Chapter 1

Introduction

The research set forth in this dissertation is replicated almost verbatim from manuscripts that either been published or will be submitted for publication by peer-reviewed journals. As such, each chapter has its own introduction and literature review. Therefore, I will present a very broad commentary of quasar astronomy here, along with the motivation for and organization of this dissertation.

1.1 The Need for This Research

Astronomy is the oldest scientific field, with the first-known star chart appearing on a ivory tablet made of mammoth tusk dating back over 32,500 years and the earliest known astronomical site at Nabta Playa in Egypt built more than 7,000 years ago (see Figure 1.1). The origins of astronomy are seated in religion, mythology, and astrology, though its calendrical uses did not go unobserved. Astronomy became disentangled from these ideologies with the onset of astrophysics, a field that has greatly expanded our understanding of our place in the Universe as well as spurring technological advancement.

It is for these reasons why astronomy research remains relevant in today's society. NASA's *Astrophysics* strategic objective is to "discover how the universe works, explore how it began and evolved, and search for life on planets around other stars" (NASA Astrophysics, 2020). Their Science Mission Directorate goals include 1) probing the origin and destiny of

Figure 1.1: Left: The Ach Valley mammoth tusk fragment, interpreted as a star map of Orion Image credit: `astronomytrek.com/is-the-ach-valley-tusk-fragment-an-ancient-star-map/`. Right: Reconstruction of the Nabta Playa Stone Calendar at Aswan. Photo by: Raymbetz, `experience-ancient-egypt.com/ancient-egyptian-culture/ancient-egyptian-science/egyptian-astronomy`.

our universe, including the nature of black holes, dark energy, dark matter and gravity (*"How does the universe work?"*), and 2) exploring the origin and evolution of the galaxies, stars and planets that make up our universe (*"How did we get here?"*).

Quasar research addresses both of these overarching questions. A quasar is a type of active galactic nucleus (AGN) and is powered by a supermassive black hole (SMBH). Most major galaxies are believed to have SMBHs at their centers that coevolve with their host galaxies (e.g., Fabian, 2012; Kormendy & Ho, 2013; Kormendy & Richstone, 1995). Astronomers can look at quasars across the history of the Universe in order to study galactic evolution (e.g., Weedman, 1986), specficially the galaxy-SMBH coevolution, throughout time. This, in turn, can help us understand how galaxies form and develop into the structures we know today.

1.2 Discovery of AGN

The discovery of AGN came from the development of radio astronomy, which coincided with advancements in radio technology during WWII (Shields, 1999). Karl Jansky first discovered radio waves coming from the Milky Way (Jansky, 1933). A decade later, Carl

Seyfert published a list of odd spiral galaxies with excess light from the nucleus (Seyfert, 1943). Additional observations noting bright emission lines opposed to the usual galactic absorption (Baade & Minkowski, 1954), point radio sources (Matthews, Bolton, Greenstein, Mnch, & Sandage, 1961), and high redshift of hydrogen lines (Schmidt, 1963) led to the classification of quasi-stellar objects (QSOs), specifically the quasi-stellar radio sources called *quasars*.

1.3 Quasar Astronomy

Galactic *activity* refers to "the existence of energetic phenomena in the nuclei, or central regions, of galaxies which cannot be attributed clearly and directly to stars" (Peterson, 1997, p. 1). The activity in AGN is galvanized by the accretion of matter onto the central SMBH (Lynden-Bell, 1969; Salpeter, 1964; Zel'dovich, 1964). The important features of AGN and quasars are discussed below.

1.3.1 Observed Properties

AGN have diverse observed properties. Perhaps most notable is that AGN emit considerable amounts of energy in every region of the electromagnetic spectrum (Wilkes, 2004), though they tend to have significant variations in flux. In addition to the prominent radio waves, they exhibit strong x-rays, broad emission lines in the ultraviolet and infrared, and a non-stellar ultraviolet/optical continuum (Netzer, 2013; Weedman, 1986), as seen in Figure 1.2. From these observations, astronomers have been able to draw some conclusions about the physical properties of AGN and specifically quasars.

Distant: The shift in emission lines observed in quasar spectra indicates that there is significant cosmological redshift at play. The cosmological redshift is given by

$$z = \frac{\lambda_{obs} - \lambda_{rest}}{\lambda_{rest}}, \tag{1.1}$$

where λ_{obs} is the observed wavelength of the spectral features and λ_{rest} is the rest-frame measurements of spectral features that would be expected to be found in a laboratory setting.

