

INVESTIGATING SUPERMASSIVE BLACK HOLES AND THEIR VARIABILITY BY USING A STRUCTURE FUNCTION

by

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A THESIS SUBMITTED IN PARTIAL FULFILMENT OF
THE REQUIREMENTS FOR THE DEGREE OF

BACHELOR OF SCIENCE

in

Honours Mathematics

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MOUNT SAINT VINCENT UNIVERSITY

March 10, 2019

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ABSTRACT

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Our universe is pockmarked with galaxies as far as we can currently observe from our humble planet. The currently accepted theoretical model is that at the center of these galaxies are super-massive black holes holding them together. This has been proven for a majority of these observable galaxies, including our own, and for some the central black hole is actively accreting matter. We call the galaxies hosting these black holes active galaxies. Active galaxies are of particular interest because they are some of the brightest objects in the night sky and yet their emission spectra are incredibly variable. Unfortunately since the data acquired from these objects is generally unevenly sampled, we cannot use a Fourier analysis as it suffers from windowing and aliasing. For these reasons we turn to the structure function which has a similar effect as the Fourier analysis but with the added benefits of remaining in the time domain and sporting a robustness against windowing and aliasing due to uneven sampling.

by *Derek Blue*

submitted on March 10, 2019:

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Chapter 1

INTRODUCTION

1.1 OVERVIEW

This chapter will give an overview of the theoretical models used by modern astronomers and physicists to describe black holes. The majority of this thesis is concerned with the analysis of the electromagnetic spectrum emitted by real super-massive black holes at the centers of various galaxies by using a structure function, which will be described in detail.

To begin, this chapter will give a brief overview of galaxies, active galaxies, black holes and their similarities and differences. This chapter will then go into detail on how we can observe these astronomical objects and the model used to explain what we observe from active galaxies. Finally, this chapter will go over what is expected from the work that was conducted and the motivation behind it.

Before we can dive into the work that was conducted for this thesis we must first understand the objects that were observed and how they are classified.

1.2 GALAXIES

Galaxies are relatively faint objects in comparison to close stars when being observed with the naked eye. So it comes as no surprise that they were not discovered

HUBBLE-DE VAUCOULEURS DIAGRAM

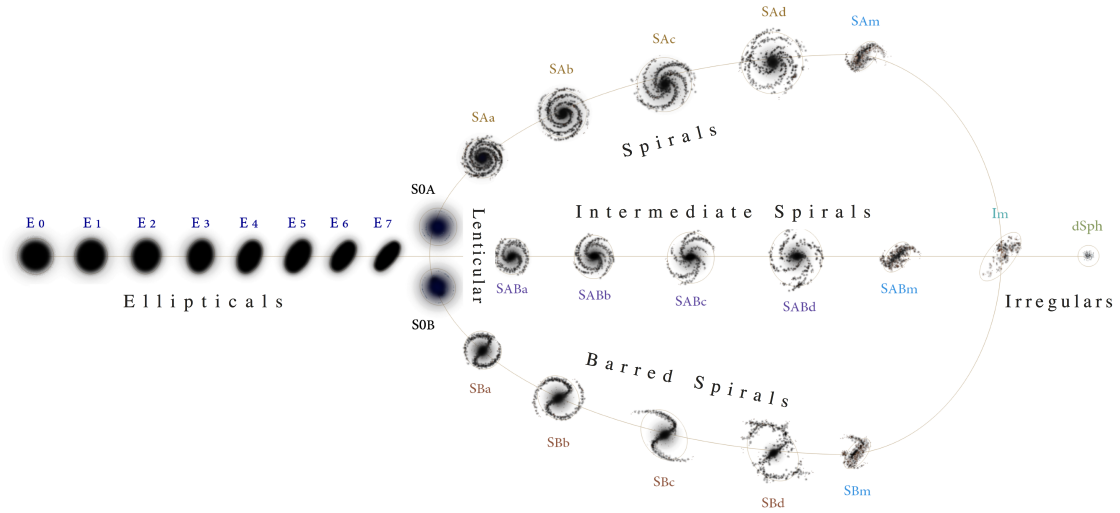


Figure 1.1: Hubble-de Vaucouleurs diagram for galaxy morphology.

until telescope technology had advanced to a sufficient degree as to allow a significant enough amount of light in to view very distant objects. In 1845, William Parsons of Ireland built a telescope that would be the largest of its time. In using this telescope he was able to observe groupings of stars and gas and dust distant from our own Milky Way. Initially Parsons believed galaxies to be nebulae but soon concluded that they were "great clouds of stars" Seeds and Backman (2013).

