Calculating $M_{BH}$ Scaling Relations for AGNs using 2D Galaxy Decomposition Software to Analyse HST Images

March 2023

Written by
Jewel Arianna Capili

Advised by
Dr. Vardha N. Bennert

A senior thesis presented to
the Department of Physics
at California Polytechnic State University

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1 Introduction

Active Galactic Nuclei (AGNs) are among the brightest objects in the observable universe, able in some cases to outshine their entire host galaxies \(^1\). The first AGN was observed less than a century ago by American astronomer Carl Seyfert (Seyfert, 1943), sparking a long line of studies centered on these fascinating objects. In the center of AGNs are drastically distorted regions of spacetime from which no light can escape - supermassive black holes (SMBHs) up to billions of times the mass of our sun that are powered by accretion (Hoyle and Fowler, 1963; Salpeter, 1964; Lynden-Bell, 1969). Accretion occurs when matter orbiting a black hole loses angular momentum and begins spiraling in towards the singularity, growing the mass of the BH. The infalling matter rotates rapidly in an accretion disk, where friction produces the large amounts of light that reach our telescopes on Earth. While data from the Hubble Space Telescope (HST) launched in 1990 made it possible to confirm that SMBHs lurk in the center of most galaxies, “active” galaxies are distinguished from their quiescent counterparts by the fact that their central SMBHs are growing through accretion, producing the bright source that we identify as an AGN. The amounts and types of radiation emitted by AGNs depend on the specific properties of the host galaxy and central SMBH, but over the years astronomers have identified overall trends in radiation signatures and have attempted to classify known AGNs into a coherent system. The classification system is quite elaborate, and though a simpler unified model of AGN structure (discussed further below) has been proposed we are still seeking a better understanding of the mechanisms that give rise to the extreme diversity of AGNs. Understanding how SMBHs co-evolve with their host galaxies - in other words, how the properties of one impact the properties of the other - is a vital first step towards this goal.

All AGNs have a so-called broad-line region (BLR) surrounding the central SMBH and a narrow-line region (NLR) that forms beyond the dust sublimation radius. The emission lines from both are Doppler-broadened, with typical widths (measured in velocity units) ranging from \(500 \, \text{km} / \text{s}\) up to \(10,000 \, \text{km} / \text{s}\) for the BLR and \(200 \, \text{km} / \text{s}\) to \(900 \, \text{km} / \text{s}\) for the NLR depending on the object’s particular properties. Since the BLR is closest to the continuum source and reprocesses energy from the accretion disk, it can be useful in determining the mass of the central BH through a process known as reverberation mapping (see Section 1.2). The emission lines from the BLR are characterized by logarithmic line profiles. Emission lines from the NLR have non-Gaussian line profiles and display asymmetry. The nearly-ubiquitous ”blue wing” seen in [OIII] \(\lambda 5007\) lines in the NLR spectra is thought to indicate the presence of outflows in addition to the obscuring dust (Vaona et al., 2012). The blue wing arises

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\(^1\)The information in this introduction draws from An Introduction to Active Galactic Nuclei by Bradley M. Peterson, 1997
from an outflow oriented towards the observer, while the corresponding red wing is not visible since it is obscured by dust on the far side of the AGN. Additionally the NLR is the only component of AGNs that is spatially resolved in the optical, making it a useful source of information regarding the AGN fueling mechanism.

It is difficult to definitively classify and identify different types of AGNs since there is still uncertainty as to how much of the variability we observe in their properties is a result of our limited conditions of observation (e.g., viewing angle or dust obscuration) as opposed to the intrinsic properties of the objects in question. Nevertheless, astronomers have made attempts to distinguish the various types that they have so far observed, with Seyfert galaxies, their subtypes (Type 1 and Type 2 Seyferts) and radio-loud counterparts (BLRGs and NLRGs) being some of the most heavily-studied AGNs in the astrophysical community. Below is a brief summary of the properties of these objects:

- **Seyfert galaxies** have bright nuclei and are typically spiral galaxies. Their spectra are characterized by strong, high-ionization emission lines. Seyfert galaxies can be divided into 2 subclasses:
  
  Type 1 Seyferts with both narrow and broad lines corresponding to the presence of low- and high-density ionized gas particles respectively, and

  Type 2 Seyferts displaying only the narrow lines (see Figs. 1 and 2 for typical spectra).

  Both types of Seyferts have weak absorption lines due to starlight dilution by the featureless continuum emitted by the accretion disk.

- **Radio-loud AGNs** sometimes have powerful jets made up of sub-relativistic electrons moving around magnetic field lines and emit synchrotron radiation in the radio regime. When our line of sight is directly along these jets the active galaxies appear to us as blazars or BL Lac objects. Two types of these radio-loud galaxies have been identified:

  Broad-line radio galaxies (BLRGs) are similar to Type-1 Seyfert galaxies and exhibit both broad and narrow lines in the optical, while

  Narrow-line radio galaxies (NLRGs) resemble Type-2 Seyferts and exhibit narrow Balmer lines (Osterbrock and Pogge, 1985). Both BLRGs and NLRGs occur in elliptical galaxies.

  Included in this subcategory of radio-loud AGNs are quasars, some of the brightest objects ever observed (Matthews and Sandage, 1963; Schmidt, 1963). Since the majority of quasar host galaxies have been found to have high redshifts that locate them in the early Universe (2dF QSO Redshift Survey, see Fig. 3), it is plausible that manifesting as a quasar is a common phase in galaxy evolution.
The unified model of AGNs posits that all AGNs have the same essential structure and that the differences observed in their basic features (resulting in the highly diverse classifications briefly discussed above) are due mainly to the angle from which we view them. In this model (see Fig. 4) all AGNs are axially symmetric, composed of an accreting central SMBH surrounded by a BLR, NLR, an obscuring dust torus, and possibly ionization cones of ionized gas making up an extended narrow-line region (ENLR) (Peterson, 1997). The optically thick torus has been confirmed by observations in at least some galaxies (Elitzur 2006) and obscures emission to varying degrees depending on viewing angle (Fig. 3). Type 1 Seyfert and BLRG spectra arise from viewing the AGN and its torus face-on (in radio-quiet and radio-loud galaxies respectively) while Type 2 Seyfert and NLRG spectra arise from an edge-on view. In the edge-on orientation, the dusty torus blocks our view of the central accretion disk, its power-law continuum, and the BLR, resulting in no broad lines being observable in the spectrum. Similarly, viewing galaxies that produce a jet directly along our line of sight results in the observation of a quasar or BL Lac object. For the edge-on case it becomes plausible that we still see the AGN continuum through the dust torus if we introduce the presence of a ”scattering medium” above the torus that scatters light to the observer. The fact that broad lines in Type 2 spectra are seen in polarized light arising from scattering suggests that they arise from light from the BLR passing through such a scattering medium, and strengthens the argument for the unified model of AGN (Peterson, 1997).

This introduction has provided a brief overview of the properties of AGNs and touched on a few of their most common classifications. The following subsections will highlight information more specifically relevant to this study, including the significance of $M_{BH}$-host galaxy scaling relations and ways of calculating them for distant galaxies; the methods of data collection and reduction used on the images in this study; and a discussion of previous studies that have analysed AGNs included in our sample population. In the remaining sections of this paper, we will describe the methods of analysis adopted in this study (Section 2), including an overview of the software used to perform 2D galaxy decomposition on our sample of HST images. Results will be presented in Section 3, with a subsequent discussion of their relevance and a comparison with previous studies. Section 4 will summarize our findings and outline potential avenues for future research.

