On Supermassive Black Holes

Joshua Lewis
Section 008

1. A Brief History and Introduction

The concepts behind a black hole are amazing and frightening and almost impossible to comprehend. The fact that there can be a point in space around which nothing, not even light, can escape its grasp is horrifying to imagine. What's worse is the recognition that there are billions, if not trillions of these monsters lying invisible to the naked eye and many other forms of detection. Still, within the last 40 years a new form of these incredible objects has taken ahold of the scientific community in the form supermassive black holes. First proposed by Donald Lynden-Bell in 1971, the first supermassive black hole was discovered in 1974 right in the center of the Milky Way. Before understanding what a supermassive black hole is, however, an introduction to black holes themselves may be necessary. (Celottie et al 1999) (Lynden-Bell 1969)

The concept of bodies that do not allow light to escape did not actually begin in the 20th century. In 1784, John Michell described a body (often referred to as a "dark star") that has an escape velocity high enough to contain light. This body would not be directly observable, but could be indirectly observed by the motion of revolving bodies around the central one. What Michell did not know was that he was describing an early concept of a black hole. John Michell is widely accepted as being the first to recognize the possibility of massive objects that do not allow light to escape them. (Celottie et al 1999)

In 1915 Albert Einstein published his renowned paper on General Relativity. In doing so, he marked the beginning of human understanding of gravitation as the distortion of the geometric plane of spacetime. Spacetime is the combination of the three dimensions of space and one dimension of time into a single entity; that is, it is a simplification of the physical theories associated between them. Unlike a simple geometric plane, however, the plane of spacetime presented by Einstein is curved. (Adams, 1997)

One of the key concepts in Einstein's theory were the Einstein Field Equations, which essentially describe the way gravitation behaves due to this curvature of spacetime. At the time, Einstein was unable to solve his equations, but by 1915 Karl Schwarzschild was able to produce a solution for the gravitational field outside a mass that is spherical, non-rotating, uncharged, and symmetric. This solution has been useful for discovering properties of a Schwarzschild black hole, which is distinguished by its event horizon—the spherical area around the black hole that marks the point where even light cannot escape its gravitational pull. In a non-rotating black hole, this point is the Schwarzschild radius of the mass, or the radius of the space that the mass of an object would need to be compressed in order for the object to keep light bound by its gravitation. Although the Schwarzschild radius exists for every object, only objects with sufficient mass can overcome the outward pressure being applied by degenerate matter. (Celottie et al 1999) (Adams, 1997)

Degenerate matter is matter which is compressed so tightly that it produces a tremendous outward pressure because the Fermions inside cannot move to a lower energy level. The basis for this matter is the Pauli Exclusion Principle which states that no two Fermions can have the exact same quantum state. In fact, the force due to this matter is so great that it can keep certain stars from collapsing completely. Such is the case with white dwarfs, which are made up of mostly degenerate matter. However, an object with sufficient mass can overcome this outward pressure with its enormous gravitational force. In the case that the gravitational force exceeds all outward pressure due to degenerate matter, the object will undergo gravitational collapse and turn into a singularity—forming a black hole. In this state, spacetime almost ceases to be relevant. The concepts of "space" and "time" no longer apply. (Kovetz et all 1973)

An upper limit on the mass that an object can hold before collapsing into a black hole was not given until Subrahmanya Chandrasekhar computed a limit on the mass of white dwarf stars in 1930. Chandrasekhar took into account the electron degeneracy pressure that counterbalanced the gravitational force trying to collapse the star, and eventually determined a limit of about 1.44 solar masses for a white dwarf before the star collapsed into a black hole or neutron star. Robert Oppenheimer, along with his colleagues, would later compose another limit called the Tolman-Oppenheimer-Volkoff limit which predicts the required mass of a neutron star to collapse into a black hole at about three solar masses. It is possible that a sufficiently massive neutron star could collapse into what is called a Quark star, but for what is known, a black hole is the most likely route. (Celottie et al 1999)

