Stellar Disruptions of Super Massive Black Holes

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Abstract: Here I explain clearly the effects that a super massive black hole has upon the stars that venture too close to it. After introducing the notion of what a black hole is, and the properties and importance of super massive black holes in galactic nuclei, I go through what happens when a star passes close enough to become bound and distorted by the hole. This situation causes a flare to erupt, as the material from the bound star is swallowed. Expected observational effects relating to such stellar disruptions are then described, and expectations of observations by astronomers are explored.

Keywords: Black Hole – Super Massive, Tidal Disruptions. AGN. Accretion Disk.

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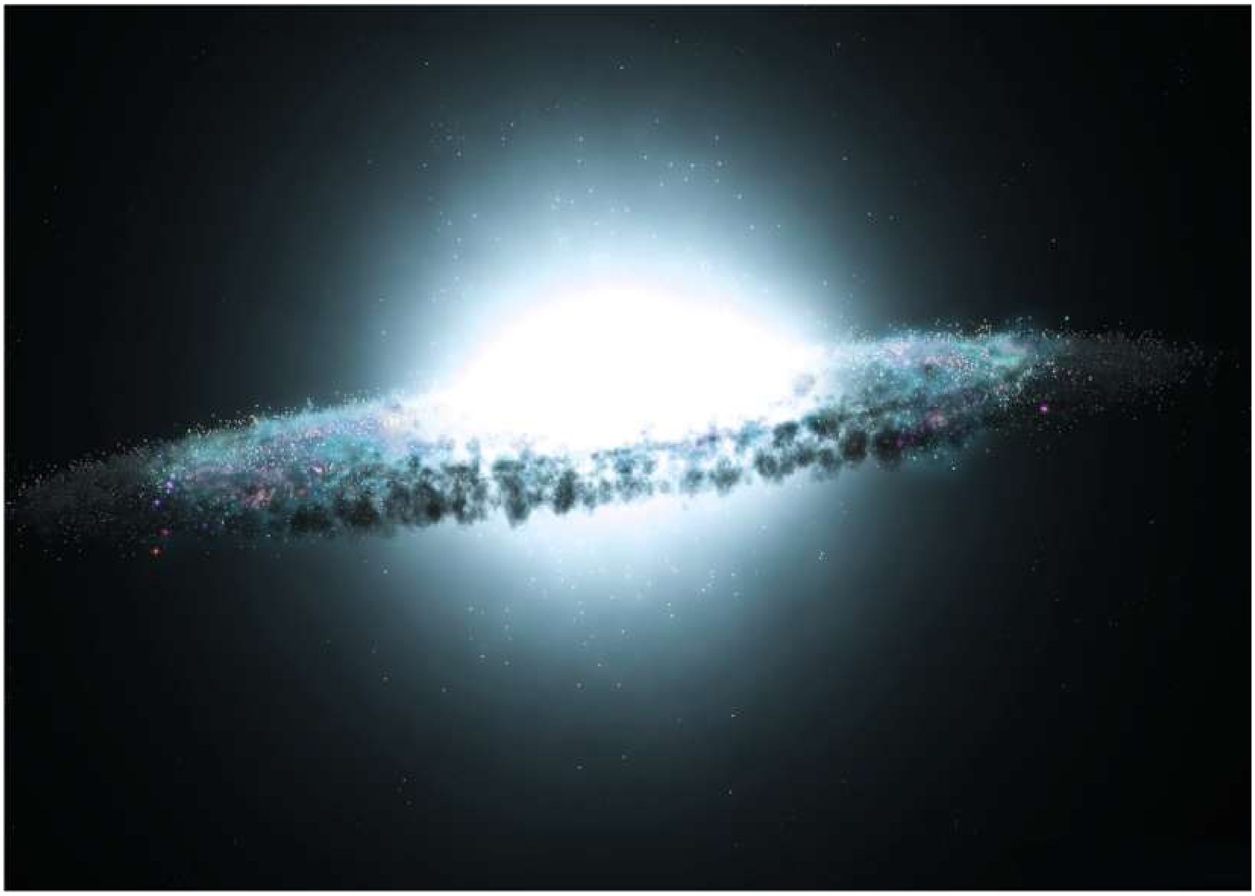


Black holes are one of the most mysterious objects in our universe.