1.1 $M_{BH}$ Scaling Relations

Relationships have been found between $M_{BH}$ and other host-galaxy parameters (e.g. stellar velocity dispersion $\sigma$, stellar mass, and luminosity; Bennert, Treu, Ding, et al. (2021)), that indicate a co-evolution of central SMBHs and their host galaxies. This study presents the scaling relation between $M_{BH}$ and galaxy bulge
Figure 1: Optical spectrum of two different Type-1 AGNs (IZw1, top, with broad FeII emission lines and NGC 5548, bottom). Brackets denote so-called forbidden lines that are only seen in the NLR and not the BLR (Image taken from Dultzin et al. 2007).

Figure 2: Example of Type-2 AGN spectrum, with only narrow lines present. This figures is a composite spectrum formed from a sample of ninety-four [Ne v]-detected galaxies in Mignoli et al. (2013). Absorption lines from stars in the host galaxies are also visible. (Image taken from Mignoli et al. 2013).

(spheroid) luminosity $L_{sph}$ for 6 AGNs (see Fig. 5 for an example), a relation which would facilitate the study of distant active galaxies by allowing astronomers to estimate the mass of the central black hole from bulge luminosity measurements alone. However, as we will see shortly when discussing the fitting process for each
active galaxy here, the calculation of this relation can be affected by the presence of dust in the host-galaxy of the AGN that absorbs light in the visible spectrum, thereby complicating the process of obtaining an accurate value of host-galaxy bulge (spheroid) luminosity from the HST images. The most robust scaling relation that exists in the literature is that between $M_{BH}$ and stellar velocity dispersion $\sigma$ (a measure of the spread of stellar velocities in a galaxy, or how fast on average stars are orbiting in the galaxy), which is not discussed here but is explained thoroughly in Bennert, Treu, Ding, et al. (2021) alongside some very exciting findings. Plotting scaling relations for many different AGNs against each other facilitates generalizations of how AGN and host-galaxy properties co-vary. The acquisition of higher-resolution images and the development of more accurate methods of image analysis is pivotal to the search for consistent scaling relations, which is the goal of this paper.

1.2 Methods of Calibrating BH Mass

Reverberation mapping (RM) is a technique that uses light travel times to estimate the radius of the broad-line region surrounding black holes using observed time delays between continuum and BLR emission. Because the BLR clouds are ionized directly by light from the accretion disk, any fluctuations in the continuum will pass through the clouds and be re-emitted by the BLR clouds upon recombination as broad emission lines (e.g., the Balmer series in the optical). By measuring the time delay between continuum and BLR fluctuations and assuming a constant speed of light, we can calculate the distance light has traveled and thus find the radius of the BLR, which is directly correlated to BH mass by the equation

$$GM_{BH} = fR_{BLR} \Delta v^2$$

(1)
Figure 4: The Unified Model of AGNs suggests that the different types of observed AGN can be explained by different viewing angles (Image taken from Beckmann and Shrader (2012)).

Figure 5: An example of a scaling relation comparing $M_{BH}$ to bulge luminosity. (Image taken from Bennert et al. 2021).
where $v$ is the velocity of the BLR clouds that can be directly determined from the width of the broad lines, and $f$ is a ‘virial factor’ that varies depending on the geometry and velocity structure of the BLR (Peterson 2006). $f$ is traditionally found by matching the $M_{BH} - \sigma$ scaling relation of the AGNs to the corresponding relation of quiescent galaxies (Bennert, Treu, Ding, et al., 2021).

The single-epoch method is another way of calibrating $M_{BH}$ that combines the width of broad emission lines with the AGN luminosity to estimate the radius of the BLR. Although this method is simpler than RM, it is based on a relationship between the BLR radius and AGN luminosity calculated from RM AGNs that comes with its own intrinsic level of uncertainty (Mejia-Restrepo et al. 2018). Beyond the local Universe, the single-epoch method is used to estimate $M_{BH}$ for Type-1 AGNs.

1.3 Objectives of the Current Study

In this study, our goal is to contribute to the quest for these scaling relations by obtaining exact measurements of certain host galaxy properties through 2D image decomposition. The sample population is 14 AGNs with diverse morphologies (see Table 2 for a breakdown) whose BH masses have already been estimated using reverberation mapping. Images of these 14 objects taken by the Hubble Space Telescope are fed into the software GALFIT (Peng et al., 2002) to reproduce 2-dimensional models that allow us to separate and identify individual galaxy components (i.e., galactic bulge, disk, and in some cases bar) and estimate their radii and luminosities. These measurements are then used in combination with the measured BH mass for each galaxy to obtain scaling relations, which we hope will shed some light on how AGNs and their host-galaxies co-evolve.

This study is a follow up to Bennert, Treu, Ding, et al. (2021), which sought to establish a local baseline for $M_{BH} - host$ galaxy scaling relations from a sample of
66 Seyfert-1 galaxies taken from the SDSS (Bennert et al. 2021; see also senior thesis by Isak Stomberg published at Kennedy Library, Cal Poly\(^2\)). The main difference in the analysis conducted here is the use of reverberation mapping to determine BH masses in the present sample, which is a more accurate technique compared to the single-epoch method used to estimate BH masses in Bennert et al. 2021 (see Section 1.3 for a brief discussion of the single-epoch method).

1.4 Sample Population

Our sample population is comprised of 14 AGNs imaged by HST. These 14 reverberation-mapped AGNs were selected because they were all also observed with Keck/OSIRIS, an integral-field unit spectrograph in the near-IR. As part of another project, stellar-velocity dispersion ($\sigma$) will be determined from CO absorption lines seen in these spectra. Here, we focus on the HST images.

Although the original sample size included 14 objects imaged by HST, only 6 will be analyzed in depth in this paper due to complications in the fitting process (arising most likely from the presence of dust lanes in the images). However, the selected subsample is still representative of a range of galaxy morphologies including one elliptical galaxy fitted by only a bulge component, four galaxies fitted with both a bulge and a disk, and one spiral galaxy viewed face-on. We find that the sample data extends the baseline of scaling relations for low-mass objects when plotted with data from Bennert, Treu, Ding, et al. (2021), with the exception of a single outlier (Fig. 18). Table 1 contains redshift, right ascension, and declination information for each of the host galaxies as well as data regarding the instrument and filter used during imaging.

\(^2\)https://digitalcommons.calpoly.edu/physsp/157/
<table>
<thead>
<tr>
<th>Object</th>
<th>log $M_{\text{BH}}$ ($M_\odot$)</th>
<th>RA (hh:mm:ss)</th>
<th>Dec (dd:mm:ss)</th>
<th>z</th>
<th>Instrument</th>
<th>Filter</th>
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<td>-13:24:53</td>
<td>0.0146</td>
<td>WFC3</td>
<td>F547M</td>
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<td>F547M</td>
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<td>0.0352</td>
<td>ACS</td>
<td>F550M</td>
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<td>F550M</td>
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<td>+08:52:26</td>
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<td>ACS</td>
<td>F550M</td>
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Table 1: Information on BH mass taken from the AGN Black Hole Mass Database (Bentz and Katz, 2015)