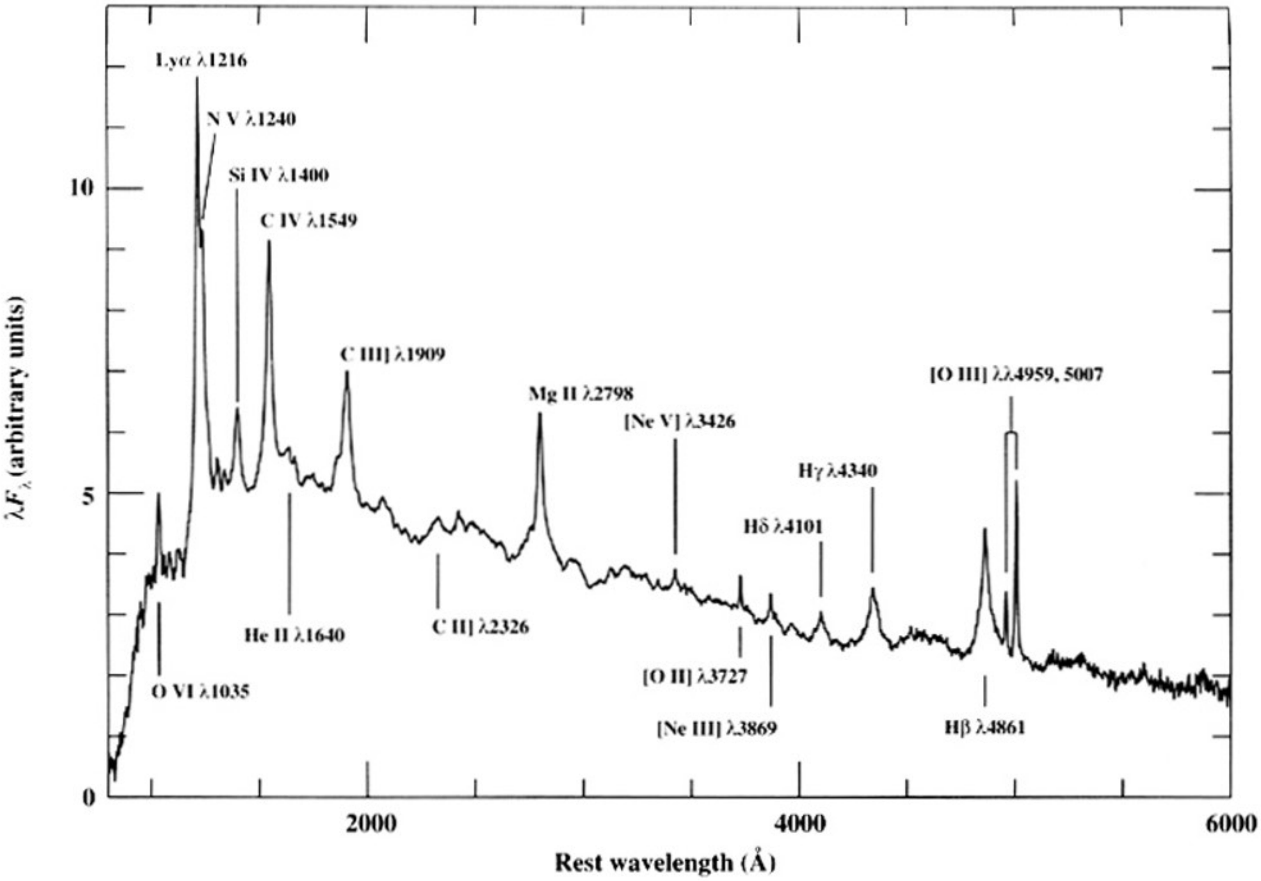

Figure 1.2: An average rest-frame quasar spectrum with prominent emission features labeled. This composite was formed by combining over 700 spectra from the Large Bright Quasar Survey (Francis et al., 1991). The flux scale is in arbitrary units.