Once thought to be theoretical fantasy, black holes are now an undisputed reality. Although all black holes share the same fantastic properties and theories – such as the capture of light, infinite density singularities, warping of space-time, possible time travel, time acceleration and deceleration – one class in particular is even more amazingly counterintuitive: the super massive black holes which reside in the centers of galaxies. These black holes have the equivalent mass of over a million suns and continue to devour any material or stars that venture too close. The study of such super massive black holes is of great importance to astronomers and physicists alike, not only due to their unique nature which acts as a bridge to physics not yet conceived, but also to their clear participation and relation to galaxy formation, in which the conditions necessary for our existence were set into motion. In order to study these monstrous fissures in our space-time continuum, one must learn the basics of what these holes actually are, learn what effects they cause to the objects around them, and then finally putting these effects into use for observational procedures. Here we attempt to discuss such aspects of super massive black holes in a concise and complete way, without the interruption of ideas with mathematical formulas.

Black Holes: An Overview

In the early 20th century, Albert Einstein published his General Theory of Relativity, changing the way everyone looks at the universe. Before Einstein, space was assumed to be flat, meaning that if you were to consider the universe as two-dimensional, we would all be living on a flat plane much like a piece of paper. This plane would have no idea of a third dimension, and thus no “outside”. The plane would be static and unable to bend since there is no third dimension to bend into. Einstein changed all that by theorizing that the universe is in fact curved, and the gravity of an object with some mass causes distortions in the fabric of space-time, much like a ball resting on a rubber plane causes an indentation in the plane. The more massive the object is, in the same volume, the “deeper” it will sink into the plane, and the more it will distort the fabric. This distortion can be viewed as a gravity well, causing objects near it to accelerate towards the object.

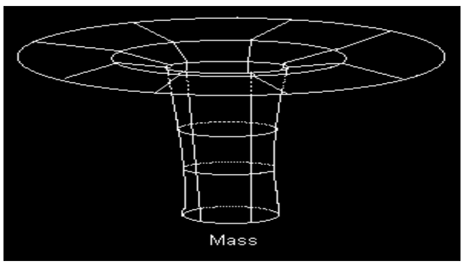


Figure 1: Analogy of Curved Space

In 1916, a physicist by the name of Dr. Karl Schwartzschild started to try to solve Einstein’s equations of General Relativity. His solutions, which were the simplest to derive, found that if a mass were to be compressed into a small enough volume, the space-time fabric would be so distorted, that nothing within a certain distance near it could escape falling into the gravity well, not even light. [1]

Such an object is what a black hole is defined to be. Just how much compression does one need to create a black hole? If one were to compress the mass of the earth into a volume small enough to create a black hole, the volume necessary to contain the entire earth would be a sphere with a radius of only about nine and a half centimeters! [2] This density requirement seemed to many to be so extreme, that the likelihood of anything in nature actually creating a black hole was deemed to be almost impossible. Over the years however, the evidence that black holes do in fact exist has increased to the point that they are now an undisputed reality of the cosmos.

Black holes come in two main sizes. Those that are about three times the mass of our sun, and those that has a mass of over one *million* of our suns. The low mass black holes are created when a star uses up all of its fuel and, due to gravity, collapses in on itself. The origins of the super massive variety of holes however, are somewhat unknown. This, along with the apparent relation between super massive black holes and galaxy evolution [3], is a reason that studying super massive black holes is considered very important. The study of such holes requires their detection, which when it comes to black holes, is very troublesome.

As mentioned before, when anything (even light) gets to within a certain radius of a black hole, it is trapped and swallowed. This radius is known as the Schwartzschild radius, or event horizon. Because not even electromagnetic radiation (light) can escape the horizon, black holes are not visible at all by normal means (to see an object, it has to emit electromagnetic radiation or reflect it into your eye, telescope, or other detector). Thus whatever the black hole really is -- be it a singularity of infinite density as predicted, or some new kind of exotic quantum gravity -- it is hidden from our universe forever. Since black holes cannot be seen in a classic manner, astronomers must strive to find effects caused by the holes on the surrounding areas in order to infer the black hole’s existence. (Actually black holes do radiate tiny amounts of particles and light, an effect known as Hawking Radiation. However, this effect is so slow, that it is negligible in our discussion).