1.5 Observation and Data Reduction

The archival HST images were all taken for the purpose of imaging the host galaxies of reverberation-mapped AGNs (HST-SNAP-9851, HST-GO-10516, HST-GO-10833, PI: Peterson; HST-GO-11662, PI: Bentz) and are thus of the necessary quality for the purpose of our goal. Of the 14 objects, 12 have been observed with ACS/HRC (F550M), consisting of 2 short exposures, 2 medium exposures, and 2-6 long exposures, all at the same pixel location. The 2 remaining objects (NGC 4748, NGC 6814) were imaged with WFC3/UVIS (F547M) in a similar fashion. The HST archival images already come fully processed using the standard pipeline. We started with the fit (for ACS/HRC) or “flc” (for WFC3) extension of the fits files. L.A. Cosmic (Laplacian Cosmic Ray Identification; van Dokkum 2001, PASP, 113, 1420) was run to remove cosmic rays. All long exposures were carefully checked for saturation, especially that of the bright AGN point source. For objects with saturated pixels, the shorter exposures were scaled according to exposure time and used to replace the saturated pixels. Pyraf package “astrodizzle” was then used to combine the long exposures. After some
experimentation, the following parameters were adopted:

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<th>final_bits</th>
<th>finalwcs</th>
<th>final_pixfrac</th>
<th>Final Pixel Scale (\text{/pix})</th>
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<td>ACS/HRC</td>
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<td>0.9</td>
<td>0.035&quot;</td>
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<tr>
<td>WFC/UVIS</td>
<td>336</td>
<td>336</td>
<td>yes</td>
<td>0.9</td>
<td>0.025&quot;</td>
</tr>
</tbody>
</table>

For objects without any saturated pixels, all exposures were combined with astrodrizzle directly in the same way. The sky background was carefully subtracted out before the analysis. For all objects, PSF stars were created from suitable stars in the field-of-view (FOV) of each object that met the following criteria: bright, unsaturated, free from nearby objects, and located close to the AGN/center of the FOV with an overall profile as expected for a PSF star. We chose the best PSF star for each object. For 8/14 objects (all imaged with ACS), there was no suitable PSF star in the FOV. For those, we use a PSF from another object, chosen closest in time. In addition, for ACS, we used the TinyTim package to create artificial PSF stars at the location of each AGN, assuming a power-law for the AGN spectral distribution. TinyTim models the HST optics, including the specific camera and filter system (Krist 1993, ACS Instrument Science Report; ISR 2003-06; Baltimore, MD: STScI). For all objects, masks were created for any nearby sources. Data reduction, selection of PSFs, and creation of masks was performed by Dr. Vardha N. Bennert.

1.6 Previous Analysis

The HST images analysed in this study have been previously analyzed for the main purpose of creating the relationship between BLR radius and AGN luminosity in Bentz, Peterson, et al. (2009) and Bentz, Denney, et al. (2013). This is an essential relation for secondary methods of determining $M_{BH}$ such as the single-epoch method. The focus of previous analyses was on determining a host-galaxy free AGN luminosity by disentangling the host from the AGN, and taking extra care to ensure a well-fitted PSF. While the total luminosity of the host can be recovered with relatively small uncertainties in such an approach, the uncertainties of the exact properties of different host-galaxy components can be much larger and depend on the exact choice of host galaxy components. For example, when multiple Sersic components are used (one or two inner bulges in addition to the bulge; in one case, NGC 4748, even up to 8 different Sersic components), the Sersic index $n$ can be very low for some objects (e.g., 0.59 for
Mrk 590) and more closely resemble that of a bar than a bulge. Additionally the effective radius is very small in such models (e.g., 0.08” for Ark 120), possibly indicating a mismatched PSF. Using multiple Sérsic components to fit a single host-galaxy component confuses any attempt to make a physical interpretation of the host-galaxy component from resultant parameter values. We thus re-analyze the sample of AGNs found in the Bentz papers with a more conservative use of Sérsic components, using a one-to-one approach.

2 Analysis

In this study we extract the host-galaxy parameters of 14 AGNs imaged by HST and calculate their resulting scaling relations. The primary software used in this research, GALFIT, was developed by Dr. Chien Peng\(^3\) to decompose galaxy images into their individual structural components (detailed more thoroughly in Peng et al. (2002) and Peng et al. (2010)). Below is a basic overview of the fitting process and relative parameters in GALFIT, followed by a more detailed account of how the fitting was executed in this study.

2.1 Overview of GALFIT

General Fitting Process

- For each object in the present study, a science image (e.g., an HST image), PSF\(^4\), and a custom sigma image were provided to GALFIT before starting the fitting process. The sigma image contains a measure of the flux uncertainty at each pixel location ($\sigma(x, y)$), and thus directly affects the calculation of the $\chi^2$ value (see Eq. (1)). It is technically possible for GALFIT to generate a map of the flux uncertainties at each pixel without being given an external sigma image, but the calculation process is extremely sensitive to the exact method of data reduction and only proceeds reliable results if the fitting region is dominated by the sky background (Peng et al., 2002).

- Once these necessary input images have been provided, the user creates a customized input text file containing initial estimates of galaxy parameters (such as effective radius of the bulge and disk) and feeds it into GALFIT. The software then uses these parameters to generate a best-fit model in an iterative process by comparing model parameters with the actual image and making adjustments until converging at a local or global minimum.

\(^3\)https://users.obs.carnegiescience.edu/peng/work/galfit/galfit.html
\(^4\)The PSF images for all the objects referred to in this paper were pre-generated using a method discussed in Section 2.2
• What remains after convergence is a residual that can be analyzed by looking at the $\chi^2$ value, which is the sum of the differences between measured flux and values generated by the model at each pixel location. The $\chi^2$ value is calculated as

$$\chi^2 = \frac{1}{N_{dof}} \sum_{x=1}^{n_x} \sum_{y=1}^{n_y} \frac{(f_{\text{data}}(x,y) - f_{\text{model}}(x,y))^2}{\sigma(x,y)^2}$$

(2)

where

$N_{dof} = \text{degrees of freedom of the model}$

$f_{\text{data}}(x,y) = \text{data value at pixel location (x,y)}$

$f_{\text{model}}(x,y) = \text{value calculated by model at (x,y)}$

$\sigma(x,y) = \text{standard deviation of the flux at (x,y)}$

$n_x/n_y = \text{x- and y-dimensions of the image being fit}$

When the $\chi^2$ value is close to 1, we can be confident that the model parameters produced by GALFIT are an accurate representation of the host galaxy (Peng et al., 2010).

2.2 Specific Terms and Components

• PSF: The AGNs studied here are so far away that the light we receive from them can be treated as a point source while preserving reasonable accuracy. Whenever light from a point source is collected by a telescope (in this case HST) it undergoes diffraction from the telescope’s limiting aperture, and a Point Spread Function (PSF) describes the resulting light distribution in the 2D focal plane of the telescope. In this study, the PSF images were generated for a star at the same location as the AGN by Dr. Misty Bentz using the software TinyTim5.

![PSF image](https://www.stsci.edu/hst/instrumentation/focus-and-pointing/focus/tiny-tim-hst-psf-modeling)

Figure 7: PSF image used to fit objects NGC 4748 and NGC 6814

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5https://www.stsci.edu/hst/instrumentation/focus-and-pointing/focus/tiny-tim-hst-psf-modeling
• **Sérsic Profile:** A Sérsic profile is a function that represents how a galaxy’s surface brightness changes as a function of distance from the galactic center. Whether this drop-off is gradual and consistent or rapid after a certain distance varies depending on the galaxy, but typically bigger and more luminous galaxies have higher Sérsic indices. The Sérsic profile can be described by the equation

\[ \Sigma(r) = \Sigma_0 e^{-\kappa[(r/r_e)^{1/n} - 1]} \]  

where the Sérsic index is represented by \( n \). In this study, specific Sérsic index values (or a range of values) are assigned to different galaxy components (discussed below). This approach defines the galaxy components in GALFIT and allows us to communicate desired adjustments to the software with relative ease. Restricting the classification in this way gives us more control over the fitting process in the quest to obtain an accurate model of the galaxy.

