CALIFORNIA STATE UNIVERSITY, NORTHRIDGE

INVESTIGATING BLACK HOLE SPIN AND JET LUMINOSITY

A thesis submitted in partial fulfillment of the requirements

For the degree of Master of Science in Physics

By

Matthew In Ho Kim

May 2015

The thesis of Matthew In Ho Kim is approved:

David A. Garofalo, Ph.D. Date

Yohannes Shiferaw, Ph.D. Date

Damian J. Christian, Ph.D., Chair Date

California State University, Northridge

Acknowledgements

I would like to thank all of my committee members who have supported my efforts in writing this thesis.

To Dr. Shiferaw, thank you for being on my thesis committee and for your insightful comments.

To my chair, Dr. Christian, thank you for reading and editing all the revisions, and for your generous support to this endeavor.

To Dr. Garofalo, thank you for teaching me all the fundamentals of black hole physics and giving me the idea for this thesis, and all the comments via emails from other states. This work has been possible for me because of your mentorship.

I would also like to thank all the physics professors who rekindled my thirst of physics: Dr. Igor Beloborodov, Dr. Ana Cristina Cadavid, Dr. Damian J. Christian, Dr. Duane R. Doty, Dr. David A. Garofalo, Dr. Miroslav Peric, Dr. Deqing Ren, and Dr. Yohannes Shiferaw.

Dedication

This thesis is dedicated to Ms. Cecilia Kim, who has been became a widow at 34. She has spent almost all of her adult life taking care of her only son with severe Cerebral Palsy (CP). At the age of 38, Ms. Kim has immigrated to United States with her three teenage kids. None of them had skills to speak the new language at all. While working full-time, she used to scribe her son's homework (including Algebra and Trigonometry) as he dictated word by word. This had taken place before the personal computer became wildly available. This thesis is hers as much as her son's.

Table of Contents

List of Tables

List of Figures

Abstract

INVESTIGATING BLACK HOLE SPIN AND JET LUMINOSITY

By

Matthew In Ho. Kim

Master of Science in Physics

We consider a system of a spinning black hole and accretion disk and possible jet. We investigate the changes in disk and jet luminosity for different black hole masses and spins. We model after the well-known result that the innermost stable circular orbit (ISCO) decreases when going from the largest retrograde to largest prograde spins. We show while the black hole masses always increases, the spin may increase or decrease depending on whether the disk is in prograde or retrograde configuration. Matter not accreted by the black hole is available to be radiated away by the accretion disk and we show this average disk luminosity is smallest when the spin is maximum but the disk is in a retrograde configuration and largest when the spin is maximum but the disk is in the prograde configuration. We also show the jet luminosity is largest for the cases of extreme spin, both retrograde and prograde, but is slightly larger for the former case. These ideas form the foundation for a phenomenological framework explaining the variety of observed active galactic nuclei and their time evolution. In addition, the framework is scale-free which means it applies to the full range of accreting black holes from about 10 solar masses up to 10 billion solar masses. In the future, we will investigate if the disk and jet luminosities derived here are consistent with observed parameters for active galactic nuclei (AGN).

1. Introduction

A black hole is a region in space-time, where even lights cannot escape. Einstein's General Theory of Relativity shows that a compressed mass will distort space-time. The idea of black hole has been around since the late 1700's. However, Karl Schwarzschild found a solution (Schwarzschild metric), which describes a non-rotating black hole mathematically in 1916 to Albert Einstein field equations, and finally, Roy Kerr solved the exact solution (Kerr metric) for a rotating black hole in 1963.

So many aspects of a black hole have been studied, such as, Event Horizon, Gravitational singularity, Photon sphere, Ergo-sphere, Gravitational collapse, Evaporation, and etc. (Thorne, 1995). Most of these studies are attempts at understanding the fundamental ideas about black holes from their mathematical description. Galaxies with larger than average emission across most of the electromagnetic spectrum have been called active galactic nuclei or AGN. The large excess emission in AGN discovered in the 1960, coupled with their small size and short timescale variability was a puzzle at first. An accreting black hole became one of the best solutions to explain the properties of AGN and much progress was made in the late 20th century with multi-wavelength studies.

Garofalo et al 2010 attempts to explain the observations of the different types of AGN and their time evolution by making a simple assumption, which is that prolonged accretion is typical in AGN (i.e. that accretion disks last long enough to bring the black hole spin to high prograde values from whatever their original value of spin was). This simple picture produces many constraints that affect both the disk and jet powers. We will discuss the calculations of the accretion disk luminosities and jets luminosities of a rotating black hole, and therefore as a function of time in the center of AGNs in this paper. This means that we have produced a foundation for exploring the observations of AGN. Garofalo et al 2010 suggests that the observations of specific types of AGN are compatible with this theoretical scheme and we have produced an even more detailed foundation. In particular, we will explore the time evolution of radio loud galaxies and quasars in our picture.

There are not many theories of the formation of black hole jets, which are generally recognized by the scientific community. Nor the mechanism for how jets are powered. The most popular theory is the Blandford – Znajek (BZ) process. The BZ process is a mechanism for how energy is transferred from spin of a rotating black hole to jets (Blandford & Znajek, 1977). The BZ mechanism shows how to extract the rotational energy of a black hole spin and producing jets (Thorne, 1995). It requires an accretion disc with a strong polar magnetic field around a spinning black hole. The magnetic field extracts spin energy and the power can be estimated as the energy density at the speed of light cylinder times area:

$$P = \frac{B^2 r^4 \omega^2}{c}$$

where B is the magnetic field strength, and ω is the angular velocity (Lasenby, 2010-2011). The process was visualized in two ways. A black hole, with magnetic field lines, is spinning. In the first viewpoint actually, the magnetic field lines spin along with the black hole, and nearby plasma is anchored onto the field lines by electrical forces. The plasma can slide along the field lines but not across them. Since the field lines are spinning, centrifugal forces will fling them up and down the field lines, forming jets. The other viewpoint is that the magnetic fields and the swirl of space generate a voltage difference across the field lines. The voltage carries current across the magnetic field lines. This current travels across plasma, which accelerates it, creating the jets (Thorne, 1995).