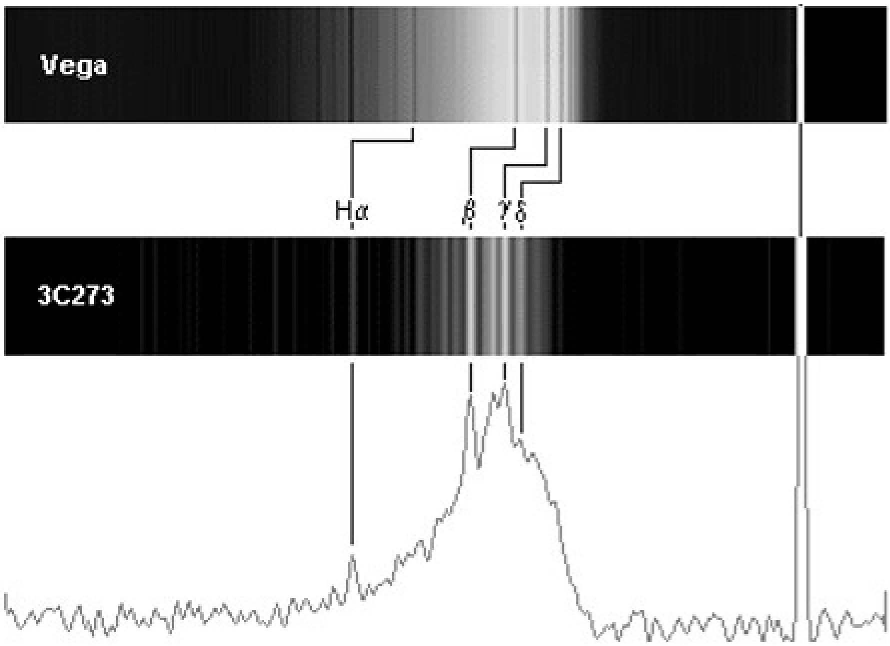

Figure 1.3: The spectrum of a nearby star, Vega (assumed to have little relative motion to Earth and therefore a rest-frame reference) compared to the spectrum of the quasar 3C 273. The shift in hydrogen spectral features of 3C 273 relative to Vega's rest-frame lines indicate cosmological redshift. Image credit: `https://www.britastro.org/journal_old/archive/redshift.htm`.

The recessional velocity due to cosmological expansion is given by

$$v = cz, \tag{1.2}$$

where z is the cosmological redshift and c is the speed of light taken to be 3×10^5 km s^{-1}. Lastly, using Hubble's law,

$$d = v/H_0, \tag{1.3}$$

where v is the galaxy's recessional velocity and H_0 is Hubble's constant taken to be $H_0 = 70$ km s^{-1} Mpc^{-1}, we can determine an object's distance from us. The first quasar identified, 3C 273, whose spectra is shown in Figure 1.3, has a redshift of only 0.158 (Schmidt, 1963), correlating to an approximate distance of 2.2 billion light-years from our Solar System.

Compact: Most observable objects outside of our galaxy appear as extended objects. However, the point-like nature of quasars suggests that they must be much smaller than a regular galaxy. The size of an object constrains how fast it can change its brightness; conversely, rapid flux variations constrain the size of the object. Astronomers have observed

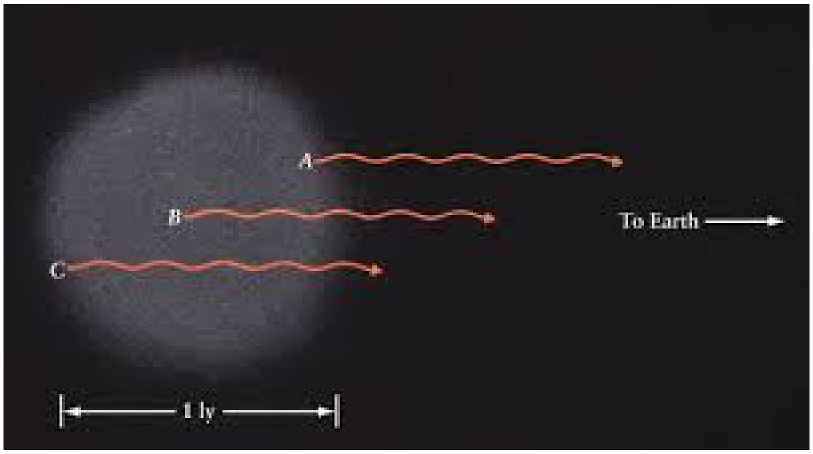

Figure 1.4: A depiction of the differences in arrival time of light from various parts of a quasar. Light leaving from the "front" side will reach us first, and light from the "back" side will reach us last. The difference between these arrival times lets astronomers deduce how large the quasar is. Image credit: `https://slideplayer.com/slide/9072189/`.

rapid and "coordinated" variability in quasars, indicating that each part of the quasar must be in contact with each other part and suggesting that they are relatively small. If a change in luminosity occurs in a quasar, we can measure the *time lag* between when first observe the change in flux (coming from the front side of the object, closest to us) and when the flux returns to normal (when the increased flux from the back side of the object, furthest from us, arrives), as illustrated in Figure 1.4. Using the simple constant velocity formula

$$d = c\Delta t \tag{1.4}$$

where d is the distance, c is the speed of light, and Δt is the measured time lag, we can determine the physical size of a quasar. Typical quasar sizes are about 1 ly, about the size of our Solar System.