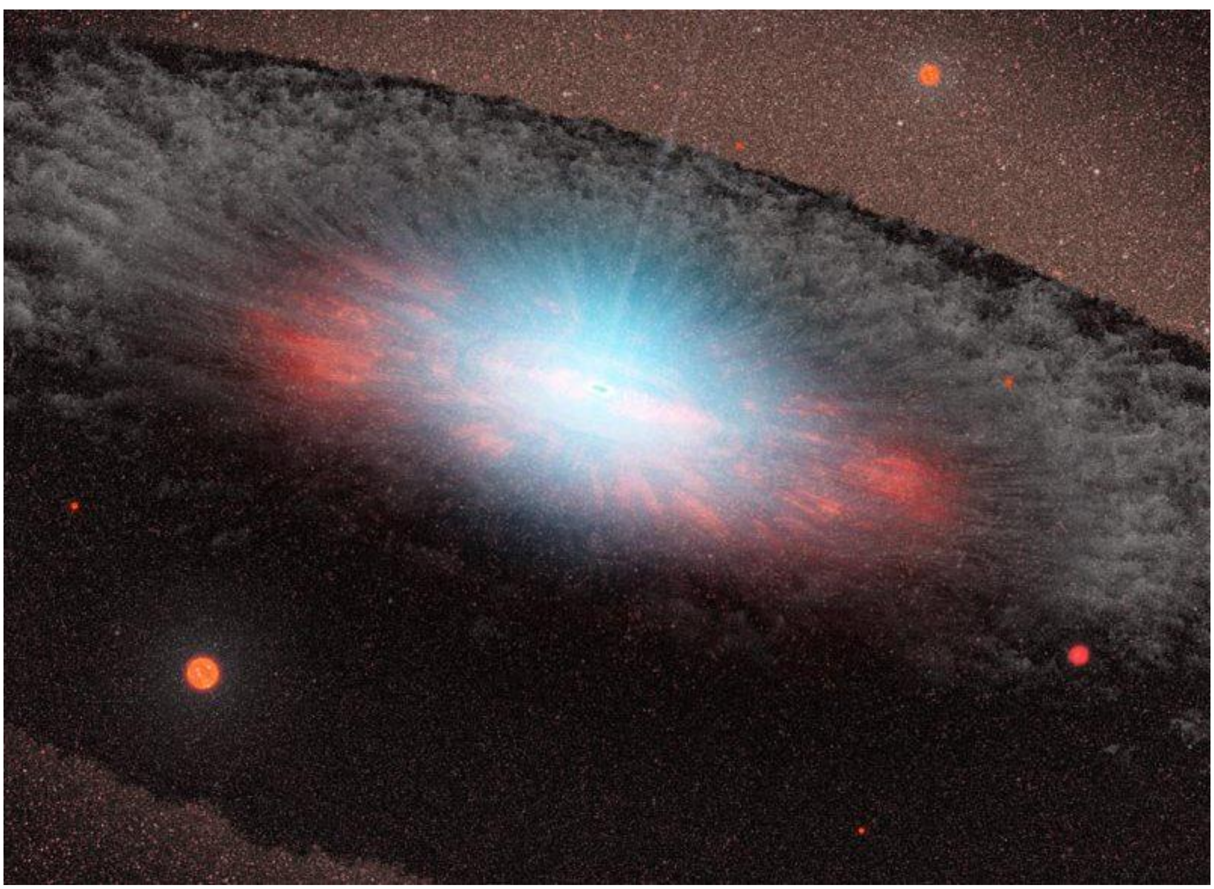
So, there is a minimum mass for an object to become a black hole, but no known upper limit to the mass a black hole can have. It has been theorized that black holes formed early on in the Universe's lifetime could have grown in mass via accretion of outside matter. As a result of billions of years of accretion, these black holes would become sizeable enough to compare with dwarf galaxies. There is more than one theory behind these kinds of anomalies, but what is certain is that there are several extremely massive structures in the universe known as supermassive black holes. (Begelman et al 2006)