Figure 8: The above graph shows different values of Sérsic indices describing how brightness falls off as a function of radius. Image published on 12 October 2008 to the Public Domain. Accessed from https://commons.wikimedia.org.

• **Bulge:** Most spiral galaxies have a dense spherical cluster of stars around their galactic centers, referred to as the bulge. While spiral galaxies have additional components besides the bulge (such as a bar and a disk), elliptical galaxies have only a ”bulge” component. This feature is defined here as having a Sérsic index ranging from \( 0.5 \leq n \leq 6 \). Within this range there are two further classifications of bulge types: pseudo- vs. classical bulge. In accordance with Kormendy & Ho (2013), a pseudo-bulge is considered to be a bulge that satisfies at least three out of four criteria:
1. $n < 2$ (while classical bulges are bulges with $n \geq 2$);
2. ratio of bulge-to-total luminosity < 0.5;
3. ratio of maximum rotational velocity at effective spheroid radius and central stellar-velocity dispersion > 1;
4. presence of a bar component (for face-on galaxies)

Classical bulges are thought to be formed by galaxy mergers and are typically centrally concentrated and mostly red. Pseudo-bulges, on the other hand, are believed to have evolved through dissipative processes and are sites of ongoing star formation with exponential line profiles (Bennert, Treu, Auger, et al., 2015).

- **Disk**: A disk is defined here as a component with Sérsic index fixed to $n=1$. Galaxy disks are sites of ongoing star formation with stars, gas, and dust rotating in a relatively flat plane around the galactic center, and are usually thin though thickness varies across galaxies. The radius of the disk component is typically larger than the radius of the bulge component of a galaxy.

- **Bar**: A bar is a component that has a Sérsic index value of $n=0.5$. Bars are central cigar-shaped structures in spiral galaxies made up of stars and gas that can affect the motion of galactic material by funneling gas inwards and acting as stellar nurseries. These structures are thought to arise from orbital resonances.

Figure 9: NGC 1300, a barred spiral galaxy clearly showing the central bulge, bar, and disk components discussed in Section 1.1.2. Image credit to Hillary Mathis/NOIRLab/NSF/AURA.
2.3 Step-by-Step Process of Running GALFIT

This study employs a bottom-up approach to guide GALFIT through the production of accurate galaxy models. One component is added to the input text file at a time, beginning with the PSF and progressing to the bulge, disk, and bar (if applicable). We then ensure convergence to a global minimum before adding another component. GALFIT and an imaging software called DS9 are used in concert, the former to produce models from input parameters once their values are estimated and the latter to visually estimate said parameters. After confirming that a global minimum has been reached in a process described below, we move on to fitting the next component (if needed). This systematic approach ensures that the model components are built on a solid foundation and minimizes the likelihood that the program will crash or produce ambiguous parameter values during fitting. When an acceptable model is generated and all the components visible in the galaxy are accounted for, we analyze the $\chi^2$ value (eq. (2) above) and free-fit all components simultaneously to ensure that we have obtained a reliable fit. Below is a more in-depth discussion of the steps followed when decomposing a galaxy using GALFIT:

- **Preliminaries:**
  - Before doing any fancy stuff, you’ll need to make sure that the control parameters on your GALFIT text file are customized to the object you wish to fit. When you create a GALFIT text file, edit parameters A, B, and C at the top of your text file such that the paths you’ve specified for your FITS file (data image), Sigma image, and input PSF image lead to the correct images for your object (see Fig. 25).
  - Next, check that you’ve specified the pixel region of your image you want GALFIT to fit. This information is listed as parameter H, and typically your pixel region should be the same as the size of your image. Parameter I is where you will input the size of your convolution box. Using values from Stomberg 2018, we recommend setting this size to 200 x 200 pixels.
  - In parameters J and K, you’ll need to enter the values for magnitude photometric zero point and plate scale x and y values respectively. Magnitude photometric zero point is determined during the process of data reduction and calibration for your science images. The plate scale values are entered in units of arcsecond per pixel and are determined by the properties of the CCD camera used in addition to the data reduction process (Fig. 25).

- Now that your control parameters are set, you can begin crafting the input parameters for your initial model. Estimate an appropriate starting value for
the integrated magnitude (this study uses a starting value of 15, as suggested in Stomberg (2017)). The type of component is specified in the first line of each component (see Fig. 12) and will need to be changed depending on the specific goals of your analysis and properties of the galaxy you wish to fit (Peng et al. 2002). In this study the only component types used were PSF and Sérsic.

- Special Case: If there is a clear neighboring object in your image (see NGC 4748 in Fig. 23 for an example), you will need to include a Sérsic component for the neighboring object as well to minimize its interference with the fit of the target galaxy

- Next, add a Sersic component for the bulge with \( n = 4 \) fixed. The number of Sersic components will depend on the morphology of the AGN host-galaxy you are trying to fit, and will be added in stages:
  - Elliptical galaxy: PSF and bulge component will be sufficient.
  - Spiral galaxy: If spiral arms are present, you will need to add a disk component to this base model;
  - Barred spiral: If a bar is present in the spiral galaxy, you should add a bar component to your model last (only after obtaining suitable global minima values for your bulge and disk components).

- Remember that the Sérsic indices of the disk and bar (if present) components must remain fixed at \( n=1 \) and \( n=0.5 \) respectively, because although certain parameters of these components are variable their Sérsic indices must remain consistent with what we described in Section 2.2.

*Note: If you are in doubt as to whether you classified your host galaxy correctly, you can check your residual image (which is determined by subtracting the Galfit model from your science image) for accuracy.

- When the first Sérsic component is added, double-check that its coordinates are set to the image center. You will want to check that the coordinates stay centered in each successive fit that you produce; although it may seem repetitive, due to the presence of high amounts of dust in the science images GALFIT may consistently produce model components with off-centered coordinates. Using DS9 (see Appendix A for a more detailed discussion on this software), open the science image of the particular galaxy you are working with and use the display to go to the analysis section. Select the 'grid' tab that appears on the option menu, and use it to visually estimate the value of the effective radius, axis ratio, and position angle for the component you are seeking to fit. Estimate the initial values for magnitude and Sérsic index as
best you can (see Section 2.4); GALFIT is not very sensitive to starting parameters of magnitude and Sérsic index, and converges quickly when given a wide range of starting values. Leave the coordinates and initial estimates for Sérsic index, effective radius, magnitude, position angle, and axis ratio free to be adjusted by GALFIT by setting the corresponding numerical value in the second column equal to 1 (see Fig. 12).

**Note:** The coordinates should only deviate from the image center by a few pixels; off-centered coordinates are a clear indication that GALFIT has fit an element of the image other than the one intended. There is the option of using a constraint file to keep the coordinates fixed or within a certain range of each other, discussed in Section 2.5.

* Once the parameters of the first component are chosen and left free for fitting, run GALFIT. Open the resulting galfit.fits file on DS9 and visually assess the plausibility of the model; check as well the $\chi^2_\nu$ value on the GALFIT text file. If both are satisfactory, proceed to the next step. Set the parameters of the present component to fixed (changing the 1 values to 0) in preparation for adding the next Sérsic component. ***This is a best-case scenario; more likely, the fit will call for adjustments. A discussion of the most common troubleshooting issues is conducted in Section 1.3.