These great clouds of stars are now theorized by modern astronomers and physicists to contain supermassive black holes at their centers holding them together. Supermassive black holes, as their name suggests and as this chapter will explain later are extremely massive.

Since their discovery, many various types of galaxies have been discovered and categorized into three groups (Figure 1.1¹).

¹https://commons.wikimedia.org/wiki/File:Hubble-de_Vaucouleurs_Galaxy_Morphology_Diagram.png

1.2.1 ELLIPTICAL GALAXIES

Seeds and Backman (2013) Describes elliptical galaxies as round or elliptical with no visible gas and dust and lacking hot bright stars. These galaxies classified from E0 to E7 based on how elliptical they are.

1.2.2 SPIRAL GALAXIES

Spiral galaxies are the most popular of the classifications of galaxies, and also the most pleasing to the eye. They consist of a disk and spiral arms extruding from their center. Spiral galaxies have some extremely unique characteristics, the least of which are their spiral arms from which they derive their name. A sub-class of spiral galaxy known as the *Barred Spiral Galaxy* is called so because of the presence of a uniquely inherited bar at their center from which their spiral arms protrude.

1.2.3 IRREGULAR GALAXIES

Not quite belonging to either the spiral nor the elliptical classes of galaxies, *Irregular Galaxies* are collections of gas and dust with no real structure or shape. An example of irregular galaxies in our own relative backyard would be the Magellanic Clouds. The Small and Large Magellanic Clouds have virtually no proper geometric structure and are interacting gravitationally with our own Milky Way.

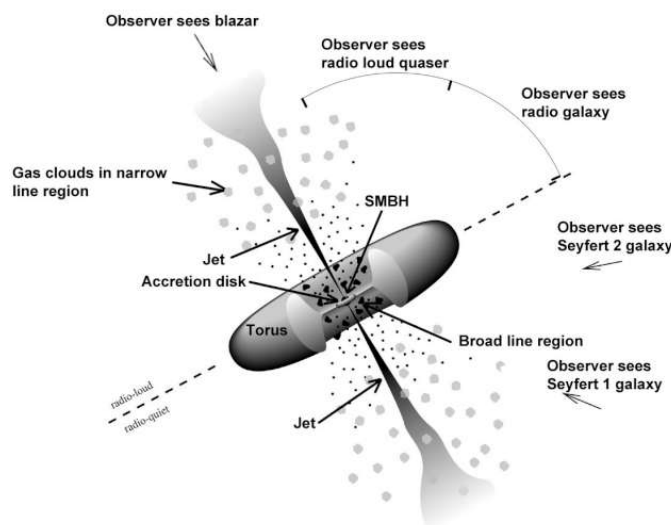


Figure 1.2: Unified model of Active Galactic Nuclei(AGN).

1.3 ACTIVE GALAXIES

Thanks to advances in technology, such as the radio and X-Ray telescopes, modern astronomers and physicists have identified a new type of galaxy, the *Active Galaxy*. Active galaxies are galaxies who are theorized to have an actively accreting super-massive black hole at their center. This accretion by the central black hole generates immense amounts of energy across the electromagnetic spectrum. This central black hole and its accompanying accretion disc are known as the nucleus of an active galaxy and are referred to as Active Galactic Nuclei(AGN).

1.3.1 THE UNIFIED MODEL

In order to help understand what we observe and to help produce new methods of observing AGN, the unified model was developed (Figure 1.2²).

In the unified model the nucleus of the active galaxy consists of a supermassive

²<https://fermi.gsfc.nasa.gov/science/etev/agn/figure1.jpg>

black hole surrounded by a torus of dust and gas from which it is accreting through an accretion disc formed by the gravitational pull of the supermassive black hole. Since there are a number of different types of active galaxies that have been observed, in the unified model this is described by and viewing angle to the galaxy that the observer has. For instance if an observer is viewing an active galaxy from close to edge-on, then they will see either a radio galaxy or a Seyfert 2 AGN. If however they are observing from a higher angle, then the observer will see a quasar or a Seyfert 1 depending on whether the object is radio loud or not. And finally observing from an angle equivalent to directly above will result in the observer viewing a blazar.

