The Historical Development of Supermassive Black Holes and Their Formation in the Early Universe

by

Carlos M. Cordero

A CAPSTONE PROJECT

submitted in partial fulfillment of the requirements for the acknowledgement

Honors Distinction

Physics
School of Engineering, Mathematics, and Science

TYLER JUNIOR COLLEGE
Tyler, Texas

2015

Abstract

Black holes are a prediction of Einstein's theory of gravity, foreshadowed by the hypothesis of John Mitchel who first suggested the theoretical scenario for an object with strong gravitational pull where light could not escape it. The simplest kind of black hole was discovered by Karl Schwarzschild using Einstein's field equations, and Oppenheimer was one of the first men to consider the physical existence of black holes. The subject gained life, but the newly discovered material puzzled and challenged the scientific community to wonder how a black hole is formed. Moreover, In 1960 John Lynden bell proposed that a black hole a billion times the size of the sun (supermassive black hole – SMBHs), existed in the center of the Milky Way, which caused more questions to arise, and answers to reveal without any relevant and concise evidence support. Different explanations about how SMBHs are formed and can reach massive sizes of billions times the sun have been proposed. However, recent research and discovery of quasars has shown that SMBH have been around in earlier stages of the universe, and how they gained so much mass in such a short time remains an open field of research. Yet, some simulations have been tested in order to explain the formation of this massive objects, and organize the stages and origins of SMBHs.

Introduction

The term black hole was popularized by John Wheeler to describe the theoretical entity with strong gravitational pull where not even light could escape it (Thorne, 1994). Black holes went from a theoretical discussion to an influential entity in the universe yet to be seen, and then to one of the most massive entities in the universe. But the most notorious question found in this research was when? And how? Such enormous objects formed? Supermassive black holes (SMBHs) are thought to reside in the cores of galaxies; they are massive entities that are thought to fuel the bright quasars and are also responsible for blasting out radiation and ultra-fast winds to their host galaxy (Chou & Clavin, 2015). Although the formation of stellar black holes has been described as the catastrophic collapse of neutron stars to black holes (Bennet, Donahue, Schneider, & Voit, 2014), the formation and origins of SMBHs remains an open field of investigation to date. However, some simulations have been carried to propose explanations to how such massive entities, a billion times our sun, could form. The purpose of this research is to gather material about supermassive black hole formation and origins

1.1 Gravity

The gravitational force is one of the most important components in a black hole since this force is responsible for the continuous collapsing that a star undergoes before it becomes a black hole.

Galileo Galilei studied the motion of bodies in the 16th century and early 17th century. Galilei experiments consisted of dropping objects from high altitude, and measuring balls rolling down an incline surface, which lead to his most important contribution to the understanding of gravity: force pulling the objects down accelerates them at the same rate (Galilei, 1638). In 1687 Isaac Newton contributed to what we know today as gravity through his material "Principia" describing gravity through his inverse-square law of universal gravitation (Newton, The Mathematical Principles of Natural Philosophy (translated by Andrew Motte), 1846) shown below in equation #1

$$F = G\frac{m_1 m_2}{r^2}$$

Equation 1

where *F* represents the force of action, *m* are the masses of the two interacting objects, *r* is the distance between the two masses, and G is the gravitational constant (Halliday, Resnick, & Jearl, 2011). Newton explained his hypothesis as follows:

> "I deduced that the forces which keep the planets in their orbs must [be] reciprocally as the squares of their distances from the centers about which they revolve: and thereby compared the force requisite to keep the Moon in her Orb with the force of gravity at

the surface of the Earth; and found them answer pretty nearly” (Chandrasekhar S. , 1995).

The gravitational constant in Newton’s law was measured by Henry Cavendish in 1797 using a torsion balance invented by John Mitchel, Cavendish was able to measure the force exerted between two balls of lead of different sizes (Vernon, 1894), and he determined G to be $6.74 \times 10^{-11}\ \mathrm{m}^3\ \mathrm{kg}^{-1}\ \mathrm{s}^{-2}$

1.2 Conceptualizing Black Holes

In the 18th century, a hypothesis formulated by John Mitchell was proposed while considering different methods to determine the mass of a star.