The other mechanism for jet formation is called Blandford-Payne, (BP), (Blandford & Payne, 1982). The mechanism is illustrated by a self-similar magnetohydrodynamics (MHD) solution, with the gas being regarded as cold and starting from rest at the equatorial plane, with the disk itself in Keplerian orbit about a black hole. It is shown that a centrifugally driven outflow of matter from the disk is possible if the poloidal component of the magnetic field makes an angle of less than 60 degrees with disk surface. At large distances the outflow forms a pair of collimated, antiparallel jets, while close to the disk it is probably driven by gas pressure in a hot, magnetically dominated corona (Blandford & Payne, 1982). In the BP process, a baryon-rich outflow can be launched centrifugally via the open magnetic field threading the disk. It is argued that the baryon-rich jet can also play important role in the collimation of the central jet (Wei, et al., 2012).

If we assume that both BZ and BP mechanisms produce black hole jets and outflows in active galactic nucleus (AGN), then it would indicate that the black hole jets are dependent to the black hole spins (Garofalo, 2009b). Figure 1 shows a cartoon of how jet luminosity changes with black hole spins and contributions from BZ + BP + Disk wind.

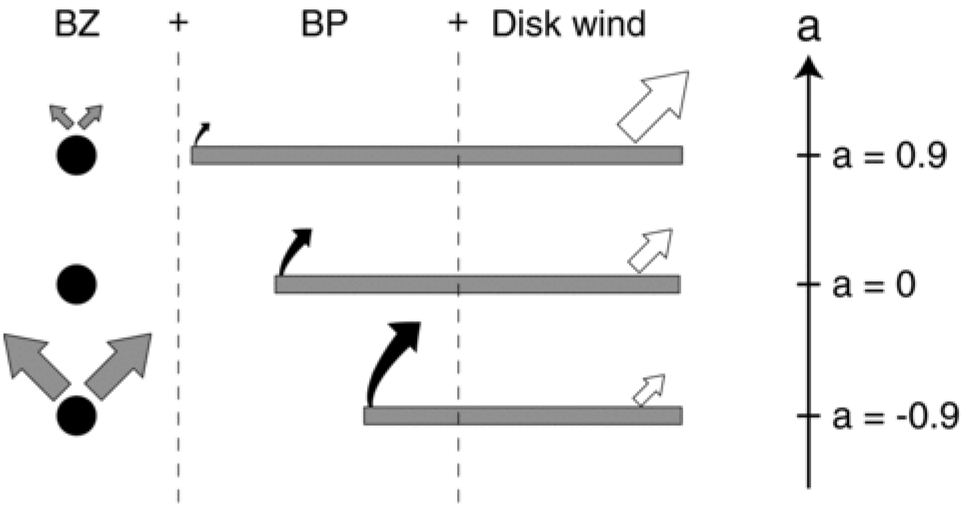

Figure 1. BZ and BP **(Garofalo, Evans, & Sambruna, 2010)**.

The Penrose process (Penrose, 1969) is a mechanism that explains how energy can be extracted from a black hole. It states that a spinning black hole has some energy can trapped and the black hole jets might be the energy source of the accreting black hole (Narayan, McClintock, & Tchekhovskoy, 2013).

In this framework, everything of interest depends on the size of the gap region between the accretion disk and the black hole. Therefore, we illustrate the accretion disk luminosity and jet power in terms of the innermost stable circular orbit (ISCO) which captures the gap region size for a given black hole spin. The disk and jet power also depend on the mass of the black hole so we want to keep track of the mass of the hole as it accretes. Therefore, our calculations will involve general relativity.

2. Calculations

In this chapter, we set up the steps that will allow us to calculate black hole Jet Luminosity as a function of spin. In section A, we show how the spin and ISCO are calculated. In sections B and C, we derive the mass and change in mass as a function of spin, and lastly in section D, we calculate the Jet luminosity as a function of spin. This calculation includes contributions from both the BP and BZ mechanisms and is our current best estimate for the luminosity a black hole jet produces.

A. Spin and Radii

In the general theory of relativity (GR), the potential for particles is given by (Hobson, Efstathiou, & Lasenby, 2006);

$$V \equiv E^2(r^3 + A^2 r + 2MA^2) - 4AMl - (r - 2M)l^2 - m^2 r(r^2 - 2Mr + A^2)$$

where E, l, and m are binding energy, angular momentum, and particles mass. The black hole radius in the Kerr metric (Moderski & Sikora, 1996):

$$\tilde{r}_h = \frac{c^2 r_h}{GM} = 1 + \sqrt{1 - A^2}$$

$$r_h = \frac{GM}{c^2}\left[1 + \sqrt{1 - A^2}\right]$$

You can solve for the marginally stable orbit ISCO (Moderski & Sikora, 1996):

$$\tilde{r}_{ms} = \frac{c^2 r_{ms}}{GM} = 3 + Z_2 + [(3 - Z_1)(3 + Z_1 + 2Z_2)]^{\frac{1}{2}}$$

$$r_{ms} = \frac{GM}{c^2}\left\{3 + Z_2 + [(3 - Z_1)(3 + Z_1 + 2Z_2)]^{\frac{1}{2}}\right\}$$

$$Z_1 = 1 + \sqrt[3]{1 - A^2}\left[\sqrt[3]{1 + A} + \sqrt[3]{1 - A}\right]$$

$$Z_2 = \sqrt{3A^2 + Z_1^2}$$

where A is the dimensionless spin of the black hole.