High Energy: Quasars are believed to be very high-energy objects because high ionization states of atoms have been observed (see Figure 1.2). Each successive ionized electron is much harder to remove than the one before because the nucleus has a stronger pull on it. In order to overcome the nuclear pull of valence electrons, the photons bouncing around the quasar must have sufficiently high energies. Additionally, the broad absorption lines observed in quasar spectra indicate that gaseous regions are rotating very fast, requiring high energies. Gases that are at rest will produce a very fine, defined spectral line; however, rota-

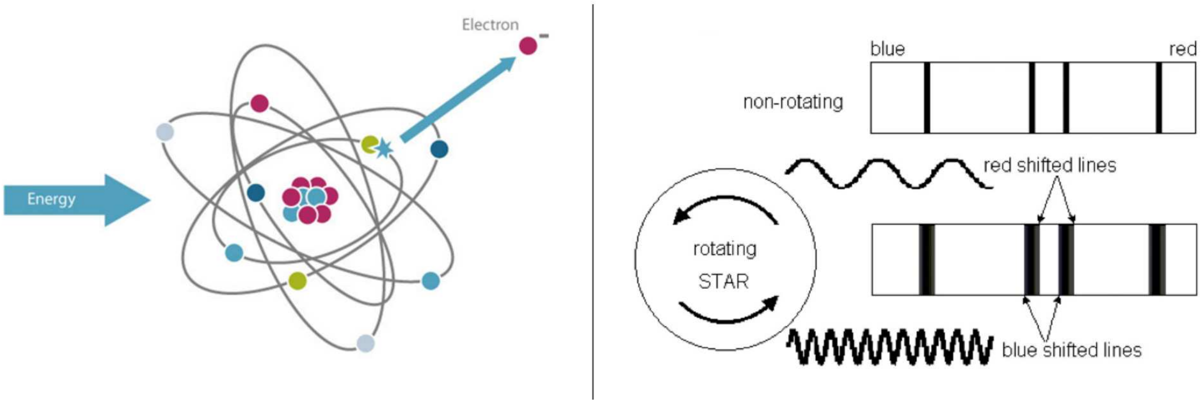

Figure 1.5: Left: A graphical depiction of the ionization process. Image credit: `https://sites.google.com/a/lansinglions.org/astronautmegashock/how-does-nasa-deal-with-static-electricity-buildup`. Right: A graphical depiction of the mechanism for spectral line-broadening. Image credit: `https://scienceready.com.au/pages/stars-spectra`.

tion of gas around a central mass will result in some of the gas appearing redshifted (moving away) and some appearing blueshifted (moving closer). The very broadened spectra lines indicate that the gas within a quasar is moving very fast, requiring very high energies.

Extremely Luminous: Since quasars are located great distances from our Solar System, they must be extremely luminous to produce the measured fluxes. The relationship between observed flux and intrinsic luminosity is given by

$$F = \frac{L}{4\pi d^2} \tag{1.5}$$

where F is the observed flux, L is the intrinsic luminosity, and d is the distance of the object from the observer. It is already established that quasars are extremely distant; therefore, they must also be extremely luminous in order for us to observe them. There is a limit to their luminosity, however. The *Eddington luminosity* is the maximum luminosity a body can have while still maintaining hydrostatic equilibrium (the balance between gravity and radiation pressure). A derivation of the Eddington luminosity is given in Appendix A.

The inward gravitational force is described by Newton's Universal Law of gravitation:

$$F_g = \frac{GM\mu m_p}{r^2} \tag{1.6}$$

where G is the universal gravitation constant of $G = 6.67 \times 10^{-11}$ N m^2 s^{-2}, M is the mass of the central black hole), μ is the mean mass number of the particles characteristically orbiting