Mitchel recognized Newton’s idea that light consist of very little mass (Newton, Opticks, 1730), and he reasoned that this minuscule mass that formed light would have their speed reduced by a star’s gravitational pull (Mitchel, 1783). The escape velocity is the “initial speed that will cause [an object] to move upward forever” (Halliday, Resnick, & Jearl, 2011). Newtonian mechanics conveys that a projectile of mass *m* speeding away from the surface of earth with velocity *v*, has kinetic energy given by equation #2 given below

$$K = \frac{1}{2} m v^2$$

Equation 2

and potential energy,

$$U = -\frac{GMm}{R}$$

Equation 3

where *M* is the mass of the planet and *R* is the radius of the planet. However, the projectile will come to a halt and have no kinetic and potential energy at infinity (Halliday, Resnick, & Jearl, 2011), therefore escape velocity is given by the following formula,

$$K + U = \frac{1}{2}mv^2 + \left(-\frac{GMm}{R}\right) = 0 \qquad \rightarrow \qquad v = \sqrt{\frac{2GM}{R}}$$

Equation 4

Since Newton argued that light had mass, what would happen if the gravity pull from a star was greater than the escape velocity of light? In Mitchel's time, the constant for the speed of light had not yet been measured, so Mitchell assumed that light's behavior would be similar to throwing a rock in the air, eventually slowing to a halt and falling back down (Bennet, Donahue, Schneider, & Voit, 2014). It was here where one of the properties of what it's known today as a black hole was first hypothesized: assuming the gravitational pull of a start being greater than the escape velocity of light, then such star would be not visible since light cannot escape it (Mitchel, 1783).

Almost two centuries later in 1915, a new theory was confirmed that would reconceptualize the idea of black holes. Albert Einstein (1914-1917) developed his theory of general relativity to describe the interaction of gravitational force as a consequence of spacetime bent or curved by mass and energy. These interactions are described by the equation 5

$$R_{\mu v} - \frac{1}{2}g_{\mu v}R + g_{\mu v}\Lambda = \frac{8\pi G}{C^4}T_{\mu v}$$

Equation 5

where $R_{\mu v}$ is the Ricci curvature tensor, $g_{\mu v}$ is the metric tensor, Λ is a cosmological constant, *G* is Newton's gravitational constant, *C* is the speed of light in a vacuum, *R* is the scalar curvature and $T_{\mu v}$ is the stress-energy tensor (Einstein, 1914-1917). These field equations anticipated the existence of black holes.

Karl Schwarzschild solved Einstein's field of equations in 1916 for the gravitational field outside a non-rotating body (Thorne, 1994), and also used the equations to derive the point where the escape velocity of a black hole equals the speed of light (Bennet, Donahue, Schneider, & Voit, 2014) shown below

$$R = \frac{2Gm}{c^2}$$

Equation 6

Schwarzschild proposed that "any mass could become a black hole if that mass were compressed into a sufficiently small sphere" (Stein, 2011).

In 1931, Subrahmanyan Chandrasekhar made contribution to the study of black holes by finding the mass limit of white dwarf stars (Chandrasekhar S. , 1994). Chandrasekhar's work showed that there is a white dwarf limit of 1.4 solar masses, which is the minimum mass that must be surpassed for a start to collapse into a smaller entity (Carroll, 2013). Therefore, "the existence of such a mass limit therefore sparked the thought that the ultimate fate of more massive stars might be infinitely compact configurations which we now call Black Holes" (Bhattacharya, 2011). Nonetheless, the scientific community was not ready for the concept yet, since that smaller entity happened to be a neutron star, and neutrons had not yet been discovered (Bhattacharya, 2011). In addition, Sir Arthur Stanley Eddington – a renowned physicist in the 1930's – found the idea of white dwarfs collapsing to a smaller state absurd and speculated that some type force would prevent gravity from making any object collapse even more (Wali, 1982).