Before testing whether you have reached a local or global minimum, make a copy of the output text file and save it with a name that will indicate what the fit is and what stage it is in (e.g., 'galfit.b' to indicate a fit with only a bulge component). This is an extra-cautious way to ensure you can retrace your steps if you encounter any serious issues during the fitting process.

* To test for a local or global minimum, shift the final parameter values produced by GALFIT to a value greater or smaller than your initial estimate (Sérsic index and effective radius are usually the parameters most sensitive to change, and Sérsic index is only applicable to the bulge - changing it by $\Delta n \pm 1$ should be sufficient; for effective radius, $|\Delta r_{\text{eff}}| \leq 20$ pixels or so with more or less depending on the size of the object should be sufficient). Then run the file again to see if GALFIT converges to the same values as before.

If decreasing the initial values slightly doesn’t change the resulting fit, try increasing them by the same amount and running GALFIT again (it isn’t necessary to make copies of these test runs - the sole purpose is to investigate the robustness of the fit). If the fit that results from both of these operations converges to the same parameter values, we assume a global minimum has been reached!
If either increasing or decreasing the parameter values changes their outputs significantly, this is a sign to keep exploring potential fits until a stable minimum is reached. In a simulation varying multiple parameters it is usual to find examples of parameter degeneracy; ideally, though, once you’ve generated multiple models there will be a specific parameter set (or range) that clearly stands out as the most physically likely model given what you know about your system. See the last bulleted item in this list for reasons on why parameter degeneracy arises and how you can extract results from the maelstrom you may find (though usually it isn’t that dramatic).

• Once you are confident a global minimum has been achieved, set the parameters of the present component to fixed (changing the 1 values to 0) and add the next Sérsic component. When you think you have converged at a reasonable set of parameters for the second component, set the parameter values for the first component free and run GALFIT again. Setting the first component fixed before adding a new component is not strictly necessary for the fitting process, but was done here to ensure that the second component had somewhat realistic initial parameter values before running both components through GALFIT in an effort to avoid crashing. For the most part all of the steps outlined above will be repeated, excepting the procedure for deciding an appropriate value for Sérsic index; since the bulge is the only component in a GALFIT input file that will have a range of possible Sérsic values, altering this parameter will not be necessary for the disk or bar components.

• When all desired components have been added to the model according to the process described above, set all parameter values that can be fit (i.e., radius, position angle, magnitude) to free (if you have not done so already) so that GALFIT fits them all simultaneously.

• Brief Discussion on Parameter Degeneracy: When analyzing galaxies with a software that allows manipulation of many physical properties of the system at once, parameter degeneracy inevitably arises. Many factors contribute to this - the difficulty of imaging objects that are so far from Earth, the presence of dust lanes that could obscure a galaxy’s true form - the list goes on. Checking whether a fit is a global or local minimum is one way we attempted to maximize the likelihood that a best fit was truly achieved for the galaxies in this study. Additionally, monitoring the $\chi^2$ value for each fit produced facilitated our process of selecting a single model from multiple possible models with equally-convincing residuals.
2.4 Estimating Initial Parameters:

- Here are some loose, general suggestions for estimating initial parameters:
  
  (a) **Magnitude**: Choose an initial magnitude for the component you would like to fit; as mentioned above GALFIT is not overly sensitive to starting parameters of magnitude and will quickly adjust this value. The starting magnitude for the PSF component used in this study is 15 (as recommended by Stomberg (2017)).

  (b) **Effective Radius** ($r_{\text{eff}}$): Estimate an appropriate initial value for effective radius using the grid display feature on DS9 (discussed above and in Appendix A). In each analysis presented here, the initial estimates for $r_{\text{eff}}$ of the disk was greater than that of the bulge, but in some galaxies the final model showed that the opposite produced the best fit.

  (c) **Sérsic index** ($n$): For the bulge, set the initial Sérsic index to $n = 4$, since this is comfortably within the range of Sérsic indices characteristic for bulges (see Section 1.1.2). The Sérsic indices of the disk and bar are fixed to $n=1$ and $n=0.5$ respectively, so once the bulge is fit your Sérsic index fiddling is complete.

  (d) **Axis ratio** ($b/a$): This parameter is the ratio formed by the semi-minor and semi-major axes of the galaxy and can be judged visually on DS9; an axis ratio of 1 indicated a perfectly circular object, while a smaller ratio indicates greater ellipticity.

  (e) **Position Angle**: This can be estimated visually using DS9.
Figure 10: Sample input text file for object Mrk 5548; the $\chi^2$ value at the top left shows the quality of the fit.

---

```plaintext
# Image and GALFIT control parameters
A) ../allscience/13227_5548_cutout.fits  # Input data image (FITS file)
B) 13227_psf.fits  # PSF (FITS file)
C) ../allscience/13227_1000_std.fits  # Sigma image name (made from data if blank or "none")
D) ../allscience/13227_psf_SUB_ACS.fits  # Default PSF image and (optional) diffusion kernel
E) 1  # PSF fine sampling factor relative to data
F) none  # Bad pixel mask (FITS image or ASCII coord list)
G) 1  # File with parameter constraints (ASCII file)
H) 1000 1 1000  # Region to fit (xmin xmax ymin ymax)
I) 100  # Size of the convolution box (x y)
J) 0.025 0.025  # Plate scale (arc sec) (arcs per pixel)
K) regular  # Display type (regular, curves, both)
L)  # Choose: Bsmoothize, 1model, Dmingblock, 3subcomps
```

Figure 11: Close-up of where input image locations are specified in the text file; in lines A), B), and C), a relative path of the images is given since they are stored in a directory different to the one GALFIT is currently running in. Each object has a custom data and sigma image, with a generic PSF.
Figure 12: Close-up of where component parameters are specified in the text file; the first specification is component type, which here is the PSF. Entering a 1 in the second column sets the parameter free to be fit, while entering a 0 keeps it fixed; here we see that all the PSF parameters except coordinate and magnitude are fixed.

```plaintext
# INITIAL FITTING PARAMETERS
#
# For component type, the allowed functions are:
# sersic, expdisk, edgedisk, devauc, king, nuker, psf,
# gaussian, Moffat, Fierz, and sky.
# Hidden parameters will only appear when they're specified:
# Bn (=integer, Bending Modes).
# C0 (diskyness/boxyness).
# Fn (=integer, Azimuthal Fourier Modes).
# R0-R10 (coordinate rotation, for creating spiral structures).
# T0, T1, T0-T10 (truncation function).
#---------------------------------------------------------------------
# par  par value(s)  fit toggle(s)  # parameter description
#---------------------------------------------------------------------

# Component number: 1
0) psf  # Component type
1) 508.5866 499.7999 1 1  # Position x, y
3) 15.8582 1  # Integrated magnitude
4) 0.0000 0  #
5) 0.0000 0  #
6) 0.0000 0  #
7) 0.0000 0  #
8) 0.0000 0  #
9) 0.0100 -1  # Axis ratio (b/a)
10) 0.0000 -1  # Position angle (PA) [deg: Up=0, Left=90]
2) 0  # Skip this model in output image? (yes=1, no=0)

# Component number: 2
0) sersic  # Component type
1) 508.1719 508.8646 0 0  # Position x, y
3) 14.9699 0  # Integrated magnitude
4) 13.2089 0  # Re (effective radius) [pix]
5) 1.8770 0  # Sersic index n (de Vaucouleurs n=4)
6) 0.0000 0  #
7) 0.0000 0  #
8) 0.0000 0  #
9) 1.0000 0  # Axis ratio (b/a)
10) -85.0000 0  # Position angle (PA) [deg: Up=0, Left=90]
2) 0  # Skip this model in output image? (yes=1, no=0)

# Component number: 3
0) sersic  # Component type
1) 588.4852 588.4554 0 0  # Position x, y
3) 14.8664 0  # Integrated magnitude
4) 125.4615 0  # Re (effective radius) [pix]
5) 1.0000 0  # Sersic index n (de Vaucouleurs n=4)
6) 0.0000 0  #
7) 0.0000 0  #
8) 0.0000 0  #
9) 0.0000 0  # Axis ratio (b/a)
10) 29.9913 0  # Position angle (PA) [deg: Up=0, Left=90]
2) 0  # Skip this model in output image? (yes=1, no=0)
```