B. Masses

The black hole mass is different for each spin. That is, the rotating black hole can gain an increment of mass and its mass is calculated using ISCOs. The retrograde spin is labeled with negative sign, as you can see in Table 2. It also lists the mass of each spin for the black hole. For example, the mass at – 0.9 spin is a square root of ISCO at - 0.999 spin divide by ISCO at – 0.9 spin, as shown in the following equation.

$$\mathrm{m}_{-0.9} = \sqrt{\frac{\mathrm{ISCO}_{-0.999}}{\mathrm{ISCO}_{-0.9}}}$$

C. *Change in Mass*

The difference of black hole mass in each spin to next spin is labeled as Δm_{BH}. The results are in Table 3. This is not the same quantity as the rest mass presented in section 2 B. It is the difference between rest masses. For example, the difference in masses at -0.999 spin and -0.9 spin are given as:

$$\Delta m_{BH} = m_{-0.999} - m_{-.9}$$

The changing black hole mass due to spin caused by accretion of matter from last ISCO can be calculated (Raine & Thomas, 2005). The equation is given by

$$\Delta m = \int \frac{\mathrm{dm}}{\left(1 - \frac{2m}{3r_{ms}}\right)^{\frac{1}{2}}}$$

And this is solved with numerical integration. The following is example calculation.

For from spin -0.999 to -0.9:

$$r_{ms} = \frac{9m_s^2}{m}$$

$$x_{ms} = 9m_s^2$$

$$8.7m_k^2 = 9m_s^2$$

$$m_{-0.999} = \sqrt{\frac{9}{8.7}}m_{-.999}$$

$$\Delta m = \int_{m_{-0.009}}^{\sqrt{\frac{8.9972}{8.7174}}m_{-0.999}} \frac{dm}{\sqrt{1 - \frac{2}{3}\frac{m}{r_{ms}}}} = \int_{m_{-0.999}}^{\sqrt{\frac{8.9972}{8.7174}}m_{-0.999}} \frac{dm}{\sqrt{1 - \frac{2}{27}\frac{m^2}{m_{-0.999}^2}}} = 0.0166m_{-0.999}$$

$$= 0.0166m$$

D. Luminosities

The mass not transferred to the black hole is available to be radiated away in the accretion disk and thus the average disk luminosity is given by the equation:

$$\Delta m_{BH} - \Delta m$$

The jet luminosities can be founded with following equation (Garofalo, Evans, & Sambruna, 2010).

$$L_{jet} = \alpha\beta^2 m^2 j^2$$

$$\alpha = \delta\left(\frac{3}{2} - j\right)$$

$$\beta = -\frac{3}{2}j^3 + 12j^2 - 10j + 7 - \frac{0.002}{(j - 0.65)^2} + \frac{0.1}{(j + 0.95)} + \frac{0.002}{(j - 0.055)^2}$$

where j is spin. Where *j* is the normalized angular momentum and δ is 2.5.

3. Results

A. Spin and Radii

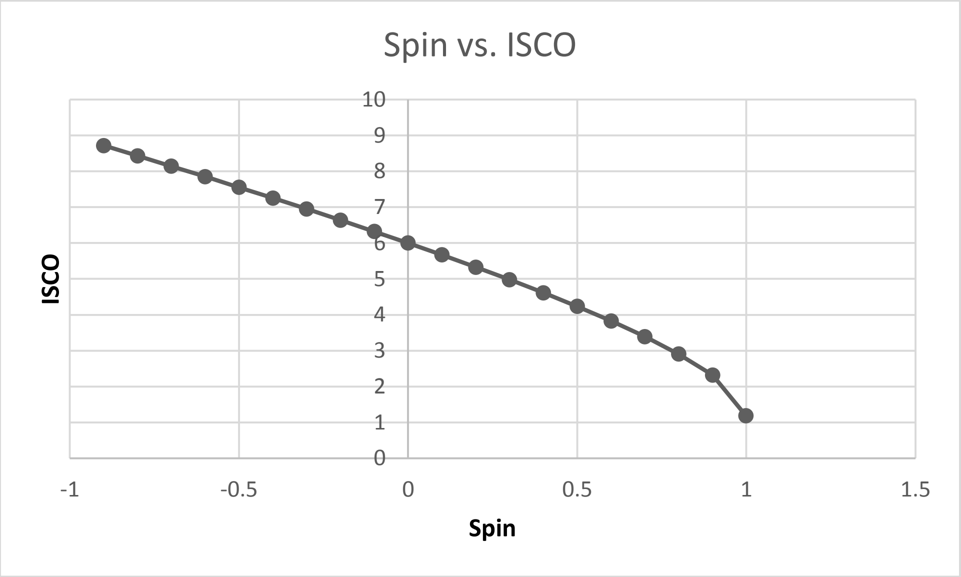

Figure 2. ISCO as a function of BH spin.

As can be seen in Figure 2, as the Black Hole's spin increases, the ISCO decreases (see Section 2A). Up to spin reaches to zero, the ISCO decreases proportionally. However, above spin 0, it decreases more rapidly.