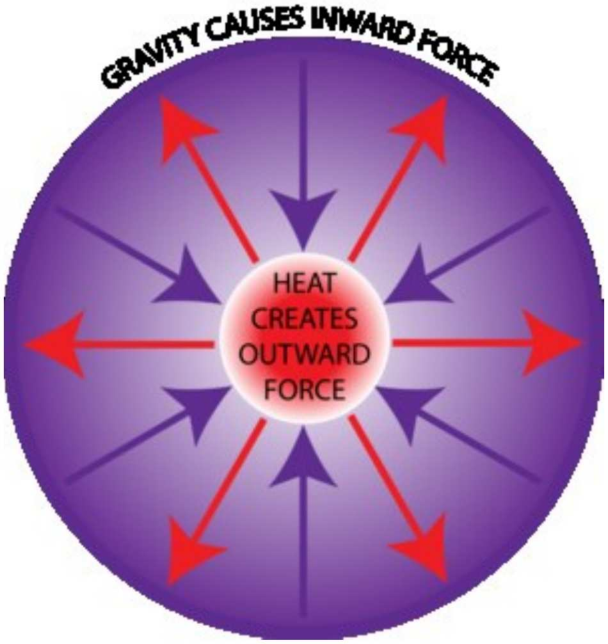

Figure 1.6: An illustrated depiction of the balance between gravitational and radiative forces that constrain the luminosity of quasars. Image credit: Gamalath and Rajapakse (2015).

the black hole (typically $\mu = 1.17$ for a fully ionized solar composition gas (Netzer, 2006)), m_p is the mass of a proton, and r is the distance from the black hole to the particle. The outward radiation force is given by

$$F_{rad} = \frac{L\sigma_T}{4\pi r^2 c} \tag{1.7}$$

where L is the intrinsic luminosity, σ_T is the cross-sectional area of an electron undergoing Thompson scattering, r is the distance from the black hole to the free electrons (where the free protons are), and c is the speed of light. Setting these two equations equal to each other to represent the balance of forces gives the formula for the Eddington luminosity, the maximum intrinsic brightness that a quasar can reach:

$$L_{Edd} = \frac{4\pi G M \mu m_p c}{\sigma_T}. \tag{1.8}$$

The existence of the Eddington luminosity suggests that there is a regulatory process within AGN. If, somehow, the luminosity got too large, there would be an increase in radiation pressure that would push the gas further away from the SMBH. This would cause the accretion process to slow down, forcing the luminosity to decrease. The decrease in luminosity would cause a decrease in the radiation pressure, allowing the gas to fall back in and enabling the onset of accretion once again. This process allows a quasar to self-regulate and remain stable for billions of years despite their natural tendency to fluctuate in luminosity.

1.3.2 AGN Taxonomy

As AGN were studied more, astronomers formulated a classification scheme based on the properties discussed above. The broadest distinction regards the intensity of the radio emission which separates the intense "radio loud" (∼10% of AGN) from the meek "radio quiet." A fairly simple classification scheme using only three parameters (radio loudness, emission line width, luminosity) is described below and displayed in matrix form as shown in Table 1.1:

Table 1.1: A simplified scheme for AGN taxonomy that only accounts for the radio-loudness of the galaxy and the thickness of its nuclear emission lines. Further sub-categories exist, but only the main categories are listed here for clarity. This tabular classification scheme is laid out in Urry and Padovani (1995). Further details may be found in the Antonucci (1993) review.

	Type 2 (Narrow Line)	Type 1 (Broad Line)	Type 0 (Unusual)
Radio Quiet	Seyfert 2	Seyfert 1	BAL QSO
Radio Loud	Narrow Line Radio Galaxy	Broad Line Radio Galaxy	Blazar
	Type II Quasar	Type I Quasar	

Radio Quiet

- Broad-Absorption Line (BAL) QSO: weak radio emission, very broad absorption lines
- Seyfert 1 Galaxies: weak radio emission, broad+narrow emission lines
- Seyfert 2 Galaxies: weak radio emission, only narrow emission lines

Radio Loud

- Narrow Line Radio Galaxy: strong radio emission, only narrow emission lines
- Broad Line Radio Galaxy: strong radio emission, broad+narrow emission lines
- Blazar: strong radio emission, spectral features obscured
- Type I Quasar: strong radio emission, high luminosity, broad+narrow emission lines
- Type II Quasar: strong radio emission, high luminosity, only narrow emission lines

1.3.3 Main Components of AGN

The study of AGN in different regions of the electromagnetic spectrum has led astronomers to identify the major regions that contribute to their structure, depicted in Figure 1.7. The six main components are discussed below.