2. Supermassive Black Holes

A supermassive black hole (SBH) can be described as a black hole that is extremely massive in scale. While this definition is technically correct (which is the best kind of correct), it does not stand up to the true importance of SBHs. SBHs are incredibly large black holes—think millions to billions of solar masses—that are believed not only to play a role in the development, but also be at the center of most galaxies including the Milky Way. The relationship between SBH and galaxy is in fact so close that some scientists believe the formation and development of a galaxy is not possible without a SBH and vice versa. Between 1999 and 2000, a proposal that there is a relationship between the mass of an SBH at the center of a galaxy and the galaxy's velocity dispersion at the galactic bulge was made. This correlation, called the M-sigma relationship, gave scientists evidence of the importance of SBHs and the vital role they play in galactic development. The exact nature of SBHs in the formation and evolution of galaxies is still unknown, and is a question that intrigues many astronomers today. (Ferrarese et al 2000) (Merritt et al 2000) (Marconi et al 2004)

SBHs themselves have characteristics besides mass that differ from ordinary black holes. Previously mentioned was the Schwarszchild radius for a black hole, which is normally the indicator for a non-rotating black hole's event horizon. The Schwarszchild radius follows the equation $r_s = \frac{Gm}{c^2}$ where r_s is the calculated Schwarszchild radius, m is the mass of the object, and G and c are universal constants. The result for most black holes is exceedingly normal. However, an interesting occurrence takes place for SBHs. The Schwarszchild radius of an object increases linearly with mass, while volume increases with the cube of the body's radius. This means that, assuming an object has constant density, as size increases, matter will accumulate more quickly than the radius will increase. For substantially large objects, like SBHs, the radius of the body may actually lie within its Schwarzschild radius. In addition, because SBHs are so large, their volumes become enormous, giving many SBHs densities lower than water, and the forces applied to an observer traveling through the black hole would not be substantial until very close to the center of the SBH. (Celottie et al 1999)

Most black holes have an accretion disc that emits radiation due to incredibly high temperatures emanating from intense pressure on gaseous matter rotating around them. As is the case typically associated with SBHs, the accretion disc for black holes of several million solar masses is bigger, better, and more prone to light shows. The rapid expansion of SBHs due to an enormous accretion of gas around it is widely believed to be the phenomenon behind quasars—incredibly bright galactic nuclei that can outshine entire galaxies in a space smaller than the Solar system. The fluctuations that quasars experience are caused by the changes in available gas for accretion. (ScienceDaily 2009) (Celottie et al 1999)



An artist's concept of a SBH accretion disc. (NASA 2008)

3. Formation and Location

Exactly how SBHs are formed is currently a mystery to modern astronomers. There are at least two strong theories that are almost direct opposites of each other. The first theory is a drastic form of the “slow and steady” principle. The first stars being formed were likely Population III stars—stars formed metal-free. This lead to stars that were very massive and very difficult to keep from collapsing. According to the theory, the massive Pop III stars would collapse and leave behind “seed” black holes of tens to hundreds of solar masses. These black holes could then accumulate mass over billions of years, leading to the SBHs seen today. (Begelman et al 2006) (PhysicsWorld 2011)

The other theory is a quicker take and focuses on the rapid collapse of highly dense gas into a massive star. The star would be very fragile and quickly undergo gravitational collapse into another kind of “seed” black hole. These black holes, however, are significantly more massive than the lighter “seeds”. The heavier “seed” black holes would be formed with millions of solar masses, starting at the supermassive range. SBHs formed in this way could continue to grow over time like their counterparts, but in this case the black holes are more likely to be formed much later than lighter “seeds” would be, so not nearly as much mass would be accumulated. (Begelman et al 2006) (PhysicsWorld 2011)