Table 1. Spin, ISCO, and Event Horizon

A	ISCO Retrograde	ISCO Prograde	Event Horizon
0	$6\frac{GM}{c^2}$	$6\frac{GM}{c^2}$	$2\frac{GM}{c^2}$
0.1	$6.3229\frac{GM}{c^2}$	$5.6693\frac{GM}{c^2}$	$1.9950\frac{GM}{c^2}$
0.2	$6.6390\frac{GM}{c^2}$	$5.3294\frac{GM}{c^2}$	$1.9798\frac{GM}{c^2}$
0.3	$6.9493\frac{GM}{c^2}$	$4.9786\frac{GM}{c^2}$	$1.9539\frac{GM}{c^2}$

0.4	$7.2543\frac{GM}{c^2}$	$4.6143\frac{GM}{c^2}$	$1.9165\frac{GM}{c^2}$
0.5	$7.5546\frac{GM}{c^2}$	$4.2330\frac{GM}{c^2}$	$1.8660\frac{GM}{c^2}$
0.6	$7.8507\frac{GM}{c^2}$	$3.8290\frac{GM}{c^2}$	$1.8\frac{GM}{c^2}$
0.7	$8.1430\frac{GM}{c^2}$	$3.3931\frac{GM}{c^2}$	$1.7141\frac{GM}{c^2}$
0.8	$8.4318\frac{GM}{c^2}$	$2.9067\frac{GM}{c^2}$	$1.6\frac{GM}{c^2}$
0.9	$8.7174\frac{GM}{c^2}$	$2.3209\frac{GM}{c^2}$	$1.4359\frac{GM}{c^2}$
0.999	$8.9972\frac{GM}{c^2}$	$1.1818\frac{GM}{c^2}$	$1.0447\frac{GM}{c^2}$

B. Masses

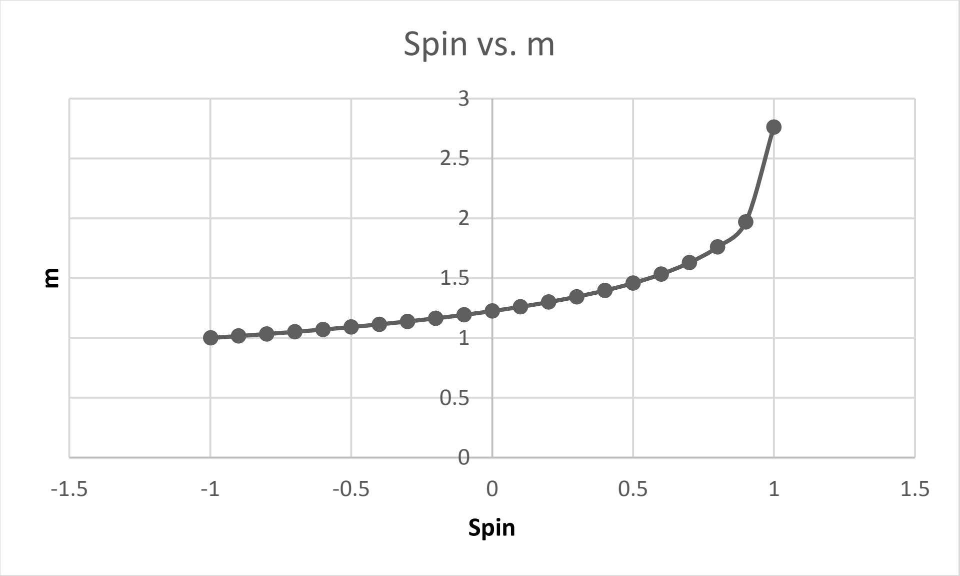

Figure 3. Black Hole spin as a function of mass.

As spin increases, mass of black hole increases proportionally until spin reaches zero. Then, it increases more rapidly as shown in Table 2 and Figure 3. Based on calculations from Section 2B.

Table 2. Spin, ISCO, radius, and mass.

A	ISCO	r_m	m
-0.999	$8.9972\frac{GM}{c^2}$		m
-0.9	$8.7175\frac{GM}{c^2}$	$9\frac{m_{-0.999}^2}{m}$	$1.0159m$
-0.8	$8.4318\frac{GM}{c^2}$	$8.7\frac{m_{-0.9}^2}{m}$	$1.0333m$
-0.7	$8.1430\frac{GM}{c^2}$	$8.4\frac{m_{-0.8}^2}{m}$	$1.0511m$
-0.6	$7.8506\frac{GM}{c^2}$	$8.1\frac{m_{-0.7}^2}{m}$	$1.0705m$

-0.5	$7.5546\frac{GM}{c^2}$	$7.9\frac{m_{-0.6}^2}{m}$	$1.0913m$
-0.4	$7.2543\frac{GM}{c^2}$	$7.6\frac{m_{-0.5}^2}{m}$	$1.1137m$
-0.3	$6.9493\frac{GM}{c^2}$	$7.3\frac{m_{-0.4}^2}{m}$	$1.1379m$
-0.2	$6.6390\frac{GM}{c^2}$	$6.9\frac{m_{-0.3}^2}{m}$	$1.1641m$
-0.1	$6.3229\frac{GM}{c^2}$	$6.6\frac{m_{-0.2}^2}{m}$	$1.1929m$
0	$6\frac{GM}{c^2}$	$6.3\frac{m_{-0.1}^2}{m}$	$1.2246m$
0.1	$5.6693\frac{GM}{c^2}$	$6\frac{m_{0}^2}{m}$	$1.2598m$
0.2	$5.3294\frac{GM}{c^2}$	$5.7\frac{m_{0.1}^2}{m}$	$1.2993m$
0.3	$4.9786\frac{GM}{c^2}$	$5.3\frac{m_{0.2}^2}{m}$	$1.3443m$
0.4	$4.6143\frac{GM}{c^2}$	$5\frac{m_{0.3}^2}{m}$	$1.3964m$
0.5	$4.2330\frac{GM}{c^2}$	$4.6\frac{m_{0.4}^2}{m}$	$1.4579m$
0.6	$3.8291\frac{GM}{c^2}$	$4.2\frac{m_{0.5}^2}{m}$	$1.5329m$
0.7	$3.3931\frac{GM}{c^2}$	$3.8\frac{m_{0.6}^2}{m}$	$1.6295m$
0.8	$2.9067\frac{GM}{c^2}$	$3.4\frac{m_{0.7}^2}{m}$	$1.7606m$

0.9	$2.3209\frac{GM}{c^2}$	$2.9\frac{m_{0.8}^2}{m}$	$1.9702m$
0.999	$1.1818\frac{GM}{c^2}$	$2.3\frac{m_{0.9}^2}{m}$	2.7610m

Note: Retrograde spin is labeled with negative sign.