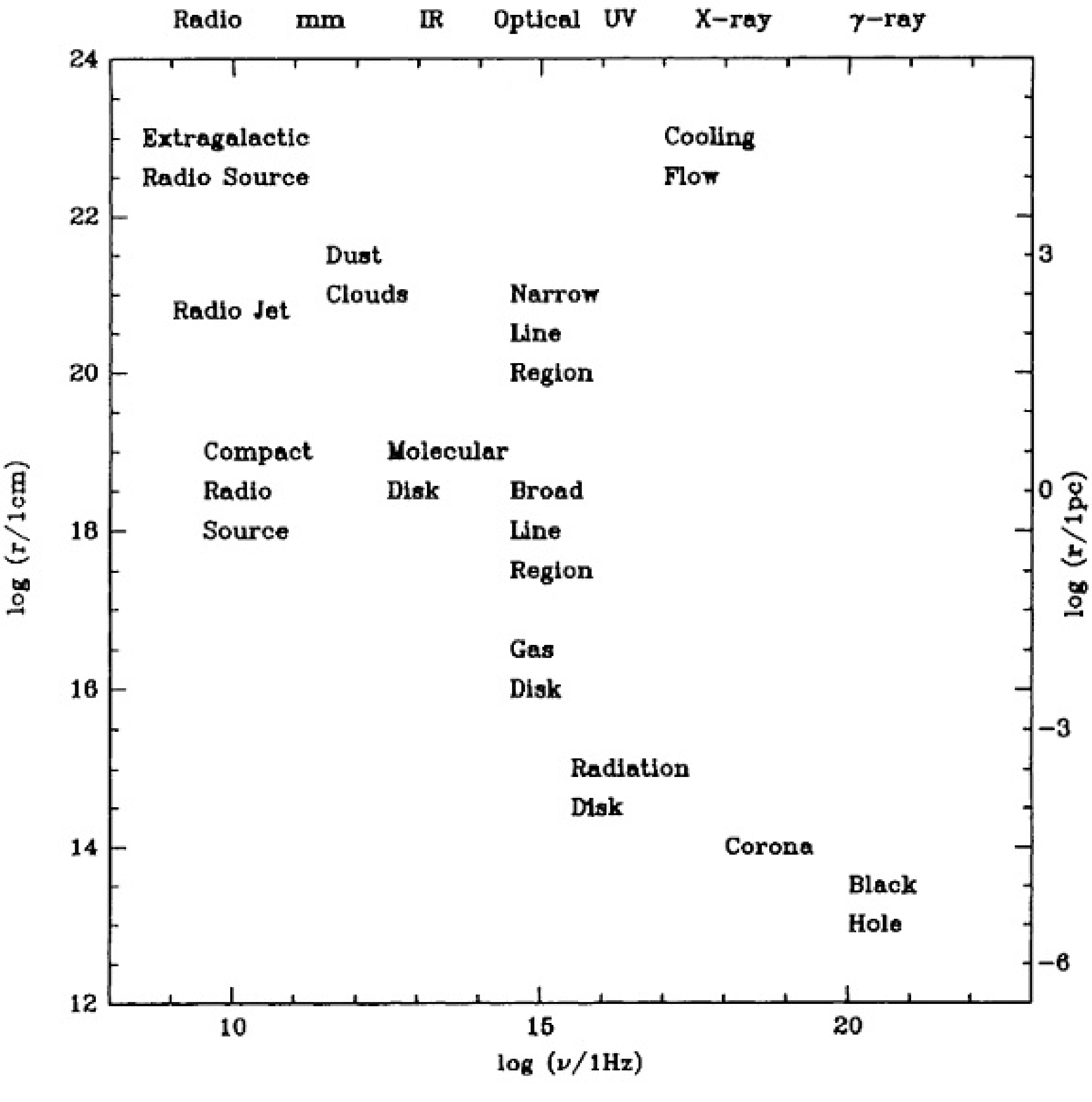

Figure 1.7: Schematic illustration of the range of activity of AGN according to their observed frequency. Some structural components, like the radio jets, can be observed directly while others, including the black hole and accretion disk, must be inferred indirectly. Image credit: R. D. Blandford (1990).

Supermassive Black Hole: Every massive galaxy in the Universe is believed to host a supermassive black hole at its center (R. D. Blandford, 1990; Richstone et al., 1998), though astronomers must use indirect methods of detecting them (e.g., Fabian, 1999; Haehnelt & Kauffmann, 2000; Kauffmann & Haehnelt, 2000). These black holes are millions to billions of times more massive than our Sun, though all of this mass is located at one point called the singularity. By studying AGN we can learn how the central black hole contributes to galactic evolution (Netzer, 2013).