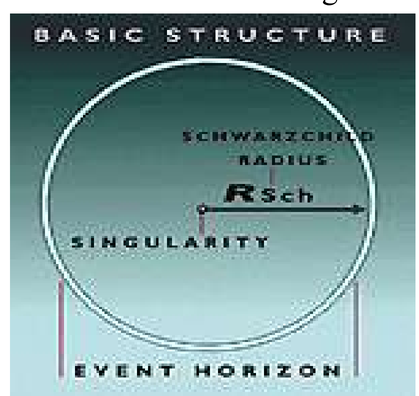


Figure 2: Black Hole Structure

Gravitational Effects and Accretion

At large distances, black holes have the same gravitational effects as anything else with the equivalent mass. For example, if the Sun were to miraculously and suddenly become a black hole, the Earth's orbit would not change at all. The gravitational effects of black holes at close distances are far more interesting, including creating huge tidal forces as well as allowing extremely fast orbits of stars.

Tidal force is the force caused by the difference of the gravitational attractions from one radius to another. A common measure of tidal force is the G scale used on earth. The gravitational pull on a person's head is just slightly less than the pull on the persons feet. This is considered 1G and is due to the fact that gravitational attraction lowers the farther you travel from the center of an object pulling on you. This force is not that much (although 15G's can kill you) because the earth's radius is around 5000km, and an average person is less than 2m tall. With a black hole, this situation is much more extreme. Since a black hole has enormous mass concentrated in such small volumes, the difference of gravitational force between one radius and another is enormous. This causes any material near the black hole to stretch into long thin streams.

Figure 3: Artist's Conception of Accretion Around a BH

Another effect the gravity of a black hole has is allowing extremely fast orbits of stars around it. For an object to have a stable orbit around a central mass, it must have a particular angular speed. This speed depends on the mass of the central object and the distance the orbiting object is to it. The closer the orbiter is, the faster it has to go. Because black holes allow objects to get closer to the center of their orbits than any other object of equal mass, they allow extremely fast orbits. In fact, at 1.5 times the event horizon radius, there is something called the photon sphere, where the stable orbital speed is the speed of light, (so only photons of light can be stable there). [4]

A combination of fast orbital speeds and tidal forces brings about a phenomenon called an accretion disk. When a lot of material gets closer than a certain radius to a black hole (mass dependant), it begins to spiral into the black hole. Tidal forces causes the material to stretch into thin streams, creating a disk of debris. Such an accretion disk, given enough material, can emit lots of radiation. How it works is that when material at a closer radius and hence faster speed, rubs with material at a larger radius, it causes a lot of friction. This friction in turn causes intense heat, thus emitting radiation. The same thing happens when you rub your hands together quickly. You cause increased heat, and thus increased infrared radiation to emit from your hands. Of course, a black hole's accretion disk glows with much higher energy spanning the entire electromagnetic spectrum including X-ray.

Accretion of material into a black hole can power immense energy outpour, given enough material. Active Galactic Nuclei, which include quasars and blazers, are thought to be fueled by such a process. Also, Gamma-Ray Bursts, which are some of the most powerful explosions in the universe, could be caused by the accretion of a neutron star onto a black hole. [5]