C. Changing Masses

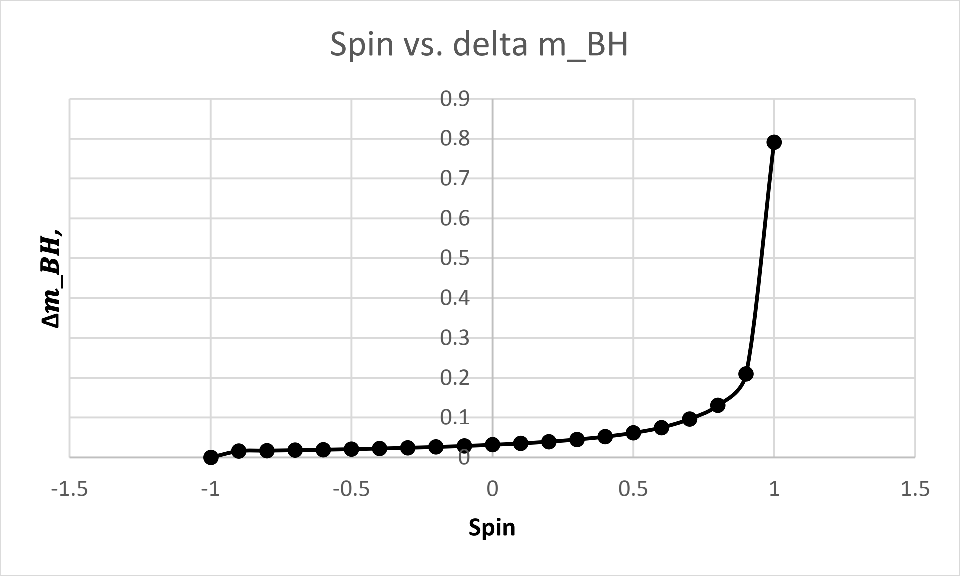

Figure 4. Black Hole change in mass as a function of spin.

Shown in Figure 4 is the change in black hole mass (the difference between rest masses) as a function of spin from equations presented in Section 2B. As spin increases, the change of black hole mass increases only slightly, except at the largest prograde spin, 0.999.

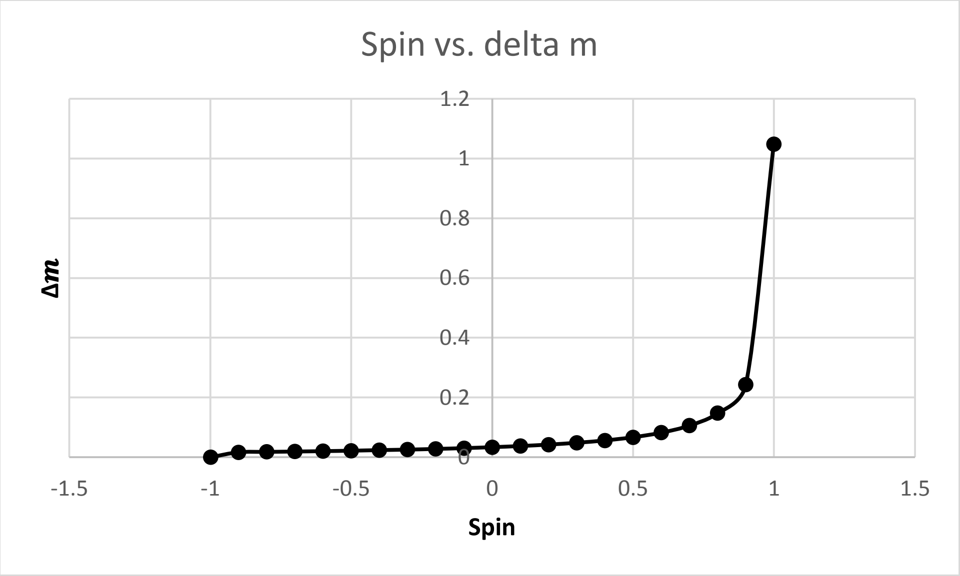

Figure 5. Increase in black hole mass as a function of spin.

Figure 5 presents the increase in black hole mass as a function of spin based on equations in Section 2C. Again, as spin increases, the changing black hole mass due to the accretion of matter from last ISCO barely increases until spin zero. Then it increases dramatically above spin 0.95.

Table 3. Spin, ISCO, mass, Δm_{BH}, Δm, and $\Delta m - \Delta m_{BH}$.

A	ISCO	m	Δm_{BH}	Δm	$\Delta m - \Delta m_{BH}$
-0.999	$8.99718\frac{GM}{c^2}$	m	0	0	0
-0.9	$8.71735\frac{GM}{c^2}$	$1.015923m$	$0.015923m$	$0.01656m$	$0.00064m$
-0.8	$8.43175\frac{GM}{c^2}$	$1.032985m$	$0.017062m$	$0.01777m$	$0.000708m$
-0.7	$8.14296\frac{GM}{c^2}$	$1.05114m$	$0.018155m$	$0.01894m$	$0.000785m$
-0.6	$7.8507\frac{GM}{c^2}$	$1.07053m$	$0.01939m$	$0.02026m$	$0.00087m$
-0.5	$7.55458\frac{GM}{c^2}$	$1.09131m$	$0.02078m$	$0.02173m$	$0.00095m$
-0.4	$7.25427\frac{GM}{c^2}$	$1.11367m$	$0.02236m$	$0.02372m$	$0.00136m$
-0.3	$6.94927\frac{GM}{c^2}$	$1.13789m$	$0.02422m$	$0.02538m$	$0.00116m$
-0.2	$6.63904\frac{GM}{c^2}$	$1.16413m$	$0.02628m$	$0.02769m$	$0.00141m$
-0.1	$6.32289\frac{GM}{c^2}$	$1.19288m$	$0.02875m$	$0.03036m$	$0.00161m$