In 1932 the experiments carried by James Chadwick using radiation of beryllium, and paraffin lead him to discover an unchurched particle with nearly the same mass as protons – predicted by Ernes Rutherford in 1920 – called neutrons (James, 1932). With this new discovery, "Landau speculated that stellar corpses above the white dwarf limit might collapse until neutron degeneracy pressure halted the crush of gravity" (Bennet, Donahue, Schneider, & Voit, 2014), but most astronomers were skeptical about the possibility of neutron stars. Nevertheless, the first explicit prediction of neutron stars was exposed by Walter Baade and Fritz Zwicky in 1933 in trying to elucidate the energy released in supernova explosions, stating that "with all reserve we advance the view that supernovae represent the transition from ordinary stars into neutron stars, which in their final stages consist of closely packed neutrons" (Baade & Zwhicky, 1934) (check source Baade W, Zwicky F. Phys. Rev. 45 138 (1934)).

The newly concepts of science in the 20th century would soon back up the existence of black holes as well as other newly proposed concepts not thoroughly understood. Robert Oppenheimer, with the help of Hartland Snyder, suggested a scenario where the static distribution of a white dwarf star could not happen if the gravitational effect of any escaping radiation during the late stages of contraction were ignored, as well as the deviations from spherical symmetry produced by rotation. Therefore, they concluded that "we should now expect that since the pressure of the stellar matter is insufficient to support it against its own gravitational attraction, the star will contract" (Oppenheimer & Snyder, 1939). These hypothesis meant that the internal pressure could not overcome the crush of gravity, and that there was not known force that could stop continuous collapsing.

The existence of other supermassive objects was confirmed by Jocelyn Bell in 1968 after coming "upon inexplicable, metronomically regular radio blips from isolated spots in the sky… [Concluding] that the blips came from hitherto unknown objects, massive yet remarkably small" (Colligan, 2009). These unknown objects are pulsars, and were later identified as fast spinning neutron stars (Colligan, 2009).

The discovery of these entities helped the scientific community to assimilate the concept of black holes stating that nature was far stranger than they had expected. Different works were carried by scientist in the matter of black holes like the exact solution for a rotating black hole (check Roy Ker's work), and black hole thermodynamics by James Bardeen and Jacob Bekenstein. One of the most relevant works was made by Stephen Hawking's "Particle Creation by Black Holes," where he proposes through quantum mechanical effects that black holes "create and emit particles as if they were hot bodies." (Hawking, 1975) This concept was known as Hawking radiation: the radiation predicted to be released by black holes, due to quantum effects near the event horizon.

At this point, black holes were only a theoretical entity that the scientific community had yet to observe in nature yet. It was only possible to assume they existed because of surrounding material that was being channeled by its own gravity force so fast that it would emit X-rays that could be detected from earth. Such was the case of Cygnus X-1, the first candidate for a black hole. This popular galactic X-ray source was discovered in 1964 during rocket flight, and it is estimated to have a mass of 14.8 $M_{\odot}$ (Bowyer, Byram, Chubb, & Friedman, 1965)

1.3 Definition of Black Hole

A theoretical entity predicted by Einstein theory of general relativity that has a gravitational pull so strong that not even light can escape from it (Bennet, Donahue, Schneider, & Voit, 2014). This paper focuses on supermassive black holes.

1.4 Types of Black Holes

1.4.1 Primordial Black Holes: black holes that formed by thanks to the extreme density of matter present during the universe expansion, and not by gravitational collapse. Since they were formed very early in time, they might have evaporated (Novikov, Polnarev, Starobinsky, & Zeldovich, 1979)

1.4.2 Stellar Black Holes: formed by the gravitational collapse of a star. The average size is $10M_{\odot}$.

1.4.3 Supermassive Black Holes: these black holes are massive and can reach billion of solar masses, and are responsible for most active galactic nuclei (AGN) (Kormedy, 1995) . How they form remains an open field of study.

