mixed outwards by the convection. As a star nears the end of its life cycle and enters the multi-shell burning phase described previously, the mixing of heavier elements within high metallicity stars would lead to shorter nuclear burning phases as there's less material in the core to undergo fusion and less heavy elements synthesized as a result. This leads to a much smaller core when the star collapses and therefore reduces the likelihood of a black hole forming from a high metallicity star despite its potentially large initial mass. Stars of over 70 Solar Masses can avoid collapse into a Black Hole due to the mass loss of its core by the same principle (Belczyński et al., 2020b) [9].

4. Black Holes

4.1. General Relativity and Black Holes

Black Holes are objects shrouded by mystery as it pushes our understanding of space and time to the limit. Predicted initially by Eistein's General Relativity and the Schwarzschild Solution in 1916, Black Holes are points of mass (singularity) so great that not even light can escape its gravitational pull within the Schwarzschild Radius, given as $\frac{2GM}{C^2}$. General Relativity predicts many features which has since been used to detect objects with large masses which include Gravitational Lensing and Gravitational redshift. Gravitational lensing is the bending of light due to the curvature in space-time by objects with very large masses. This has since been used to not only detect Black Holes and other large celestial objects but also to prove the existence of Dark Matter due to the gravitational lensing after a Bullet Cluster Collision. Gravitational Lensing also gives a Black Hole with an accretion disc the double ring appearance as light from behind the Black Hole is bent to the observer. Gravitational Redshift is the doppler shift of electromagnetic waves due to an object's gravitational attraction which results in the decrease of its frequency and increase of its wavelength. This phenomenon is due to the loss of energy as light travels away from a source of gravitational attraction and since energy of a photon is plank's constant times the frequency, the decrease in energy would result in the decrease of frequency and the red-shifting of light coming away from an object of a large mass.

Black Holes present many interesting thought experiments such as what would happen as a person falls into a black hole. To the frame of reference of the person falling in, provided the tidal force doesn't rip apart the body instantaneously, they wouldn't notice anything different as they cross the event horizon (point beyond which not even light escapes) as their free-falling inertial frame means they feel no force acting on them as they fall into the Black Hole. However, to the perspective of a person observing far away. They would observe that the person's time slows down as they approach the singularity due to gravitational time dilation while the light travelling from the person would undergo more and more gravitational redshift. This would continue until the person reaches the event horizon at which point to the perspective of the observer far away, the person would seem like their time stops and that person would never enter the black hole as relativity predicts time dilation to be infinite at the event horizon. This means that an object would never to detected to have entered a Black Hole to the perspective of the observer far away to their perspective all the information is still stored at the surface of the event horizon.

4.2. Examples

At 7000 light years away from the Earth in the Cygnus Constellation, Cygnus X-1 is a binary star system that is a strong X-ray source and provided clear evidence for the existence of Black Holes in the late 20th century. The main star HDE 226868, a hot supergiant of 27 Solar Masses, orbits an invisible object with a period of 5.6 days. After analysing the orbit of HDE 226868, the mass of this object was determined at around 16 Solar Masses. An object of this size should have a detectable spectrum but none was detected in 1964 and later analysed extensively in 1971, this led to the companion to becoming the first ever suspected Black Hole. Material from HDE 226868 is torn from the star itself towards the Black Hole due to its immense gravitational force and forms the Accretion Disc, a ring of extremely hot plasma, which is an ionized gas, orbiting the black hole at near relativistic speeds. As matter falls towards the Black Hole, GPE is converted to KE and this heats up the plasma to millions of degrees as heat is generated by friction within the accretion disc itself. Another way of analysing this would be conservation of angular momentum. As material gets closer to the centre of rotation, that of the Black Hole singularity, it has to speed up to conserve angular momentum. $\boldsymbol{L = MVR}$ therefore as R, Radius, decreases V, Velocity, has to increase so that L, Angular Momentum, is conserved. As material is heated to millions of degrees in the accretion disc, they emit strong X-rays in all directions and this was detected and analyzed by scientists using the Uhuru X-ray satellite in 1971 to confirm the existence of a Black Hole within Cygnus X-1.

Being a binary system much like Cygnus X-1, V381 Nor is a Micro-quasar sitting 17,000 light years from the Earth near the galactic centre of the Milky Way with a mass of around 10.6 Solar Masses. Galaxy rotations is linked with the mass of the SMBH at the centre and binary systems like V381 Nor produce strong gravitational waves that can be detected (Mirza et al., 2017b) [10]. V381 Nor has an accretion disc fed by its primary star's atmosphere and winds and emits powerful beams of charged particles from its poles making it a quasar. Orbiting plasma in the accretion disc creates a very strong magnetic field as stated by the Ampère-Maxwell law, as a moving charged particle induces a magnetic field on its surroundings. The poles of a Black Hole's magnetic field is located above and below the disc itself and charged ions are sped up by the magnetic field, in the case of V381 Nor up to half the speed of light and shot outwards into space in the form of radiational jets. These jets were detected in 1998 when V381 Nor suddenly became 1.5 times brighter than the most intense X-ray source in the sky, the Crab Pulsar, as the poles by chance pointed at the Earth.

Sagittarius A* is a Supermassive Black Hole that lies at the centre of the Milky Way. With a mass of 4.6×10^6 Solar Masses and around 25,000 light years away from the Earth Sagittarius A^* acts as the galactic centre for our Milky Way. A Black Hole of this size cannot form directly from a Type II collapse of a star and two possibilities on its formation would be that a much smaller Black Hole swallowed tremendous amounts of gas and dust from its surrounding or that multiple mergers of smaller ones to allow for a Black Hole of this size to exist. Huge amounts of Radio Waves are detected from Sagittarius A* most likely due to the Synchrotron Radiation as a result of free electrons travelling through the Black Hole's Magnetic Field. Sagittarius A* was first detected in the 1974 when radio-astronomers Bruce Balick and Robert L. Brown detected a point-like source towards the Galactic Centre (Balick, B. & Brown, R. L. 1974) which they concluded had very similar properties to that of "more energetic nuclei of other galaxies in terms of their size and brightness".

5. Conclusion

The evolution of a star's core as it collapses depends on the mass of the core itself due to electron and neutron degeneracy pressure. Cores of less than 1.4 solar masses form white dwarfs, 1.4 solar masses and 3 solar masses the core forms a neutron star while cores of over 3 solar masses form Black Holes. The collapse of a star occurs through a supernova, driven by the fusing of the electron and the proton to form a neutron and neutrino a shockwave is sent from the core through the rest of the star which rips the star apart in an explosion. The types of supernovae which interest the formation of a black hole would be Type II, the conventional supernova related to the collapse of a star and also type Ia which occurs when a white dwarf gains enough mass for its core to collapse. The likelihood of a star forming a core large enough for a Black Hole to form is dependent on the metallicity of the star as high metallicity leads to higher radiational opacity resulting in higher rate of mass loss through stellar winds and greater convection within the star which both results in a smaller core in the time of collapse. Black Holes could also form from material fall-back after the supernova has occurred and a proto-neutron star is formed as when the neutron star gains enough mass it will collapse again into a Black Hole. Material fall-back can also be influenced by the metallicity as heavier elements would be less likely to completely escape the gravitational well of the collapsed core and would eventually fall back. Famous Black Hole systems include Cygnus X-1, a Black Hole and main-sequence binary system, V381 Nor, a micro-quasar near the galactic centre of the Milky Way and Sagittarius A*, the supermassive Black Hole of 4.6 million Solar Masses at the centre of the Milky Way.

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