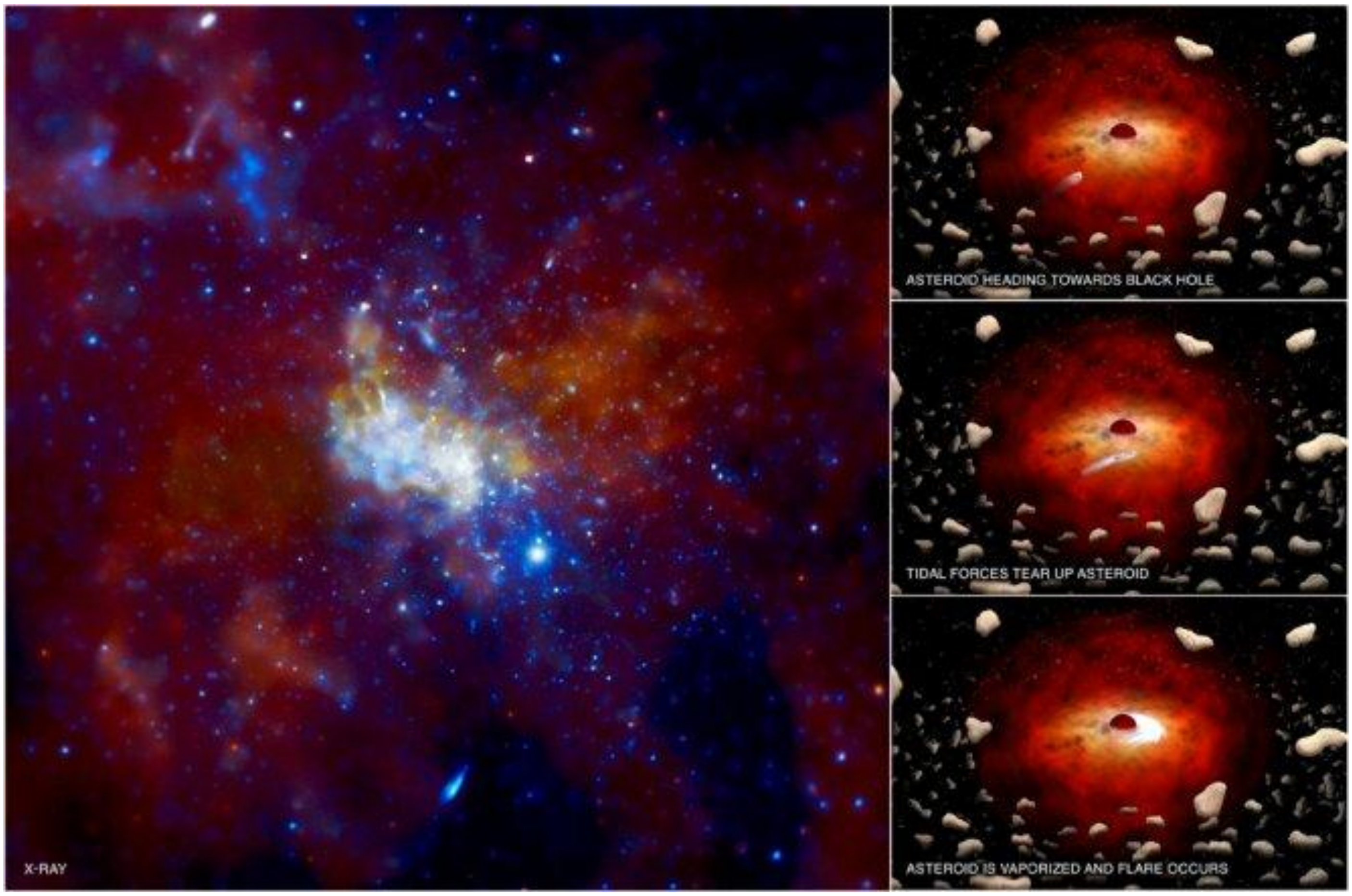
An alternative “seed” is also a possibility for SBH formation. If dark matter played a pivotal role in early star formation and if dark matter compression was great enough, weakly interacting massive particles could annihilate in order to produce energy that would counterbalance gravitational collapse of the star. Instead of nuclear energy producing an outward force in these stars, the annihilation energy keeps the star from collapsing in on itself.