1.5 Supermassive Black holes (SMBHs)

These types of black holes are billion times the size of our sun. Donald Lynden-Bell hypothesized in 1969 that these massive black holes resided in the nuclei of the Milky Way (Lynden-Bell, 1969), and they are now found in the nuclei of local galaxies (Khandai, Feng, DeGraf, Di Matteo, & A.C. Croft, 2015). Black holes are mysterious stellar objects that can only be assume to exist because of the activity of matter around it (Bennet, Donahue, Schneider, &

Voit, 2014). However, the question that many scientists are trying to answer is how and under what circumstances did such supermassive black holes grow? Despite years of study, the formation of supermassive black holes still remains a topic of research. What we do know is that SMBHs had to exist at an earlier period in order to explain early quasars of z~6. Quasars are the most luminous entities in the universe and they are powered by SMBHs when they devour surrounding mass (Di Matteo, et al., 2011). Recently, a newly discovered quasar hosting a SMBH of ~ $1.2\ \text{x}10^{10}M\odot$ present less than one billion years after the big bang "presents substantial challenges to theories of the formation and growth of black holes and coevolution on black holes and galaxies" (Wu, et al., 2015). This imposes new hypothesis about the origins of SMBHs, and redefines the circumstances under which they were formed.

1.6 Stages of Supermassive Black Hole (SMBH) Formation

The following stages that black hole undergoes as it gains mass were the most commonly studied stages that theorize SMBH origins and formation. These stages were studied through simulations carried by different scientists in this particular field. It also contains other studies with similar arguments, but carried under different circumstances that hypothesize the development of the earliest SMBHs.

1.6.1 Collapse

When a star's internal pressure has been overpowered by its own gravitational pull, it can continue to shrink until it becomes a black hole (Bennet, Donahue, Schneider, & Voit, 2014).However, how are stars formed in the first place? Hydrogen and helium were the only chemical elements produced in the big bang, and thanks to gravity, hydrogen and helium agglomerated as gas clouds were the first star formation occurred through the continuous condensation and collapsing of this gas, eventually becoming a star cluster (Bennet, Donahue, Schneider, & Voit, 2014). The stars inside the cluster can continue to change, eventually depleting their internal fuel and "undergo supernova explosions that can leave behind compact stellar mass remnants" (Shapiro & Teukolsky, 1985), like white dwarfs, neutron stars, and ultimately stellar black holes. Shapiro and Teukolsky use Zel'dovich and Puduret's argument that "the combined effects of secular core collapse, i.e., the 'gravothermal catastrophe' [stellar evaporation] and start-start collisions and coalescence would inevitably drive a star cluster core to states of ever-increasing central density and red-shift" (Shapiro & Teukolsky, 1985) to assume that the cluster – assumed to be formed of neutron stars, stellar black holes and other stars – would become relativistically unstable at which point it would undergo catastrophic collapse to a supermassive black hole on a dynamical time scale (Shapiro & Teukolsky, 1985). However, Shapiro and Teukolsky hypothesized that the first supermassive objects formed from the condensation of dark matter, and neglect the influence of ordinary matter in this process (Shapiro & Teukolsky, 1992). Dark matter is a theoretical type of matter that accounts for most of the matter in the universe (Bennet, Donahue, Schneider, & Voit, 2014). In addition, Melia argues that that the collapsing of ordinary matter into SMBHs could be questioned since ordinary matter was not compact enough to undergo continuous collapsing into a SMBH (Melia, 2003).