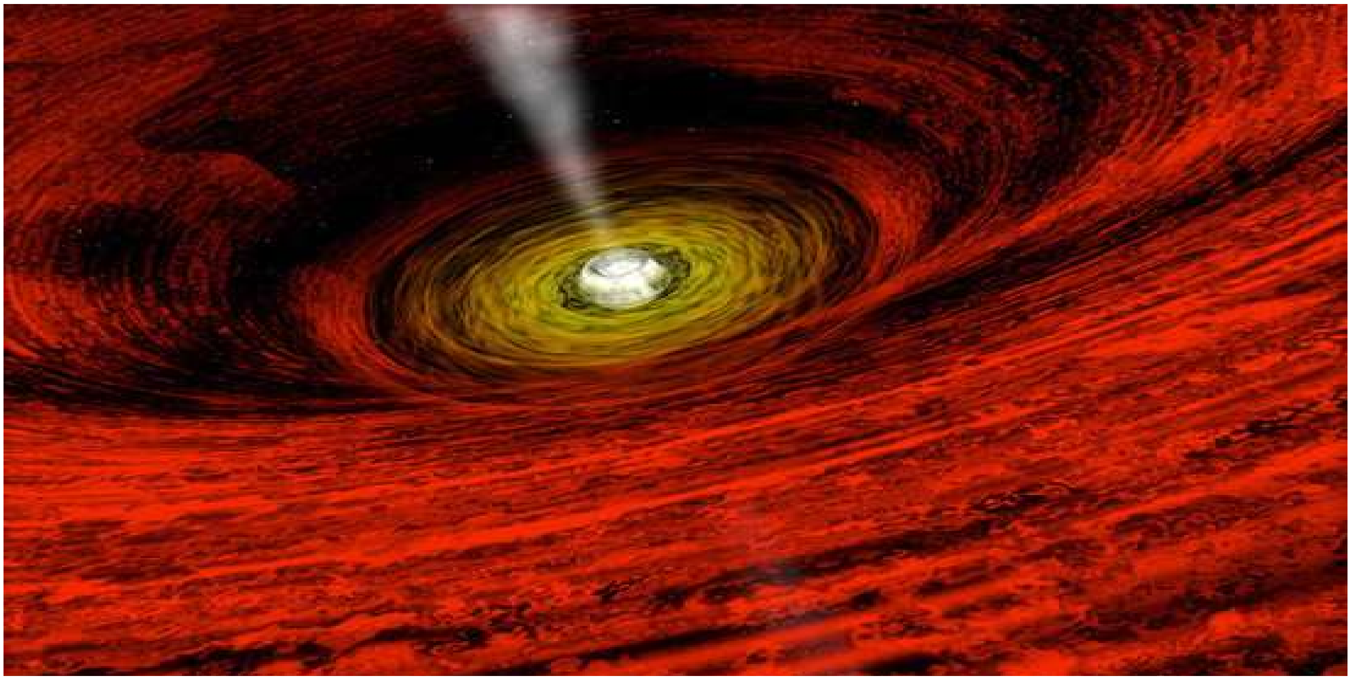


Figure 4: Artist's Conception of a Super Massive Black Hole at the Center of a Galaxy

Super Massive Holes Eat Stars

Super massive black holes are thought to reside in the center of most galaxies including our Milky Way. Recently, as will be discussed later, this has been proven to be true at least for our Milky Way. In such a location (the center of the galactic bulge), the stellar density is quite larger than in the galactic disk where we reside, and this combined with velocity dispersion, makes the occurrence of a star getting too close to the hole an unavoidable event.

Stars that are in orbit around the galactic center are usually pretty stable in their orbits. However, due to the massive amounts of stars, there is always the possibility of one star altering the orbits of other stars. This causes a velocity dispersion of stars. If the distribution of stars in the bulge had a well-defined core, then a star that happened to be inside that core would be most affected by the other stars, not the central black hole. Only when the star got to within a certain radius, would the black hole's gravitational effects take precedence and affect the star. [6]

This is precisely when a stellar disruption takes place. As with all flybys, if the star is going fast enough, and at a large enough radius, it will flip past the black hole before the hole has time to disrupt the star. This speed would have to be ~1000km/s for a one million solar mass BH.

If the black hole does capture the star, there are two possibilities. One, the star is so close that the hole eats all of it very quickly. The other, and observationally more useful option is that only some of the star gets bound to the black hole, while the rest gets flung out with intense speed. The material that is left over forms an accretion disk that can last up to a few years, thus causing a flare. Because the stars near the hole have close to radial orbits, this is the kind of flare expected to happen when a star gets close.

As such a star approaches the black hole, tidal forces begin to act on it, deforming the star into a watermelon shape. Due to gravitational effects, the stars orbital speed increases and the star also begins to spin faster. This brings about a situation where one side of the star is spinning along faster than the orbital direction, while the other side is spinning against the orbital direction. Since the rotation of the star is so fast, the side of the star in which the rotation is opposite the orbital direction is traveling much slower than the required stable orbital speed, and so tries to fall in closer. This effect is so great that it literally shreds the star apart, causing about half the star to form a long accretion stream, while the other half becomes unbound from the hole, and flies out of the vicinity at intense speeds causing a large stellar wind. [6]