When these stars finally do undergo gravitational collapse, the result would be large black holes likely close to if not exceeding the lower limit for SBHs. (Begelman et al 2006)

Regardless of the theories of formation, the locations of SBHs provide important information on their backgrounds. As previously mentioned, the first SBH discovered, known as Sagittarius A*, was detected within the Milky Way. The claim that this galaxy contains a SBH was tested by (A Ghez 1998) and the same conclusion was drawn—a SBH exists at the heart of the Milky Way Galaxy. Meanwhile, others such as (John Kormendy et al 1995) sought out objects within other galaxies. (John Kormendy et al 1995) used a three-step process to find SBHs.

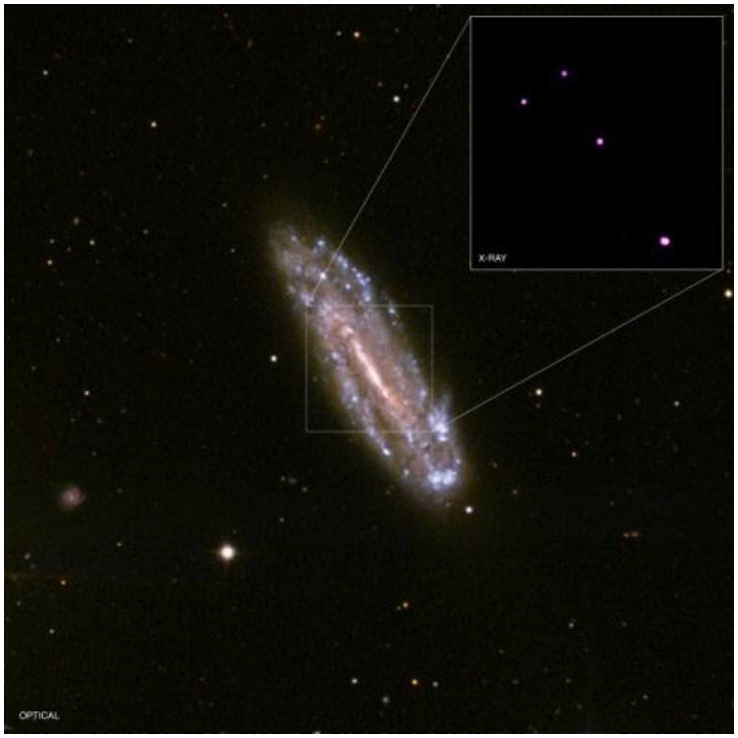
The first step is to search for central dark masses with a high mass-to-light ratio. This ratio suggests the presence of a "massive dark object" (MDO). Next, whether or not the MDO is a black hole must be determined by ruling out plausible alternatives, such as if the object is actually a cluster of stellar remnants. These two processes are done repeatedly to gain information on galactic nuclei, and a statistical survey is finally done to map information on black hole properties and locations. (John Kormendy et al 1995)

MDOs have been found within galaxies such as M31, M32, M87, and others. Though over 40 SBHs have been detected in galaxies—and it is believed that they reside in almost all galaxies—not all MDOs detected turn out to be SBHs, and other gas and stellar dynamical methods must be done to hone in on these central black holes, the ones that are key to understanding the galaxies they reside within. (John Kormendy et al 1995)



A Chandra X-Ray Observatory image showing Sagittarius A* and an X-ray flare. Accessed November 14, 2012 (NASA 2012)

Some galaxies known to contain SBHs in them include the Milky Way, the Andromeda Nebula, and M87. The Andromeda Nebula's SBH is approximately 30 million solar masses, while M87's SBH is around 3 billion solar masses. In comparison, the Milky Way's own SBH is only about 4 million solar masses. (HubbleSite 1997) (A Ghez 1998)



Revealing a tiny SBH, only about 360,000 solar masses, in the center of NGC 4178. Accessed November 13, 2012 (NASA 2012)

4. Conclusion

SBHs continue to be an intriguing part of astronomy not only because of their reputations as extremely large black holes, but also because of the profound physics behind their formation, development, and unexpectedly active role in most galaxies and quasars. Here, an introduction to concepts behind black holes and their relationship with SBHs was given along with a brief history behind the beginnings of research into black holes and the profound affects that a number of scientists had on the human knowledge of black holes. Some of the consequences of SBHs were also described, including the theories behind their formation, and way in which they may be found by astronomers.