1.4 BLACK HOLES

To understand black holes, one must first understand escape velocity and how it relates to astronomical objects. For any given object, the escape velocity is the velocity required by any object or particle in order for that object or particle to escape the gravitational well created by the initial object. For example, in order for a probe to leave our Earth and visit the other planets of our solar system, that probe must first reach the escape velocity for the Earth. Mathematically speaking the escape velocity is defined as:

$$v_e = \sqrt{\frac{2GM}{r}} \quad (1.1)$$

where v_e is the escape velocity, G is the universal gravitational constant, M is the mass of the object to escape from, and r is the distance from the center of said object.

When $v_e \geq c$ at a given r , where c is the speed of light, then nothing, not even light

can escape the gravitational well created by the object in question.

In this case the object in question would be referred to as a black hole and the radius from the center of the object r is defined as the event horizon. There exists a more in depth definition for the black hole that will be discussed in section 2.1. Black holes are commonly classified according to their mass due to the relationship between their mass and the radius of their event horizon, given by:

$$r_s = \frac{2GM}{c^2} \quad (1.2)$$

where r_s is the Schwarzschild radius as defined in section 2.1.

1.4.1 STELLAR MASS BLACK HOLES

Stellar mass black holes are those black holes that are most commonly depicted in fiction and film. With masses ranging from $10M_\odot$ to 10^2M_\odot where M_\odot is the mass of our Sun, known as a solar mass.

1.4.2 INTERMEDIATE-MASS BLACK HOLES

Intermediate-mass black holes (IMBH) are theorized to be those black holes with significantly more mass than a stellar mass black hole but less than a supermassive black hole. There have been a couple of IMBH candidates in our own galaxy and others nearby. Intermediate-mass black holes have masses between 10^2M_\odot and 10^5M_\odot . Since this thesis is concerned with AGN and thus supermassive black holes, we will not discuss IMBHs in more detail.

1.4.3 SUPERMASSIVE BLACK HOLES

With masses ranging from $10^5 M_\odot$ and up, supermassive black holes are believed to be at the centers of most large galaxies holding them together. There is observational evidence that our own Milky Way is host to one such monster, Sagittarius A*. When one of these supermassive black holes is actively accreting from its surrounding galaxy, we can it the nuclei of an active galaxy as discussed in section 1.3.

1.5 HOW AGN ARE OBSERVED

Since AGN are so far away and their central engines so massive that light cannot escape them, how then can we observe them? The answer to that question is that we cannot and still have not *directly* observed one yet. We can however indirectly observe them, by their gravitational effect on their surroundings, and in the case of AGN by observing the emission they produce through their accretion process.

1.5.1 ORBITAL X-RAY TELESCOPES

A description of the orbital observatories used and the bands of the EM spectrum they can observe

1.6 EXPECTED RESULTS

What is expected to be achieved from this project

Chapter 2

THE GENERAL RELATIVISTIC DESCRIPTION

2.1 GENERAL RELATIVITY

An introduction to general relativity and its relation to black holes.

2.1.1 AN INTRODUCTION TO TENSORS

An introduction to tensors and their mathematical properties

2.1.2 THE METRIC TENSOR

Role of the metric tensor

2.1.3 THE SPACETIME INTERVAL

Role of the spacetime interval

2.2 THE KERR SPINNING BLACK HOLE

Description of the concept of the Kerr spinning black hole and its importance.

2.2.1 THE KERR SOLUTION

The mathematics of the Kerr solution.

2.2.2 PROPERTIES OF THE KERR SOLUTION

Properties of the Kerr solution.

Chapter 3

STATISTICAL ANALYSIS

3.1 THE STRUCTURE FUNCTION

(Collier and Peterson, 2001) What the structure function is and how it applies to this data sample. Why it was chosen.

3.2 THE DATA

An overview of the data. This section will contain many figures.

Chapter 4

PROGRAMMING SFA

4.1 SFA USAGE AND DESCRIPTION

A description of what SFA was developed for and its usage.

4.2 THE SFA ALGORITHM

4.2.1 PROCESS

The logical process SFA follows to generate the structure function

4.2.2 COST AND COMPLEXITY

An overview of the general running cost and Big-Oh order of SFA

4.3 EXPECTED OUTPUT

What one should expect for results from running SFA

Chapter 5

RESULTS AND CONCLUSIONS

5.1 RESULTS

A review of the results of running SFA on observational data

5.2 CONCLUSIONS

Theoretical conclusions based on the findings of SFA

Chapter 6

FUTURE WORK

Potential future work and applications of SFA

Appendix A

Structure Function

If you wanted an appendix, it would go in like this. It would be referenced using Appendix A.

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