Although the previous studies proposed the creation of supermassive black holes through the collapsing of star clusters, some other works support the possibility of SMBH formation through direct collapse. Some alternative ideas is to produce a 10^5 $M\odot$ SMBH directly, other than stellar seed accretion (Haiman, 2010). The process would happen if the gas that cools and collapses in dark matter halos avoids fragmentation and sheds angular momentum efficiently, and collapse rapidly, but these conditions are unlikely to be met unless the gas remains relatively warm (Haiman, 2010). Haiman's research explains that the gas present in the dark matter haloes, when collapsing in isolation, forms H_2 efficiently and cools to temperatures of T ~ 300 K, but argues that no fragmentation was seen, and the gas is expected to ultimately fragment on smaller scales that have not yet been resolved (Haiman, 2010). In addition, earlier research explains the creation of SMBH with an intermediate massive stellar entity as follows:

> "Low spin system would be more susceptible to the formation of a SMBH. If H_2 cooling is suppressed inside these systems, then their gas will not cool below 10^4 K. When the temperature to which the gas cools is only somewhat lower than the viral temperature of the host galaxy or system, we expect that fragmentation into small clumps will be avoided, and the gas will tend to condense isothermally into large clumps. Such large clumps may then collapse to form a SMBH possibly through the intermediate stage of a supermassive star. The viability of this scenario relies on the suppression of molecular H_2 cooling, which when present is capable of cooling the gas to a temperature as low as 200 K" (Bromm & Loeb, 2003).

On the other hand, Begelman explains the creation of black holes without a stellar precursor, arguing that "If the inflow rate [of matter] is high enough, however, the core will be so tightly bound by the time nuclear reactions start that the energy release will be insufficient to halt core contraction" (Begelman, 2008)

1.6.1.1 Black hole seeds

Previously, it was mentioned that the origins of SMBHs can be the collapsing of dark matter and star clusters. However, this collapsing of either type of matter had a starting point where the fast infall of gas in galactic nuclei formed black hole seeds (Begelman, 2008), and these seed were hundreds solar masses. Some studies refer to black hole seeds formed from direct collapsing of dark matter as “heavy seeds”, and the ones derived from remnants of Population III stars are called “light seeds” (Volonteri, 2010).

Population III stars are metal poor star hypothesized to be the first born star created in the universe (Puget & Heyvaerts, 1980). These type of stars provide evidence that massive black holes could have formed at early stages with high red shift where fragmentation must have been inefficient (Combes, Barret, Contini, & Pagani, 2003). Light seeds are theoretically small and formed at z ~ 20-30 ref).

Once seeds are formed, their growth begins when matter that surrounds it begins to interact with the black hole seed.

1.6.2 Accretion

A well-known phase for SMBH growth is accretion, which is inevitable during the active stage of galactic nucleus (Volonteri, 2010). As previously explained, when a black hole seed forms, especially a light seed, it is embedded in an envelope of more than a hundred times its mass (Begelman, 2008). Accretion onto a black hole happens via an accretion disk, which is solely the diffused matter (envelope) that surrounds a central body in an orbital motion, and accretion inside massive envelopes can lead to very rapid growth of the black hole (Begelman, 2008). When this matter touches the black hole, it launches relativistic jets of outflows of energy (Gultekin, Cackett, Miller, & Di Matteo, 2012), having then some quasar like activity. These jets of energy occur in bigger proportions when powered by SMBHs, and the general consensus among researchers is that quasars and active galactic nuclei are SMBHs accreting surrounding matter (Richstone, et al., 1998). Quasars were firstly identified as high red shift sources of electromagnetic energy, and they were first observed in the 1950's (Shields, 1999). Luminous quasars have been detected at very high red shifts, $z > 6$, in early phases of the universe as soon as 1 Gyr (giga year: 10^9 years or a billion years) (Silk & Rees, 1997).If quasars are powered by SMBHs, how they grew so fast and in such a short timespan remains an unanswered question. Nevertheless, the first seeds must have appeared in an early epoch, $z > 10$, in order to have sufficient time to grow via gas accretion and mergers (Di Matteo, et al., 2011)

Several scenarios have been studied and simulated to understand how accretion aided early SMBH growth. The first possibility is gas concentrated sufficiently to enable rapid accretion onto a black hole seed (Volonteri, 2010). However, several studies point out that the matter surrounding the black hole seed needs to be accreted at an Eddgington Rate in order to fulfill rapid growth (Hopkins, et al., 2005).