0	$6\frac{GM}{c^2}$	$1.22456m$	$0.03168m$	$0.03355m$	$0.00187m$
0.1	$5.66930\frac{GM}{c^2}$	$1.25977m$	$0.03521m$	$0.03741m$	$0.00220m$
0.2	$5.32944\frac{GM}{c^2}$	$1.29932m$	$0.03955m$	$0.04217m$	$0.00262m$
0.3	$4.97861\frac{GM}{c^2}$	$1.34432m$	$0.045m$	$0.04830m$	$0.00327m$
0.4	$4.61434\frac{GM}{c^2}$	$1.39638m$	$0.05206m$	$0.05609m$	$0.00403m$
0.5	$4.23300\frac{GM}{c^2}$	$1.45792m$	$0.06154m$	$0.06681m$	$0.00527m$
0.6	$3.82908\frac{GM}{c^2}$	$1.53289m$	$0.07497m$	$0.08214m$	$0.00717m$
0.7	$3.39312\frac{GM}{c^2}$	$1.62946m$	$0.09657m$	$0.10589m$	$0.00932m$
0.8	$2.90665\frac{GM}{c^2}$	$1.76055m$	$0.13109m$	$0.14770m$	$0.01661m$
0.9	$2.32088\frac{GM}{c^2}$	$1.9702m$	$0.20965m$	$0.24352m$	$0.03387m$
0.999	$1.18176\frac{GM}{c^2}$	2.76104m	0.79084m	$1.04792m$	$0.25708m$

D. Luminosities

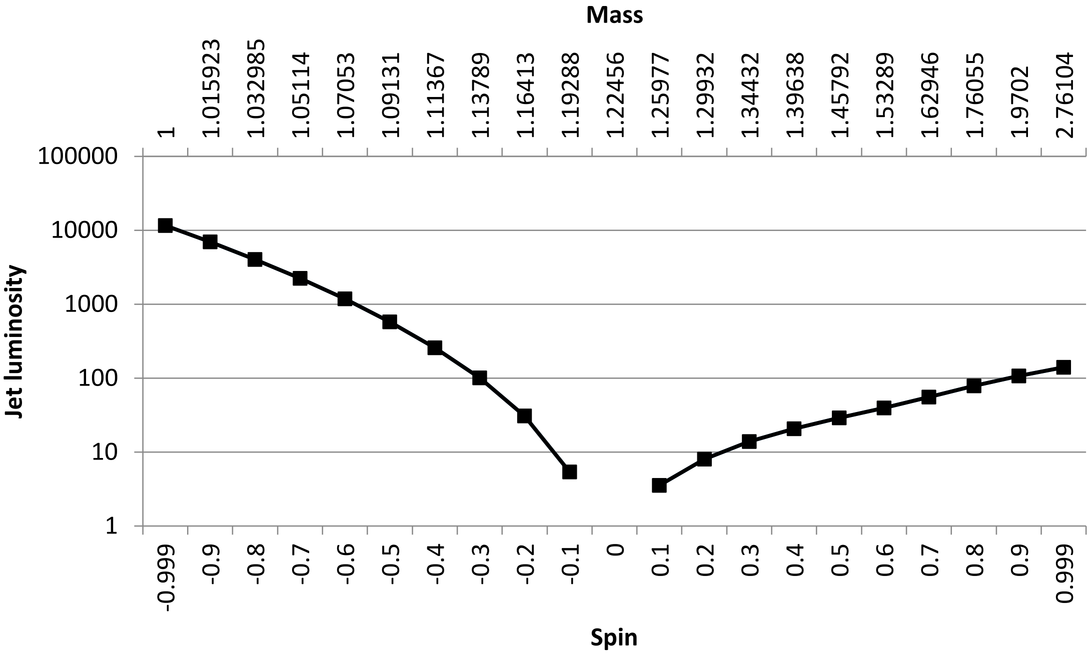

Figure 6. Jet luminosity as a function of spin plotted on the logarithm scale.

The mass not accreted by the black hole is available to be radiated away by the accretion disk, but first we investigate the luminosity in the jet given by the changing black hole mass and equations in Section 2D. We show the jet luminosity as a function of spin in Figure 6. The retrograde (negative) spins produces slightly more jet luminosity then the prograde (positive) spins, while the mass of black hole increases. At the spin zero, there is no jet luminosity. Therefore, the Schwarzschild metric would not produce any jet luminosity.