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2.5 Troubles Encountered using Galfit

While attempting to isolate the substructures of each galaxy (bulge, disk, bar) using Galfit, we encountered a few issues consistently that are summarized here. While in some cases we discovered work-arounds that resolved these issues, there remain a few for which we were unable to find a solution (a joyous endeavor we leave to the interested reader).6

- **Coordinate Divergence**: Many of the 2D galaxy models we produced with Galfit for this study had to be excluded from our final analysis due to diverging coordinates (hence only 6 out of 14 AGNs listed in Table 2). In most cases we attempted to remedy this by introducing a constraint file, which was met with varying levels of success. The method to create a constraint file for Galfit is as follows:
  - Create a text file of the format shown in Fig. 13, tweaking the range of allowed values to match up with your particular image. This is your generic constraint file for a model with Sérsic components, which can serve as a basis for more customized constraint files if you find them necessary later on. Always make copies of the generic file and alter the copies rather than the original, so you can return to a clean slate.
  - Once your constraint file is created, go to the text file for your host galaxy model and specify the constraint file in the header (Fig. 14).
  - Now you should be ready to go! Save and exit your text file and run Galfit as you normally would.

Unfortunately, in this study creating and applying a constraint file rarely solved the problem of coordinate divergence. More frequently it seemed to suppress the fitting process altogether and all other parameters would remain frozen along with the coordinates. In these cases we resorted to removing the constraint file and just fixing the coordinates (setting 1 to 0) which seemed to preserve the freedom of Sérsic index, radius, and other parameters. However, I would still recommend trying to create a constraint file before fixing coordinates, because doing so may restrict Galfit too tightly and prevent you from identifying whether you have achieved a global minimum for a given fit. Constraint files leave more freedom for Galfit to explore the best possible fit for a specified component.

- **Component Switching**: Although this was more of a minor occurrence and usually had an easy fix, it merits some discussion here. Occasionally when

6Relevant to this discussion is Section 3.7 of Stomberg (2018), a senior thesis written by a former Cal Poly student that was leaned upon heavily in this study as a manual for using Galfit.
Figure 13: Generic GALFIT constraint file for Sérsic model. Note that the components you want to constrain are specified in the first row, individual parameters within that component in the second, and the range you wish to permit in the third. The customization potential of this file is endless, and it may be fruitful to experiment to how GALFIT responds to increasing the number of parameters constrained.

```
# Component/ parameter            constraint   Comment
# operation (see below)    range
1                      x      399 401
1                      y      399 401
1-2                    x      -1  1
1-2                    y      -1  1
2-3                    x      -1  1
2-3                    y      -1  1
2                      4      3 to 400
2                      5      0.5 to 6
3                      4      5 to 400
```

Figure 14: The blue box shows where to enter the name and path of your constraint file on the file of your model. This tells GALFIT how to access the exact limits you want it to use when running iterations.

attempting to run GALFIT after adding a second Sérsic component to the text file of a particular model, GALFIT would "invert" the components for the bulge and the disk and begin using the bulge component parameters as the basis for the disk component being introduced. To catch this, all you need to do is be mindful of the parameter evolution as GALFIT runs (see Fig. 15). You may find that the radii produced after such a switch make more physical sense, but be careful to keep the Sérsic index of whatever GALFIT thinks is the disk component fixed to 1. If the results are disturbing (unphysical) and/or you wish to have GALFIT run the components corresponding to the structures you had originally assigned (for example, bulge being represented by the first Sérsic component and disk represented by the second Sérsic
component), you could proceed in two different ways that we tried here (and probably quite a few other ways that we didn’t). The first method is that of adding a constraint file, discussed above. The second employs brute force and boils down to methodically testing a wide array of combinations of radii and Sérsic indices (usually GALFIT is most sensitive to changes in these two), probing the delicate relationships between parameters.

- **Crashing**: If you feed an unphysical number into one of the parameters on your input file, GALFIT will crash\(^7\). Sometimes, if you feed parameter values that you think are perfectly reasonable into your input file, GALFIT will still crash. When this happens, you’ll want to double check that your Sérsic indices are all proper and as they should be, but in this study the issue was usually resolved by tweaking the radius value of whatever component you are working with. Just as you would do when trying to test for a local or global minimum, try values that are slightly higher and slightly lower than your initial radius values, and after some experimentation GALFIT will (most likely) run as normal.

- **Fatal Typos**: After hours of working with GALFIT and staring at the little numbers marching across your text editor, it is not uncommon to begin making fatal typos that will leave you utterly confounded but that your research advisor or fellow students will see within moments of looking at your parameters. You may have no choice due to scheduling constraints and need to simply work with the putty-like state of your brain at these moments. But what we really recommend if you get irredeemably stuck is that you take a short break, whatever works for you - a snack, a breath of fresh air - that will enable you to return to the problem with fresh eyes and less angst.

\(^7\)Seeing the icon that pops up when this happens for the first time is truly a pleasure, so we have resisted the temptation to include a screenshot here. You might want to try it just to see.
Figure 15: This figure shows a (highly truncated) screenshot of parameter evolution as GALFIT runs an input text file for an AGN; at the top, it lists the parameters originally given, and in successive iterations you can see as those initial parameters begin to change (evident here only for the number in the last row of the second column). It also includes a helpful estimate of the number of iterations remaining in the production of each model (the "Countdown" number), which you can pretty much ignore until it begins to countdown from ten (the value usually hops around sporadically, sometimes for minutes on end).

<table>
<thead>
<tr>
<th>Initial parameters:</th>
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<td>sersic : ( 500.55, 501.27)</td>
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<td>[1.00]</td>
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<th>dChi2/Chi2: -5.43e+20</th>
<th>alanda: 1e-03</th>
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<td>---</td>
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<tr>
<td>sersic : ( 461.46, 505.90)</td>
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<td>141.14</td>
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<td>COUNTDOWN = 99</td>
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<td>---</td>
<td>---</td>
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<tr>
<td>sersic : ( 499.64, 500.29)</td>
<td>14.90</td>
<td>15.55</td>
<td>2.64</td>
</tr>
<tr>
<td>sersic : ( 461.46, 505.90)</td>
<td>14.03</td>
<td>141.14</td>
<td>[1.00]</td>
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<td>COUNTDOWN = 10</td>
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<th>dChi2/Chi2: -2.69e-02</th>
<th>alanda: 1e-03</th>
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</tr>
<tr>
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3 Results and Discussion

3.1 Fitting of Individual Objects

Although all 14 AGNs in our sample population were fitted with GALFIT, our final sample consists of only 6 objects. Difficulties in the fitting processes of the other 8 which led them to be excluded were likely due to dust obscuration in the images. Out of the 6 AGNs that comprise the final sample, 1 was fit with only a bulge component, while the remaining 5 were fitted by a model including both bulge and disk components. No evidence was found for bars in our sample of galaxies, except for an apparent visual bar in Mrk 817 that did not hold up to decompositional analysis in GALFIT. Table 3.1 includes a detailed discussion of the fits for each object. Figure 23 shows the images, models, and residuals for the 6 AGNs included in the final sample. The GALFIT fitting results are summarized in Table 2.