Two formation possibilities are given by Hu, Shen, Lou and Zhang: first, the mixture of self-interacting matter and baryon matter distributed in the early universe beginning with a rapid quasi-spherical and quasi-steady Bondi accretion of SIDM particles entrenched with Byron matter, which gives birth to significantly big black hole masses (Hu, Shen, Lou, & Zhang, 2005); second: growth of black hole mass primarily via baryon accretion, eventually leading to SMBHs of enormous solar masses, which my form either by $z \sim 6$ for a sustain accretion at the Eddington limit or at lower *z* for sub-Eddington mean accretion rates (Hu, Shen, Lou, & Zhang, 2005).

This does not support the immediate formation of a supermassive black hole in one isolated step, rather ST interprets Zel'dovich and Pudurets work as a focus of Newtonian star cluster composed of stellar mass black holes, and it reasons that such cluster would inevitably collapse to form a central supermassive black hole around which any remnant cluster stars would orbit. This first proposition refers only to the combination of single stellar black holes spread in a system which eventually merge to form a bigger entity (SMBHs). This, according to ZT, ought to be regarded as a leading contender for the rout by which supermassive black holes form in dense galactic nuclei (Shapiro & Teukolsky, 1985).

1.6.3 Merging

Galaxy merging is something common in astronomy, and since it is believed that galaxies have SMBHs in their center, it is naturally to think that they will merge too. However, it has not been possible to demonstrate how two SMBHs fuse together when galaxies are merging because it is difficult to model such a big spatial scale (Mayer, et al., 2007), therefore some simulations need to be carried. The simulation done by Mayer, Kazantzidis, Madau, Colpi, Quinn, and Wadsley suggests that

> "As SMBHs become incorporated into progressively larger halos, they sink to the center of the more massive progenitor, owing to dynamical friction and eventually forming a binary. In a purely stellar background, as the binary separation decays, the effectiveness of dynamical friction slowly declines, and the pair then becomes tightly bound, namely

by capturing stars that pass close to the holes and ejecting them at much higher velocities" (CS) (Mayer, et al., 2007)

However, if the separation between the binaries continues to reduce "the loss of orbital energy due to gravitational wave emission finally takes over, and the two SMBHs coalesce" (Mayer, et al., 2007). Black holes binary systems are two black holes orbiting about each other (Valtaoja & Valtonen, 1989). The starting details of this process is better explained in a 1989 article that clarifies that the larger black hole in the binary system collects stars around it and the smaller black hole orbits the bigger one (Valtaoja & Valtonen, 1989). This research adds that subsequent evolution of the binary system may be affected by gravitational radiation.

Other works argue that mergers aren't actually efficient contributors for SMBH growth. Di Matteo, et al., agree that the early physical conditions that allowed black hole seeds to grow into SMBHs remain a challenge to explain, but he argues that if distinct population of black hole seed range from 100- $10^5\ M_\odot$ were in place, then "growing the seeds to $10^9 M_\odot$ in less than a billion years requires extremely large accretion rates – as mergers holes are too rare and too inefficient for significant growth" (Di Matteo, et al., 2011). Another research makes a similar statement by hypothesizing that "the total mass accreted by MBHs [SMBHs] implies that at least 2-3 e-folds of the mass is grown via radiatively efficient accretion, rather than accumulated through mergers or radiatively inefficient accretion" (Volonteri, 2010). This implies that perhaps accretion contributes more to the growth of SMBHs than mergers.

The unification of galaxies produce several effects that contribute to growth of SMBHs, and trigger accretion. Mergers provide an unceasing supply of gas, which is then accreted by the central black hole of the host galaxy (Silk & Rees, 1997). This gas inflows are produced by gravitational torques during the merger, which triggers starburst – area with high rate of star formation (Hopkins, et al., 2005).