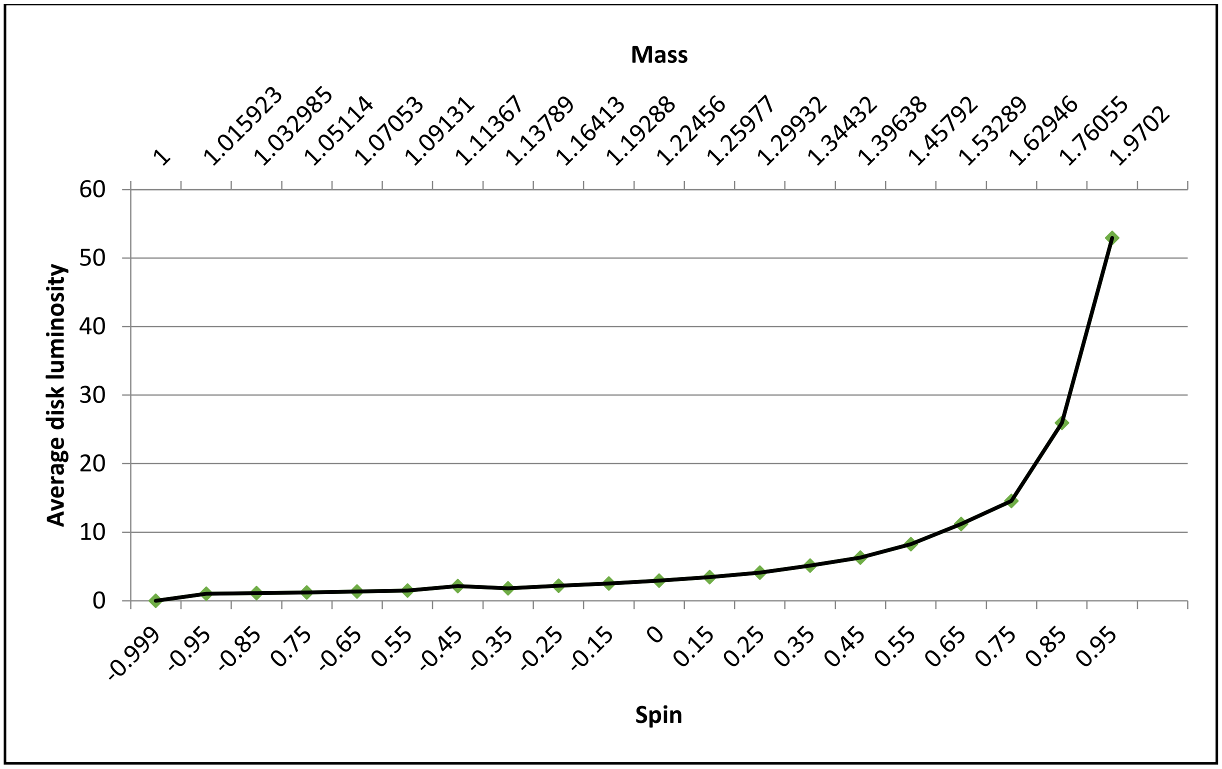

Figure 7. Spin vs. average disk luminosity.

Shown in Figure 7 is the average disk luminosity as a function of spin. As spin increases, the average disk luminosity increases steady until spin reaches 0.5 spin then the average disk luminosity increases rapidly.

Table 4. Spin, jet luminosity, mass, α, β, and Average disk luminosity.

A	Jet luminosity	m	α	β	Average disk luminosity
-0.999	$5786.7391m^2$	m	6.2475	30.4648	0
-0.9	$3606.2963m^2$	$1.0159m$	6	26.8140	m
-0.8	$2226.9638m^2$	$1.0330m$	5.75	23.4501	$1.1063m$
-0.7	$1238.8108m^2$	$1.0511m$	5.5	20.3976	$1.2266m$
-0.6	$674.5915m^2$	$1.0705m$	5.25	17.6483	$1.3594m$

-0.5	$343.6572m^2$	$1.0913m$	5	15.1937	$1.4844m$
-0.4	$159.9288m^2$	$1.1137m$	4.75	13.0253	$2.125m$
-0.3	$65.0311m^2$	$1.1379m$	4.5	11.1360	$1.8125m$
-0.2	$20.8893m^2$	$1.1641m$	4.25	9.5224	$2.2031m$
-0.1	$3.8313m^2$	$1.1929m$	4	8.2043	$2.5156m$
0	0	$1.2246m$	3.75	7.6607	$2.9219m$
0.1	$2.8045m^2$	$1.2598m$	3.5	7.1055	$3.4375m$
0.2	$6.7898m^2$	$1.2993m$	3.25	5.5622	$4.0938m$
0.3	$12.5496m^2$	$1.3443m$	3	5.0715	$5.1094m$
0.4	$20.0852m^2$	$1.3964m$	2.75	4.8384	$6.3125m$
0.5	$30.8176m^2$	$1.4579m$	2.5	4.8165	$8.2344m$
0.6	$46.6588m^2$	$1.5329m$	2.25	4.9512	$11.2031m$
0.7	$73.6974m^2$	$1.6295m$	2	5.3218	$14.5625m$
0.8	$121.2796m^2$	$1.7606m$	1.75	5.9105	$25.9531m$
0.9	$207.9717m^2$	$1.9702m$	1.5	6.6276	$52.9219m$
0.999	$545.5174m^2$	2.7610m	1.2775	7.4919	m

4. Discussion

There are no widely accepted models for the observed luminosities of BH jets and we undertook this study to provide a more physically consistent calculation of Jet luminosity. In this chapter, we discuss the physical interpretations of changes in mass and changes in luminosity with spin.

A. Physical Interpretation of the Changes in Masses

For a large retrograde orbit, the ISCO is much further from the black hole and move closer as the spin becomes more prograde. The ISCO is closest to the black hole for the largest prograde spin. The increasing black hole mass as increasing spin and the progressively changing black hole mass due to angular momentum from the accretion of matter from last ISCO indicate that the black hole is acquiring additional mass.

As matter falls onto the black hole from the accretion disk, the distance between the ISCO and event horizon changes. In addition, the black hole mass is increasing. The closest ISCO has largest the black hole mass. The calculation of Δm shows that some rest mass has been radiated away in the process of accretion. The black hole cannot be spun up to $a = m$, due to the capture of radiation that reduces the angular momentum (counter-rotating photons) is more likely than the capture of positive angular momentum (Raine & Thomas, 2005).