The accretion disk that is formed by a stellar disruption can be geometrically thick or thin. The main relevant difference in these two models is their radiation output. The thin disk emits less radiation than a thick disk, but most astronomers believe the thick disk model is most accurate. [7] The output power of such a disk can be upwards of $\sim 10^{44}$ ergs/s. To put that in perspective, our sun has an output of $\sim 3 \times 10^{33}$ ergs/s. This means that the accretion disk from a stellar disruption has an energy output equivalent to one hundred billion suns! (This is about the same output as an entire galaxy!). This energy is given off mostly in the ultra violet and possibly X ray parts of the spectrum. [8,9]

The stellar winds created by the outflow of the other half of the star's material are also very energetic. These winds can deposit up to 10^{52} ergs of energy into the surrounding interstellar medium. This is roughly equivalent to the amount of energy that a large supernova ejects into its surrounding area. Because the area around the super massive black hole is dense with gas and material, the winds from the disruption can cause shock waves and compression in the surrounding material. [10]

Figure 5: The Galactic Core's Dense Gas

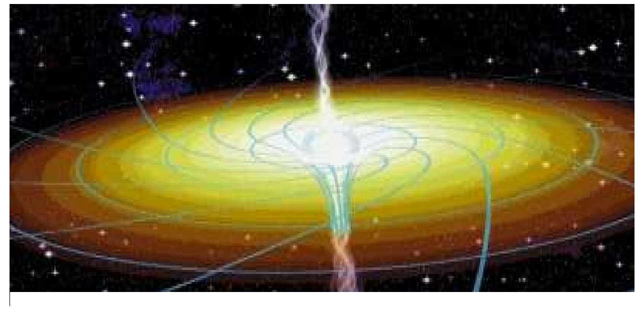


Figure 6: Conceptual Image of Accretion and Output Around Black Hole Showing Space-Time Gridlines

The flare caused by the accretion disk is short lived. The amount of time it takes for all the debris in the accretion disk to spin into the hole is on the order of months to a few years. This is due simply to the fill rate of the material into the black hole. As we shall see, this becomes very important when considering observations.

One other possible outcome of a stellar disruption comes about when a very large star, such as a red giant, gets disrupted. Due to the enormous size of the star, it is possible that only its outer shell would be stripped by the black hole, while its still-intact helium core ejects out back into the galaxy. This core would look very similar to a standard helium star created naturally at the end of the stars evolution. Although this star would not be very luminous compared to the flare (only about one hundred times the luminosity of the sun), it would in fact have a very fast velocity away from the hole, as well as a long life span, much longer than the flare. The velocity this star would travel would be upwards of 5% of the speed of light ($\sim 10^8$cm/s or 2,000,000 miles per hour). [11]

Tidal disruptions of stars around super massive black holes were once believed, due to their intense luminosity, to fuel Active Galactic Nuclei such as quasars. Quasars are believed to be caused by the accretion of material onto a black hole at the center of a galaxy. However, evidence shows that the rate of stellar disruptions cannot account for the amount of energy needed to fuel a quasar. [12] Despite its low rate, stellar disruptions would unavoidably occur eventually in any galaxy that had a central black hole. This is key to using flares to detect and learn about such super massive holes.

Observations: Is This Real?

The question by now should arise: Have we seen any of this? Have we seen super fast orbits around a tiny volume? Have we seen a flare? Have we seen stripped cores? The answers to these questions are yes, yes, perhaps, and maybe.

The first evidence that super massive black holes were real came from observing the stellar dynamics at the core of the Milky Way. As telescope technology increased, closer and closer stars relative to the center of the galaxy could be detected, and their orbits analyzed. It was found that given the amount of mass they were orbiting and the small volume this mass had to be in, any explanation besides that of a super massive black hole was very hard to believe. [13]

Recently, astronomers using new methods of adaptive optics (means of eliminating atmospheric interference of light) have strengthened the dynamical evidence for a super massive black hole in the center of the Milky Way to the point where they consider themselves having 'clinched the case'. They found a star that had an orbital period of 15 years and had a closest approach to the center of seventeen light hours. Earth by comparison is 8 light minutes away from the sun. The mass required to be contained in the small volume could only be a super massive black hole, because any other combinations of small black holes, neutron stars, etc. would quickly dissipate or collapse themselves into a super massive black hole. [14]

The only problem of using the dynamical observation technique described is that you need to be able to view stars in the most central regions of a galaxy. But, when you try to view other galaxies that are far away, this becomes impossible. Because of this, new ways of detecting the black holes are needed, and stellar disruption flares provide just such a way.