Supermassive black holes are just one category of physical phenomenon that continue to baffle and interest astronomers. Solving some of the problems behind SBHs, such as how they are formed, why they are so closely related to galaxies, and how they continue to develop would open up several doors in physics and likely raise many more questions. Black holes in general may seem like terrifying abominations of nature to those who don't understand them (that's everybody), and supermassive versions of them likely push away as many people as they draw in out of the thrill of discovery, but it's the questioning and discovery that make science what it is, and what it will hopefully always be.

Bibliography

A Celottie, J Miller, and D Sciama. 1999. “Astrophysical evidence for the existence of black holes.” *Classical and Quantum Gravity*. Accessed November 2, 2012. doi: 10.1088/0264-9381/16/12A/301

Mitchel Begelman, Marta Volonteri, and Martin Rees. 2006. “Formation of Supermassive Black Holes by Direct Collapse in Pregalactic Halos.” *American Journal of Sociology*. Accessed October 23, 2012. doi:10.1111/j.1365-2966.2006.10467.x

NASA/JPL-Caltech 2008. “An Unwelcome Place for New Stars.” *Nasa.gov* Accessed November 13, 2012.

NASA/JPL-Caltech 2012. “Revealing a Mini-Supermassive Black Hole.” *Nasa.gov* Accessed November 13, 2012.

NASA/JPL-Caltech 2012. “Supermassive Black Hole Sagittarius A*.” *Nasa.gov* Accessed November 14, 2012.

A Ghez. 1998. “High Proper Motion Stars in the Vicinity of Sagittarius A*: Evidence for a Supermassive Black Hole at the Center of Our Galaxy.” *The Astrophysical Journal*. Accessed November 11, 2012. doi: 10.1086/306528

John Kormendy, Richstone Douglas. 1995. “Inward Bound---The Search For Supermassive Black Holes In Galactic Nuclei.” *Annual Review of Astronomy and Astrophysics*. Accessed October 28, 2012. doi: 10.1146/annurev.aa.33.090195.003053

Laura Ferrarese and David Merritt. 2000. “A Fundamental Relation between Supermassive Black Holes and Their Host Galaxies.” *The Astrophysical Journal*. Accessed October 28, 2012. doi: 10.1086/312838

A Marconi, G Risaliti, R Gilli, L Hunt, R Maiolino, and M Salvati. 2004. “Local supermassive black holes, relics of active galactic nuclei and the X-ray background.” *Monthly Notices of the Royal Astronomical Society* 351: 169–185. Accessed November 11, 2012. doi: 10.1111/j.1365-2966.2004.07765.x

David Merritt and Laura Ferrarese. 2000. “The M(BH)-Sigma Relation for Supermassive Black Holes.” *The Astrophysical Journal*. Accessed November 11, 2012. doi: 10.1086/318372

PhysicsWorld. “How do supermassive black holes form?.” Last modified January 13, 2011. http://physicsworld.com/blog/2011/01/how_do_supermassive_black_hole.html

ScienceDaily. “Super-Massive Black Holes Observed at the Center of Galaxies.” Last modified December 11, 2009. http://www.sciencedaily.com/releases/2009/12/091210173609.htm

Steve Adams, Relativity: An Introduction to Space-Time Physics (CRC Press, 1997).

A Kovetz and G Shaviv. 1973. “The Electrical and Thermal Conductivities of Stellar Degenerate Matter.” *Astronomy and Astrophysics*. Accessed November 11, 2012. http://adsabs.harvard.edu/abs/1973A&A....28..315K

HubbleSite. “Massive Black Holes Dwell in Most Galaxies, According to Hubble Census.” Released January 13, 1997. http://hubblesite.org/newscenter/archive/releases/1997/01/text/

Donald Lynden-Bell. 1969. “Galactic Nuclei as Collapsed Old Quasars.” *Nature*. Accessed November 11, 2012. http://www.oa-roma.inaf.it/~fiore/agn/LyndenBell_1969.pdf