<table>
<thead>
<tr>
<th>Object</th>
<th>Integrated Magnitude</th>
<th>Radius (pix)</th>
<th>Position Angle (° from N)</th>
<th>Host</th>
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<td></td>
<td>PSF</td>
<td>Bulge</td>
<td>Disk</td>
<td>Bulge</td>
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<td>16.45</td>
<td>15.38</td>
<td>14.00</td>
<td>32.82</td>
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<td>12.63</td>
<td>12.85</td>
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<td>14.37</td>
<td>-</td>
<td>81.60</td>
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<td>17.10</td>
<td>15.22</td>
<td>27.61</td>
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<td>16.88</td>
<td>16.03</td>
<td>14.66</td>
<td>31.70</td>
</tr>
</tbody>
</table>

Table 2: GALFIT results; the 'Host' column specifies the AGN host galaxy morphology determined visually. 'B' signifies that the galaxy appears to have only a bulge component, while 'BD' indicates the presence of a visible bulge and disk in the host galaxy. 'BDB' would represent a bulge, disk, and bar component, but does not appear in this table since a bar component was not used to fit any of the galaxies listed.
Figure 16: Images for each object, with the HST image in the first column, GALFIT model in the second column, and residual image in the final column. Though the sample population of this study included 14 AGNs, we only included detailed images of the 5 we were able to obtain GALFIT results for.
<table>
<thead>
<tr>
<th>Object</th>
<th>Host</th>
<th>Description of Fit</th>
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<tr>
<td>NGC 4748</td>
<td>BD</td>
<td>NGC 4748 was fit with a bulge and disk Sérsic component, as well as a free Sérsic component to account for its neighboring object. No constraint file was used.</td>
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<tr>
<td>NGC 6814</td>
<td>BD</td>
<td>The final fit of NGC 6814 included a bulge and disk Sérsic component. The fit of the bulge component went smoothly. However, when the disk Sérsic component was added the disk coordinates GALFIT produced after being run were consistently about 10 pixels off-center, an issue that a customized constraint file proved ineffective in remedying (see Troubleshooting Section 2.5). In the end, the coordinates for the disk would only stay centered if they were forcibly fixed at the center of the image by setting the numerical value in the second column next to the coordinates to &quot;0&quot; instead of &quot;1&quot;. Although re-running the GALFIT file after making this change did not affect any of the parameter values for the disk, this is a particularly brutish method and its use should be taken into account when considering the final results for this object.</td>
</tr>
<tr>
<td>Mrk 110</td>
<td>B</td>
<td>Mrk 110 was found to be an elliptical galaxy (see Fig. 23). Only a bulge component was used in the final fit.</td>
</tr>
<tr>
<td>Mrk 590</td>
<td>B</td>
<td>After multiple fits, Mrk 590 was determined to be an elliptical galaxy with only a bulge component. Although a disk component produced a residual with a reasonably low $\chi^2$ value, GALFIT would produce a different value for $r_{eff,disk}$ each time the text file was run, leading us to conclude that if there is a disk present in Mrk 590, its radius is too close to the radius of the bulge or the dust obscuration too heavy for GALFIT to clearly differentiate between the two structures.</td>
</tr>
</tbody>
</table>
NGC 5548 | BD | NGC 5548 was fit with a bulge and a disk component, and the process was relatively straightforward. No unexpected blips came up during the fitting and no constraint file was used.

Mrk 817 | BD | This galaxy is a perfect example of the truism that looks can be deceiving. The initial visual analysis using Ds9 strongly suggested the presence of a bar, and many hopeful and frustrating hours were spent trying to force GALFIT to add a bar component after the initial bulge and disk components were added. However, consistently diverging values for the bar component’s effective radius and skyrocketing $\chi^2$ values eventually forced home the realization that a two-component model (bulge and disk) was the best result we were going to get... either no bar was present after all, or was too obscured by dust for GALFIT to fit it properly. A comparison study that analyzed the same set of galaxies using Lenstronomy also classified this galaxy as having a bulge and disk component, with no bar. If higher-quality data were available for this object (for example, data of the caliber that JWST is capable of collecting) perhaps a future group of researchers will be able to resolve the bar using 2D galaxy decomposition software similar to GALFIT.

Table 3: Description of the fitting procedures used for each individual object
3.2 Comparison with Lenstronomy

From the following comparison plots (Fig. 17) we see that the GALFIT magnitude results for different host-galaxy components found in this study agree fairly well with magnitude values calculated for the same sample using the software Lenstronomy\(^8\) in a project run by Dr. Vardha N. Bennert. In both of these studies the same HST images were fitted using the same PSF for the same number of components, varying only in the software used. A discussion of the comparison plots is given below in the order in which they appear in the figure.

- **PSF Magnitudes**: The PSF magnitudes used in GALFIT and Lenstronomy aligned very well for almost all of the galaxies, which is what we would have expected from looking at a point source with no discernible structure (at least not on the scale of the subsequently analyzed AGNs). GALFIT gave a slightly higher magnitude value for the PSF used in Mrk 590 than Lenstronomy, which may have played a part in the bulge magnitude calculated in this study being lower than that found in Lenstronomy. However, the disk magnitude results for Mrk 590 matched almost perfectly with the Lenstronomy results, giving us confidence in the fit achieved.

- **Bulge Magnitudes**: The comparison plot for bulge magnitude results shows the greatest amount of discrepancies. GALFIT calculated bulge magnitudes lower than Lenstronomy for both Mrk 590 and Mrk 110 (possible explanations for the differences in Mrk 590 discussed above). In the case of Mrk 110, GALFIT may have calculated a lower magnitude for the bulge because there wasn’t much bulge to see - if you look at the HST image of the galaxy (Fig. 23), what we can see of its structure is almost entirely PSF. This galaxy was classified as an elliptical galaxy, and while the classifications given here are by no means definitive and it may possess some internal structure beyond what we can detect, the quality of the image may be what caused GALFIT to produce the value that it did.

- **Disk Magnitudes**: Mrk 110, NGC 5548, NGC 4748, and Mrk 590 all are plotted very close to the \(x = y\) line, indicating that they agree almost exactly with the Lenstronomy results and bolstering confidence in the robustness of those values. However, NGC 6814 lies very far off the line with a much higher disk magnitude than found in Lenstronomy. We suspect that high amounts of dust in the spiral arms may account for the 5 mag discrepancy between GALFIT and Lenstronomy values for this AGN, since the results agreed quite strongly for both PSF and bulge magnitude.