Although the flares have a peak of $\sim 10^{44}$ergs/s, many other considerations must be taken into account if one wishes to observe them. Such considerations include the frequency of the flares, the orientation of the galaxy, the efficiency of light able to travel outside the core, as well as being able to distinguish the flare versus other stellar events.

The average frequency of a stellar disruption occurring in an average galaxy is about one flare every 10,000 years. [15] Thus, because flares are short lived, seeing a flare in a nearby galaxy would be quite a coincidence. The solution is to search for a flare in a large population of galaxies. John Magorrian and Scott Tremaine of Cambridge and Princeton respectively, have taken this rate as well as many other limiting factors to come up with an equation for the total rate of flares out to a given distance. This equation can be used to estimate the number of flares expected to be observed by deep sky surveys.

Another important observational question is whether the light from the flare (which is mostly in the ultra-violet frequencies) could be seen by optical instruments. Studies show that a possibility exists that the stellar winds from the half of the star's material that was ejected, could concentrate the interstellar medium in a way that when the light from the flare hits it, the material absorbs and reemits the light in the near ultra-violet to visible parts of the spectrum. [16]

Although no direct flare observations have actually been made yet, there have been several claims, including some that are possible candidates. [17]

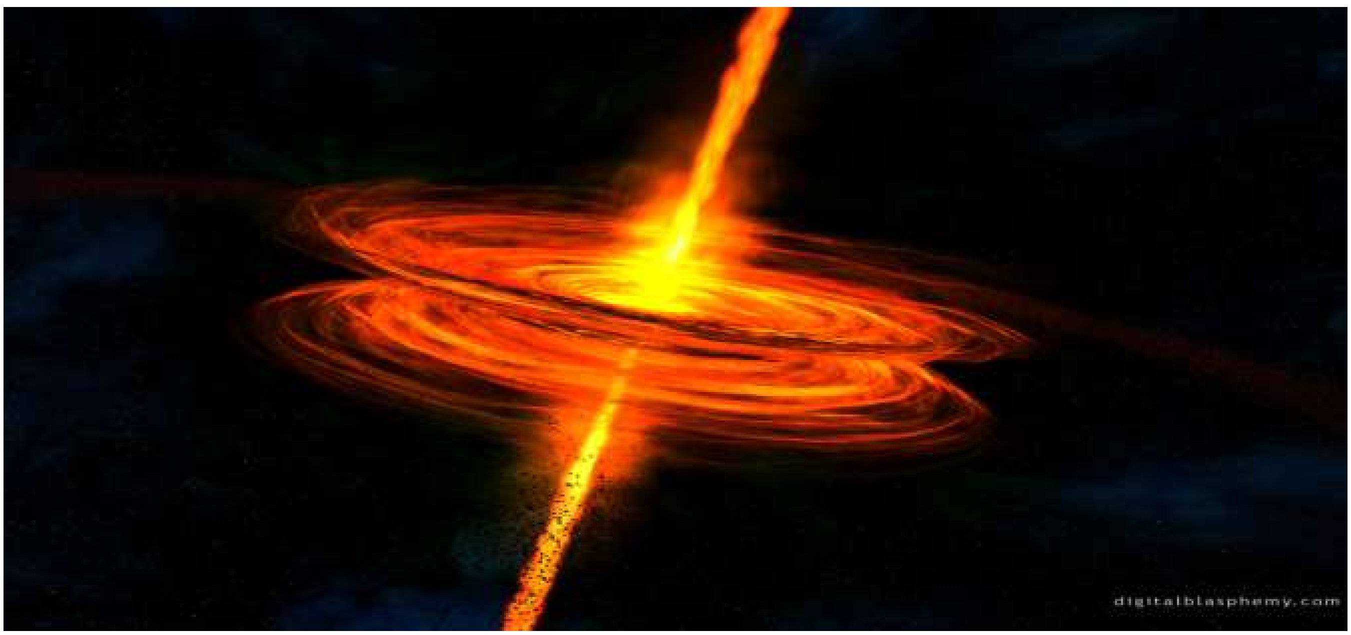
The lack of direct evidence of flares has led some researchers to try to find disruption events by looking for the stripped cores of large disrupted stars. Such observations are difficult because the core stars look very similar to standard helium stars from normal stellar evolution. Also, since the cores themselves are not extraordinarily luminous, detecting them in even nearby galaxies require the use of the Keck telescopes or the Hubble Space Telescope. One important aspect of these cores however, is that they last much longer then the disruption event that created them, and so the probability that they can be seen in nearby galaxies is very high. They would be seen as helium stars moving rapidly away from the center of the galaxy, and a ring formation of a few of these stars is to be expected. Observers must be careful in calculating the number expected to see, because the population of giant stars in the center bulge of the galaxy must be taken into account. [18]