Accretion Disk: Rings of hot gas and plasma surround and orbit the central black hole to make up the accretion disk. The material spirals inward to feed the black hole while reaching temperatures on the order of $\sim 10^5$ K (Netzer, 2013). The accretion disk can emit 1000 times more light than an entire galaxy (Fabian, 1999), shining most brightly at x-ray, ultraviolet, and optical wavelengths. Accretion has a $\sim$ 10% efficiency rate, compared to the 0.7% efficiency of nuclear fusion, which can explain the extreme luminosities of quasars (Fabian, 1999; Rees, Begelman, Blandford, & Phinney, 1982). The accretion disk is approximately 0.001 pc (1-10 light-days) across, depending on the mass of the black hole (Netzer, 2006).

Broad Line Region: Dense clouds of gas and dust circle the accretion disk, creating the broad line region (BLR). Broad spectral lines are produced by fast-moving material with speeds on the order of ~ 3000 km s^{-1} (Netzer, 2006), with high-ionization gas in broad absorption line quasars reaching speeds upwards of 10^4 km s^{-1} (Weedman, 1986). In addition to high orbital speeds, significant blueshifts of spectral lines originating from the BLR suggest that the material is also subject to winds that push it outward (Elvis, 2000). This region is brightest at UV and optical wavelengths and is about 0.01-1 pc (10-1000 light-days) in size, depending on the mass of the black hole (Netzer, 2006).

Dusty Torus: The torus is an enormous circumnuclear (donut-shaped) body of dust, with temperatures on the order of ~ 1000 km s^{-1}, that surrounds the inner portions of the AGN (Netzer, 2013). The dust greatly obscures our view of what is going on inside, however some light from the accretion disk is reflected or converted to infrared radiation (Sazonov et al., 2012). The torus glows in the infrared with its inner radius as small as 0.1 pc (100 light-days) and its outer radius as large as 10 pc (over 30 light-years) in size, depending on the mass of the black hole (Netzer, 2006, 2013).

Narrow Line Region: Slow-moving and diffuse gas clouds, with speeds on the order of $\sim 500 \text{ km s}^{-1}$, give rise to spectral emission lines with narrow profiles (Netzer, 2006). The low density of gases in the narrow line region (NLR) makes atomic collisions unlikely, meaning that atoms commonly excited into a metastable state will likely decay via a (semi-)forbidden transition (Netzer, 2006). Clouds in the narrow line region are brightest in the optical and exist about 100-3000 pc (300-10,000 light-years) from the center of the AGN, perpendicular to its rotational plane (Netzer, 2006, 2013; Weedman, 1986).

Relativistic Radio Jets: The vast majority of radio-loud AGN exhibit powerful radio jets that originate from the central continuum source Netzer (2013). Strong helical magnetic fields from the black hole eject charged particles out of the AGN at near the speed of light in the form of relativistic radio jets (R. Blandford, Meier, & Readhead, 2019; Marshall et al., 2005). AGN radio jets tend to be one-sided, strongly collumated, and polarized (R. Blandford et al., 2019; Walker, Hardee, Davies, Ly, & Junor, 2018). These jets extend far out of the host galaxy, sometimes multiple Mpc (millions of light-years) into space (R. Blandford et al., 2019).

1.3.4 Unified Model

Astronomers proposed an orientation-dependent unified model of AGN in order to reconcile the observed properties and various classifications of AGN. The presence of the dusty torus and radio jets are huge contributors to the apparent discrepancies of early AGN observations that now seem to be reconciled. Figure 1.8 illustrates this point.

1.3.5 Quasars

Quasars are the most powerful AGN, capable of producing more light than the rest of the host galaxy combined. Because quasars are so distant and compact, they cannot be spatially resolved, with the exception of the radio jets. Therefore, quasars must be studied using spectroscopy. The spectral energy distributions (SEDs) of quasars exhibit a strong