Methodology

The focus of this research was to layout the origins of supermassive black holes, and present the different hypothesis proposed so far about SMBH formation process in the early universe. Different researches were compiled and analyzed to present what is out there in the field of astronomy and astrophysics regarding SMBH formation. Some stages of the previous SMBH formation like accretion and collapsing had two different arguments, and they were presented as two possible explanations. I was particularly interested on what caused SMBH formation in the early universe, however, most of the data obtained in the researches that I used were only gathered from simulations, and not actual events since our technology has not allowed us to obtain more information about the early universe. The answer to conundrum about how SMBHs are formed has yet to be solved.

Conclusion

Early SMBHs grew through the accretion of matter and through the merger of galaxies. This process takes a significant amount of time. The information provided in the research shows quasars, which are powered by SMBHs, have high luminosities by 700MY after the big bang and have evolved into galaxies. If SMBHs form through black hole seeds, then those seeds must have preceded quasar formation and be much bigger than previously thought. This backs up the hypothesis that SMBHs could have been formed through the direct collapse of dark matter present soon after the big bang. However, there is no observational evidence supporting direct collapse hypothesis. In addition, the recent discovery of quasar SDSS J0100+2802 and quasar ULAS-J1120+0641 has confirmed that SMBHs formed earlier than 700MY before the big bang. Nonetheless, the question of how SMBHs grew so big and so quickly remains unanswered.

Acknowledgment

Special thanks to Dr. Tom Hooten whose enthusiasm, patience, and unconditional aid in the research and organizational process helped me focus and appreciate the subject in matter as well as the research field. Special appreciation to Professor Ryan Button for his guidance and advices about the research process. I also thank the honors program at Tyler Junior College for the opportunity given to me to experience a higher level of research. I will hold dear all that I have learned and experienced in this process.

Works Cited

Baade, W., & Zwhicky, F. (1934).

Begelman, M. C. (2008). Did Supermassive Black Holes Form by Direct Collapse? *American Insitute of Physics, 440*, 489.

Bennet, J., Donahue, M., Schneider, N., & Voit, M. (2014). *The Cosmic Perspective Seventh Edition .* San Francisco : James Smith .

Bhattacharya, D. (2011). Beyond the Chandrasekhar Limit: Structure and Formation of Compact Stars . *Pramana: Journal of Physics* , 29.

Bromm, V., & Loeb, A. (2003). Formation of the First Supermassive Black Holes. *The Astrophysical Journal*, 34-46.

Carroll, S. (2013). *Dark Matter, Dark Energy: The Dark Side of the Universe.* Pasadena: California Insitute of Technology.

Chandrasekhar, S. (1994). The Density of White Dwarf Stars. *Journal of Astrophysics and Astronomy* , 107.

Chandrasekhar, S. (1995). Newton's Principia for the Common Reader. *Oxford: Oxford University Press*, 1-2.

Colligan, D. (2009, November). The Discovery Interview: Jocelyn Bell Burnell . *Discover Magazine* , pp. 67-74.

Combes, F., Barret, D., Contini, T., & Pagani, L. (2003). Supermassive Black Holes (SMBH) and Formation of Galaxies . *EDP Science* , 239.

Di Matteo, T., Khandai, N., DeGraf, C., Feng, C., Croft, R., Lopez, J., & Springel, V. (2011). Cold Gas and The First Quasars in Cosmological Simulations . *Astrophysical Journal* , 1.

Einstein, A. (1914-1917). The Foundation of the General Theory of Relativity. In A. Kox, M. J.Klein, & R. Schulmann, *The Collected Papers of Albert Einstein* (p. 147). Princeton University Press.

Galilei, G. (1638). *Discorsi e Dimostrazioni Matamaiche intorno a nouve Scienze.* Leiden, Holland : The House of Elzevir .

Gultekin, K., Cackett, E. M., Miller, J. M., & Di Matteo, T. (2012). A Chandra Survey of Supermassive Black Holes With Dynamical Mass Measurements. *The Astrophysical Journal, 749*, 1.

Haiman, Z. (2010). The Origin and Detection of High-Redshift Supermassive Black Holes. *American Institute of Physics* , 219.