Several helium stars have been observed that are very good candidates for having resulted from tidal disruptions. These are still being studied, and could lead to more information about the disruption events themselves, assisting in the study of flares and observations of flare events.

Many groups are active in the search for super massive black holes including a group headed by Dr. Phillip Lubin here at UCSB. Calculations performed by this group [19] have shown that with their new telescope array, they could see a volume of space where there is an average of up to two flare events per second. This rate is for over the entire sky, but is still appealing to the group as something to be on the lookout for.

Conclusion

Through the study of super massive black holes, scientists can learn incredible amounts about black hole formation, structure, as well as clues into galaxy evolution. The central black holes of galaxies are the machines of intense energies, including Active Galactic Nuclei. If these holes reside in all non-irregular galaxies, (which current estimates show is quite probable), than they are a key element in the universe in which we live. Through the techniques described, the confirmed detection of these in galaxies other than our own should not be far off. Perhaps it will take us one step farther in explaining how our universe evolved into the place we live today.



End Notes

1 – Lindsey, 1993 1
2 – See appendix A #1
3 – Kormendy and Gebhardt, 2001
4 – Hamilton, 2001
5 – Caplan, 1999
6 – Rees, 1988
7 – Ulmer, 1999 (pg 8)
8 – Loeb and Ulmer, 1997 (pg 1)
9 – Blake (pg 5)
10 – Ulmer, 1999 (pg 3)
11 – Stefano, Greiner, Murray, and Garcia, 2002
12 – Rees, 1988 (pg 1)
13 – Ulmer, 1999 (pg 1)
14 – Physics Today, 2003 (pg 19)
15 – Magorrian and Tremaine, 1999
16 – Loeb and Ulmer, 1997 (pg 2)
17 – Ayal, Livio and Piran, 2000 (pg 1)
18 – Stefano, Greiner, Murray, and Garcia, 2002
19 - See appendix A #2

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Calculations

#1:

$r_s = \frac{2GM}{c^2}$ Event Horizon Radius

$G = 6.67 * 10^{-11} m^3 kg^{-1} s^{-2}$ Gravitational Constant

$c = 3 * 10^8 m/s$ Speed of Light

$M = 6.37 * 10^{24} kg$ Mass of Earth

so $r_s = 0.0094m$ Radius of Earth-Mass Black Hole

#2:

$H_0 = 75 \frac{km}{s \cdot 3.086 \times 10^{16} m} = \frac{2.4303 \times 10^{-12}}{s}$ Hubble Constant

$h = H_0 / (100 \frac{km}{s \cdot 3.086 \times 10^{16} m}) = .75$

$m = 20$ ~Magnitude limit for UCSB telescope

$N(z) = 0.11 h^{(2/3)} (\frac{z}{0.3})^3 / y0xb0^2$ ~Frequency of events up to z

$N_{total}(z) = [\int_0^{2\pi} (\int_0^{\pi} (N(z)) (\sin\theta) \, d\theta) \, d\phi] * (\frac{180}{\pi})^2$ Total freq of events

$d = 5.5202 \times 10^{25} m$ Distance UCSB can see flare (based on L)

$z(d) = 0.54$ Redshift at distance d

so

$N(z) = 0.11 * h^{(2/3)} (\frac{z}{0.3})^3 / y0xb0^2 = \frac{.54}{(y)0xb0^2}$

$N_{total}(z) = [\int_0^{2\pi} \left(\int_0^{\pi} \left(\frac{.54}{(y)0xb0^2} \right) (\sin\theta) \, d\theta \right) d\phi] = \frac{6.77}{(y)0xb0^2} : \frac{7.04 \times 10^{-4}}{(s) rad^2} * (\frac{180 rad}{\pi})^2 : \frac{2.31}{s}$

This implies about 2 events per second over the whole sky.