B. Physical Interpretation of the Luminosities vs Spin vs Mass

Matter not accreted into the black hole is available to be radiated away. Thus, we have found a perceptible relationship between the average disk luminosity, and the black hole mass. More black hole masses produce more the average disk luminosity as the black hole spins becomes more prograde as shown Figure 3 and Table 2. The luminosity available for the jet depends on the black hole's spin and mass. However, the jet luminosity is more dependent on the spin and not as dependent on the mass of the black hole. It does not show any correlation between the black hole mass and jet luminosity. The jet luminosity is highest at the highest retrograde spin. At zero spin, there is no jet luminosity at all. However, there is some the average disk luminosity at zero spin. It seems that there would not be jet luminosity without spin and the average disk luminosity. It seems very odd that there is some the average disk luminosity at zero spin. “A spherical blob of gas will, as a result of collisions, lose energy and angular momentum and flatten out into a disk. That’s how stars and solar systems form. And none of that depends on whether there is a central rotating black hole.”

5. Conclusion

We considered a system of a spinning black hole and accretion disk and possible jet. We investigated the changes in disk and jet luminosity for different black hole masses and spins.

The main results of this thesis are given below:

- Showed the increased mass for the highest prograde spin.
- Presented for the first time, the jet luminosity as a function of changing mass. The average disk luminosity is smallest when the spin is maximum but the disk is in a retrograde configuration and largest when the spin is maximum but the disk is in the prograde configuration.
- Showed the jet luminosity is largest for the cases of extreme spin, both retrograde and prograde, but is slightly larger for the former case.

We had produced a foundation for exploring the observations of AGN. It allows us to explore the cosmological evolution of these active galaxies. This framework also allows us to explore the different time evolutions of radio loud and radio quiet AGN, thereby addressing the decade’s long question of the nature of the radio loud/radio quiet dichotomy. In the future, we will investigate if the disk and jet luminosities derived here are consistent with observed parameters for AGN.

References

Bentz, M. C., Peterson, B. M., Pogge, R. W., & Vastergaard, M. (2009). *The Black Hole Mass-Bulge Luminosity Relationship for Active Galactic Nuclei from Reverberation Mapping and Hubble Space Telescope Imaging*. Retrieved from Cornell University Library: http://arxiv.org/abs/0812.2284

Blandford, R. D., & Payne, D. G. (1982). Hydromagnetic flows from accertion discs and the production of radio jets. *The Monthly Notices of the Royal Astronomical Society*, 199, 883-903.

Blandford, R. D., & Znajek, R. J. (1977). Electromagnetic extraction of energy from Kerr black holes. *The Monthly Notices of the Royal Astronomical Society*, 179, 433-456.

Garofalo, D. (2009a). SIGNATURES OF BLACK HOLE SPIN IN GALAXY EVOLUTION. *The Astrophysical Journal*, 699, L52-L54.

Garofalo, D. (2009b). THE SPIN DEPENDENCE OF THE BLANDFORD–ZNAJEK EFFECT. *The Astrophysical Journal*, 699, 400-408.

Garofalo, D. (2013). Retrograde versus Prograde Models of Accreting Black Holes. *Advance in Astronomy*, 213105(a).

Garofalo, D., Evans, D. A., & Sambruna, R. M. (2010). The Evolution of Radio Loud Active Galactic Nuclei as a Function of Black Hole Spin. *The Monthly Notice Royal Astronomical Society*, 406, 975-986.

Garofalo, D., Kim, M. I., & Christian, D. J. (2014). Consttrants on the radio-loud/radio-quiet dichotomy from the Fundametial Plane. *The Monthly Notices of the Royal Astronomical Society*, 442, 3097-31404.

Greene, J. E., & Ho, L. C. (2006). Measuring Stellar Velocity Dispersions in Active Galaxies. *The Astrophysical Journal*, 641, 117-132.

Haering, N., & Rix, H. (2004). On the Black Hole Mass - Bulge Mass Relation. *The Astrophysics Journal*, 604, L89-L92.

Hobson, M. P., Efstathiou, G. P., & Lasenby, A. P. (2006). *General Relativity: An Introudtion for Physics.* New York: Cambridge University Press.

Lasenby, A. (2010-2011). *Relativistic Astrophysics and Cosmology Lecture Notes.* Cambridge: Cambridge University.

McClintock, J. E., Narayan, R., Davis, S. W., Gou, L., Kulkarni, A., Orosz, J. A., . . . Steiner, J. F. (2011). Measuring the spins of accreting black holes. *Classical and Quantum Gravity*, 28, 114009.

Moderski, R., & Sikora, M. (1996). On black hole evolution in active galactic nuclei. *The Monthly Notices of the Royal Astronomical Society*, 283, 854-864.

Moderski, R., Sikora, M., & Lasota, J. (1998). On the spin paradigm and the radio dichotomy of quasars. *The Monthly Notices of the Royal Astronomical Society*, 301, 142-148.

Narayan, R., McClintock, J. E., & Tchekhovskoy, A. (2013, March 12). Energy Extraction from Spinning Black Holes via Relativistic Jets. Retrieved from Cornell University Library: arxiv.org/abs/1303.3004

Penrose, R. (1969). Gravitational collapse: The role of general relativity. *Nuovo Cimento Rivista*, 1, 252-276.

Raine, D., & Thomas, E. (2005). *Black Hole: An Introduction.* London: Imperial College Press.

Shakura, N. I., & Sunyaev, R. A. (1973). Black Holes in Binary System, Observational Appearance. *Astronomy & Astrophysics*, 24, 337-355.

Thorne, K. S. (1995). *Black Holees and Time Warps.* New York: W. W. Norton & Company.

Volonteri, M., Sikora, M., & Lasota, J. (2007). BLACK HOLE SPIN AND GALACTIC MORPHOLOGY. *The Astrophysical Journal*, 667, 704-713.

Wei, X., Wei-Hua, L., Yuan-Chuan, Z., Ding-Xiong, W., Qingwen, W., & Jiu-Zhou, W. (2012). A two-component jet model based on the Blandford-Znajek and Blandford-Payne processes. *RRA*, 12, 817.