\(^8\)https://lenstronomy.readthedocs.io/en/latest/
Figure 17: Above are shown the comparison plots for magnitudes of psf, bulge, and disk calculated using GALFIT in this study vs. those calculated with Lenstronomy (provided by Dr. Vardha N. Bennert). The values for our sample population cluster loosely around the line of exact agreement (plotted as an orange dotted line).
3.3 BH Mass Scaling Relations

The $M_{BH}$-spheroid(bulge) luminosity relations generated for the AGNs in this study are plotted in Figure 18, overlayed with the results presented in Fig. 4 of Bennert, Treu, Ding, et al. (2021) (which shows a much wider variety of scaling relations than this study, including $M_{BH} - \sigma$). The objects analyzed here lie on the lower-mass end on the plot ($10^6 - 10^8 M_{BH} (M_\odot)$), and though they represent only a few data points they clearly seem to fall along the same relation as the active galaxies plotted in Bennert, Treu, Ding, et al. (2021) and the comparison sample of quiescent galaxies taken from Kormendy and Ho (2013). This apparent agreement between relations for quiescent and active galaxies strengthens the evidence pointing towards secular evolution of black holes with their host galaxies. Additionally, the consistency of the scaling relations calculated for our sample of RM AGNs and those found for the sample with $M_{BH}$ calculated using the single-epoch method in Bennert, Treu, Ding, et al. (2021) raises confidence in the reliability of the single-epoch method as a means of calibrating BH mass in the local Universe. An interesting follow-up study might investigate scaling relations for AGNs with $M_{BH} < 10^6 M_\odot$ to test whether or not the same relation extends to lower masses.

Figure 18: This figure shows the results for the $M_{BH}$-spheroid luminosity scaling relations calculated for the AGN sample in this study. The relations from this paper are plotted in green, and are shown with the results of Bennert, Treu, Ding, et al., 2021 and the sample of quiescent galaxies from Kormendy and Ho, 2013 to demonstrate their corroboration of previous findings.
4 Conclusions

The results of this study corroborate the findings of Bennert, Treu, Ding, et al. (2021), namely that scaling relations for a diverse sample of AGNs and quiescent galaxies (Kormendy and Ho, 2013) loosely fall along the same linear relation with no significant outliers (shown in Fig. 18). The agreement of our results - calculated for AGNs with lower central $M_{\text{BH}}$ values than AGNs analyzed in either of the previous studies - implies that the $M_{\text{BH}}$-spheroid(bulge) luminosity scaling relation can be extended to lower-mass SMBHs, though further research into scaling relations of AGNs with $M_{\text{BH}} < 10^6 M_\odot$ is necessary. Secular evolution between SMBHs and the bulges of their host galaxies is one likely scenario that could account for the tightness of scaling relations across such a wide range of galaxy morphologies and $M_{\text{BH}}$s.

More than half of the AGNs in the sample population of this study were excluded from our final results due to difficulties in the Galfit fitting process. We believe that a major source of these difficulties are dust lanes obscuring the structural components of the excluded AGNs. An analysis of images taken in the NIR such as those to be taken by JWST may yield more reliable insights into $M_{\text{BH}}$ scaling relations. We hope that the encouraging agreement of our results with those of Bennert, Treu, Ding, et al. (2021) can motivate a future analysis conducted on higher-quality images of AGNs with $M_{\text{BH}} < 10^6 M_\odot$, for the purpose of probing how far the $M_{\text{BH}}$-spheroid(bulge) luminosity relation can be extended.

By some fortunate twist of fate, one of the objects included in this study, NGC 7469 (see title page), was recently imaged by the James Webb Space Telescope which became operational on July 11, 2022. JWST is one of the most powerful telescopes that has been built to-date, and is particularly relevant to the study of the co-evolution of BHs and their host galaxies because of the range of wavelengths and redshifts that it is capable of observing (0.6$\mu$m $< \lambda < 28\mu$m, 0 $< z < 10$). This telescope, collecting data primarily in infrared wavelengths, can peer further back in time than any of its predecessors and will allow astronomers to both (a): tighten $M_{\text{BH}}$-host galaxy scaling relations to a greater degree of accuracy than has ever been possible before, and (b): study these scaling relations in primordial galaxies, adding new pieces to the puzzle of how galaxy morphologies evolve (and how this evolution is impacted by SMBHs) across cosmic time. The first studies have already shown the detection of a quasar host galaxy at $z > 6$ (Ding et al., 2022), proving that JWST has ushered in a new era of AGN research that will allow astrophysicists to study the correlations between SMBHs and their host galaxies at least as far back in cosmic history as $z > 6$. 
Acknowledgements

I would like to extend a “thank you” of cosmic proportions to Dr. Vardha Bennert for being my advisor three times over in academics, undergraduate research, and this thesis, as well as being my Cal-Bridge mentor. I’m very, very grateful for her edits and advice over the course of this project that helped it ‘converge’ to its present form. Her compassion and professionalism have served as a constant example of what to strive for, and I am lucky to have gotten the opportunity to work with her and receive her continuous support, encouragement, and inspiration throughout my time at Cal Poly.

I would also like to thank Dr. Karin Sandstrom, who is also my Cal-Bridge mentor, and the Cal-Bridge program itself for allowing me to be part of its wonderful community and for its extensive support on my academic journey :)

Assistance from a National Science Foundation (NSF) Research at Undergraduate Institutions (RUI) grant AST-1909297 and a NASA ADAP grant (80 NSSC19K10 16) is gratefully acknowledged. Note that findings and conclusions do not necessarily represent views of the NSF. Data presented in this thesis was obtained with the Hubble Space Telescope.
A Guide to Visual Estimation Using DS9

The image display software DS9\(^9\) played a central role in this study, allowing us to visually analyze each HST image to obtain initial parameter estimates for our AGNs and to visually judge the quality of subsequent GALFIT models. While detailed installation instructions will not be provided here, we do recommend creating an alias to quicken the process of opening DS9 once it is installed on your computer.

When you initially open DS9, you will see a blank display window.

![Blank DS9 display window](https://sites.google.com/cfa.harvard.edu/saoimageds9)

From here, navigate to the 'File' tab and hover your mouse over 'Open as', selecting the 'Multiple Extension Cube..' option from the drop-down menu that appears.

![Depiction of what this step looks like on a Mac](https://sites.google.com/cfa.harvard.edu/saoimageds9)

\(^9\)https://sites.google.com/cfa.harvard.edu/saoimageds9
This will allow you to select the file that you wish to open; navigate to the directory containing your .fits files and hit ‘Open’ after choosing the one you wish to see.

![Figure 21](image1)

The display window should reappear, along with a new tiny pop-up window named ‘Cube’ that allows you to navigate between different images.

![Figure 22](image2)

The Cube allows you to navigate between 4 frames: the first, at least for the kinds of images analyzed in this study, will contain only header information and thus appear blank (Fig. 22); the second will display your science image; the third will display your GALFIT model by itself; and the fourth frame will show your residual image once you start actually generating models (residual = science image - model).

![Figure 23](image3)
In order to actually see your science image, you may have to switch the scale to 'zscale' within the display window. Go to 'Scale' in DS9, then select 'zscale'. You can then adjust the scale manually by holding down the right mouse button while moving your mouse across the screen. You also have the option to change from a linear to a logarithmic scale. If you navigate to 'Scale' and 'Scale Parameters' on the top panel of your screen, you will be able to manually set the limits of your logarithmic scale (e.g. low = 0, high = 1).

![Figure 24](image)

Additionally, when visually estimating initial parameters from your science image, you may find it helpful to utilize the 'grid' option listed under the 'analysis' tab:

![Figure 25](image)

Moving the cursor of your mouse over the image will show specific pixel values in the upper corner of the display window, which will facilitate the process of radius estimation. These convenient tips, while by no means comprehensive, should help you navigate the process of visual analysis using DS9 should you pursue a study similar to the one described here.
References


Mignoli, M. et al. (Aug. 2013). “Obscured AGN at $z \sim 1$ from the zCOSMOS-Bright Survey. I. Selection and optical properties of a [Ne v]-selected sample”. In: 556, A29. DOI: 10.1051/0004-6361/201220846.