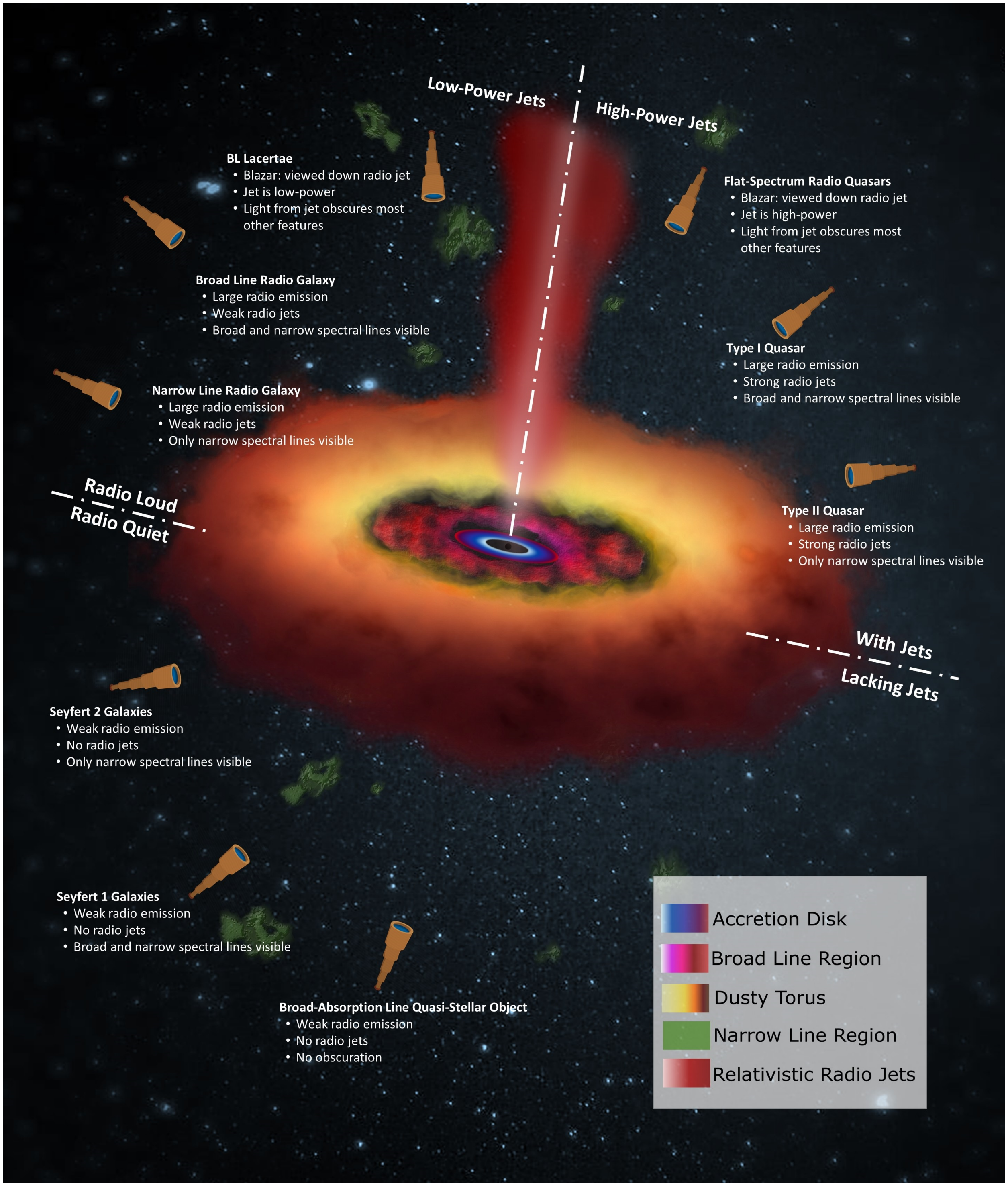

Figure 1.8: The unified model of AGN depicting the six main components (supermassive black hole, accretion disk, broad line region, dusty torus, narrow line region, relativistic radio jets) and the orientation-dependence of AGN taxonomy.

UV/optical component called the "Big Blue Bump" that is produced by accretion disk emissions, and there are numerous broad and narrow emission lines throughout the spectrum as well. Quasars are considered to be a phase of galactic evolution since they tend to be found in young galaxies and the early Universe (Netzer, 2013). By studying these objects we hope to better understand how structures in the primordial Universe began to form to produce the spectacular galaxies we see today.

1.4 Dissertation Overview

The goal of this dissertation is to improve the understanding of quasar physics by improving measurements of their physical parameters. My primary investigations have been separated into two projects in service of this goal. Chapter 2 details my project for developing a better statistical method for determining the redshift of distant quasars using the broad C IV emission line. Chapter 3 describes my work examining the quasar VIIIZw233 to determine if a tidal disruption event occurred within the galaxy recently. Lastly, Chapter 4 summarizes the main findings of my research, my interpretation of those findings, and the current state of the field at large. Throughout this work, I use standard cosmological parameters of $\Omega_\Lambda = 0.7$, $\Omega_m = 0.3$, and H_0=70 km s^{-1} Mpc^{-1}.