Halliday, D., Resnick, R., & Jearl, W. (2011). *Principle of Physics.* Hoboken, New Jersey : John Wiley & Sons .

Hawking, S. (1975). Particle Creation by Black Holes . *Communications in Mathematical Physics* , 199.

Hu, J., Shen, Y., Lou, Y.-Q., & Zhang, S. (2005). Forming Supermassive Black Holes by Accreting Dark and Baryon Matter. *The Authors. Journal Compilation*, 345-351.

James, C. (1932). Possible Existance of a Neutron" . *Nature* , 129.

Khandai, N., Feng, Y., DeGraf, C., Di Matteo, T., & A.C. Croft, R. (2015). The formation of Galaxies Hosting z~6 Quasars. *Royal Astronomical Society, 000*, 1.

Lynden-Bell, D. (1969). Galactic Nuclei as Collapsed Old Quasars . *Nature* , 223.

Mayer, L., Kazantzidis, S., Madau, P., Colpi, M., Quinn, T., & Wadsley, J. (2007, June 29). Rapid Formation of Supermassive Black Hole Binaries in Galaxy Mergers with Gas. *Science* , p. 1874.

Melia, F. (2003). *The Edge of Infinity: Supermassive Black Holes in the UNiverse.* Cambridge: Cambridge University Press.

Mitchel, J. (1783). On the Means of discovering the Distance, Magnitude of the Fixed Stars. *Philosophical Transactions of the Royal Society of London* , 50.

Newton, I. (1730). *Opticks.* London : William Innys .

Newton, I. (1846). *The Mathematical Principles of Natural Philosophy (translated by Andrew Motte).* New York : Daniel Adee.

Oppenheimer, R., & Snyder, H. (1939). On Continued Gravitational Contraction . *Physical Review* , 455-456.

Puget, J., & Heyvaerts, J. (1980). Pupulation III Stars and the Shape of the Cosmological Black Body Radiation. *Astronomy and Astrophysics, 83*, L10. Retrieved from http://adsabs.harvard.edu/abs/1980A&A....83L..10P

Richstone, D., E.A.Ajhar, Bender, R., Bower, G., Dressler, A., Faber, S., . . . Tremaine, S. (1998, october 1). Supermassive Black Holes and the Evolution of Galaxies. *Nature, 395*, A14.

Shapiro, S., & Teukolsky, S. (1985). The Collapse of Dense Start Clusters to Supermassive Black Holes: The Origin of Quasars and AGNs. *The Astrophysical Journal*, 41-44.

Shapiro, S., & Teukolsky, S. (1992). Black Holes, Star Clusters, and Naked Singularities: Numerical Solution of Einstein's Equations. *Phylosophical Transactions: Physical Sciences and Engineering, 340*, 365.

Shields, G. A. (1999). A Brief History of Active Galactic Nuclei . *The Astronomical Society of the Pacific* , 661.

Stein, J. (2011, 12 20). *The Nature Of Reality* . Retrieved from The Schwarzschild Radius: Nature's Breaking Point: http://www.pbs.org/wgbh/nova/blogs/physics/2011/12/the-schwarzschild-radius-natures-breaking-point/

Valtaoja, L., & Valtonen, M. (1989). Binary Pairs of Supermassive Black Holes: Formation in Mergin Galaxies. *The Astrophysical Journal*, 47-53.

Vernon, C. (1894). The Newtonian Constant of Gravitation . *Royal Insitution of Great Britain* , 355.

Volonteri, M. (2010). Formation of Supermassive Black Holes. *Astronomy Astrophysics, 18*, 293.

Wali, K. C. (1982). Chandrasekhar vs. Eddington-- and unanticipated confrontation . *Physics Today* , 35-37.

Wu, X.-B., Wang, F., Fan, X., Yi, W., Zuo, W., Bian, F., . . . Beletsky, Y. (2015, February 25). An ultraluminous quasar with a twelve-billion-solar-mass black hole at redshift 6.30. *Nature, 518*, 512.