Monsters on the Move: Gravitational Recoil of Supermassive Black Holes in Nearby Elliptical Galaxies

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Yashashree Jadhav

A dissertation submitted in partial fulfillment of the requirements for the degree of Ph.D. in Astrophysical Sciences and Technology in the College of Science, School of Physics and Astronomy Rochester Institute of Technology

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Rochester, NY
May 23, 2019
Cover image: Yashashree Jadhav’s rendition of a supermassive black hole.
MONSTERS ON THE MOVE: GRAVITATIONAL RECOIL OF SUPERMASSIVE BLACK HOLES IN NEARBY ELLIPTICAL GALAXIES

by

YASHASHREE JADHAV

A dissertation submitted in partial fulfillment of the requirements for the degree of

PH.D. in ASTROPHYSICAL SCIENCES AND TECHNOLOGY

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Is all that we see or seem,
But a dream within a dream?

Edgar Allan Poe

To Arun kaka.
ABSTRACT

It has long been assumed that Active Galactic Nuclei (AGN) reside at the centers of their host galaxies, but is this really true? A galaxy merger is expected to lead to the formation of a supermassive black hole (SMBH) binary, which can shrink through dynamical processes until it eventually coalesces through the emission of gravitational waves. Numerical relativity simulations show that, depending on the initial spin-orbit configuration of the binary, the merged SMBH receives a gravitational recoil kick that may reach several $1000 \, \text{km s}^{-1}$. The kick causes the merged SMBH to oscillate for up to $\sim 1 \, \text{Gyr}$ in the gravitational potential well of the galaxy, during which, the recoiling SMBH may be observed as a ‘displaced’ AGN. Displacements $\sim 10-100 \, \text{pc}$ may be expected even in nearby elliptical galaxies and can be measured as spatial offsets in high resolution optical/infrared images.

In this dissertation, I present the results of a study of $\sim 100$ nearby elliptical galaxies, that host AGN, using Hubble Space Telescope archival and new optical/infrared images, to analyze spatial offsets between the photo-center and AGN position. Evidence for significant spatial offsets has been found in about 20% of the sample of which six are considered to be robust displacements ($\sim 5 - 40 \, \text{pc}$). Three other galaxies display a dual nucleus structure. These results are discussed in the context of the gravitational recoil hypothesis and alternative displacement mechanisms, including acceleration by radio jets, are considered. A second study described in this dissertation focusses on the luminous quasar E1821+643 which has previously been identified as an SMBH recoil candidate based on the large Doppler shifts of emission lines attributed to the retained gas. Follow-up spectroastrometry revealed a spatial displacement between the nucleus and the gas emitting the [OIII] lines. Hubble Space Telescope (HST) images were used to map the
distribution of narrow-line emission on sub-arcsecond spatial scales which show that the [OIII] emission is intrinsically asymmetric. Spectroastrometry simulations reveal that the asymmetric [OIII] emission can account for only \( \sim 25\% \) of the observed displacement, which strengthens the case for a recoiling SMBH.

**Keywords:** (recoiling) supermassive black holes, gravitational recoil, active galactic nuclei, dual nuclei, spectroastrometry, individual galaxies: 3C76.1, 3C353, 3C430, M49, NGC3245, NGC3557, E1821+643, NGC4473, NGC4486b, NGC5419.
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I, Yashashree Jadhav ("the Author"), declare that no part of this dissertation is substantially the same as any that has been submitted for a degree or diploma at the Rochester Institute of Technology or any other University. I further declare that this work is my own. Those who have contributed scientific or other collaborative insights are fully credited in this dissertation, and all prior work upon which this dissertation builds is cited appropriately throughout the text. This dissertation was successfully defended in Rochester, NY, USA on May 23, 2019.
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CHAPTER 1

INTRODUCTION

This dissertation presents the results of two observational studies of Active Galactic Nuclei (AGN). The first is a study of gravitational recoil of supermassive black holes (SMBHs) in nearby elliptical galaxies using images taken by the Hubble Space Telescope (HST). The second study consists of observations and simulations of the quasar E1821+643 which is a gravitational recoil candidate as discovered by Robinson et al. (2010).

This chapter introduces the concept of gravitational recoil. Section 1.2 describes the SMBH as an AGN as well as the circumstances that lead to gravitational recoil following a major galactic merger that results in the coalescence of the resultant SMBH binary. Section 1.3 describes the methods used to identify a recoiling SMBH as well as some of the previous work done to identify such recoils. Section 1.4 provides a synopsis of the remaining chapters in this dissertation.

1.1 Overview

There is compelling evidence that a supermassive black hole (SMBH) resides at the center of every large galaxy in the universe. In addition it has been observationally established that SMBH growth and galaxy assembly are related (Ferrarese and Merritt, 2000; Alexander and Hickox, 2012). The M−σ relationship for galaxies (Fabian, 2012) relates the SMBH mass (M) and the stellar velocity dispersion (σ). SMBH grow by accreting mass and
can thus be identified as active galactic nuclei (AGN).

Galaxy mergers are thought to play a major role in galaxy and SMBH evolution. Following a major merger, the two SMBHs first form a binary at the center of the merged galaxy. If, through dynamical processes (which predominantly include interactions with stars), the binary orbit becomes small enough, the resulting SMBH binary tightens and then eventually coalesces through isotropic emission of gravitational waves (Campanelli et al., 2007) causing the merged SMBH to receive a kick (up to $\sim 1000\text{km} \text{s}^{-1}$ for certain spin configurations). Simulations of the post recoil trajectory suggest that following the initial large amplitude short lived oscillations, there is a prolonged period ($\sim 1$ Gyr) when the kicked SMBH oscillates within the galaxy core ($\sim 100$ pc) (Gualandris and Merritt, 2008). In principle, these post recoil oscillations can be observed either through emission line doppler shifts or as spatially offset AGN, assuming that the recoiling SMBH remains visible as an AGN. Thus, we expect to find such recoiling SMBHs in nearby galaxies that have undergone mergers within the past few Gyr.

In this dissertation, I present a statistical search for recoiling SMBH in nearby elliptical galaxies using archival and new images taken with the Hubble Space Telescope (HST) in multiple filters (optical and infrared (IR)). I present the results of the study of spatial offsets between the galaxy photo-center and the AGN point source in 100 galaxies. I identify and discuss the recoil candidates as well as the mechanisms that lead to the measured offsets. I also present a study of the quasar E1821+643 which has been previously identified as a candidate recoiling SMBH through spectropolarimetry observations. I present the results from a new HST image analysis conducted for this quasar as well as results from the spectroastrometry modeling which combines the HST images with Gemini data to simulate offset spectra.

### 1.2 Background: Binary supermassive black holes and gravitational recoil

#### 1.2.1 SMBH as an AGN

The mass of a SMBH ranges from $10^6$ to $10^9 \text{M}_\odot$. For example, the mass of the SMBH at the center of the Milky Way galaxy has been measured to be $4.3 \times 10^6 \text{M}_\odot$ (Gillessen et al., 2009). On the other hand, M87 contains one
Background: Binary supermassive black holes and gravitational recoil

Figure 1.1: A schematic illustration of the AGN unification model (not to scale; adapted from Fig. 1 from Urry and Padovani (1995)). This sketch highlights the different components of an AGN as described in the text.

of the most massive SMBH with a mass of $\sim 3.5^{+0.9}_{-0.7} \times 10^9 M_\odot$ (Walsh et al., 2013). The energy released by the accretion of interstellar gas in the form of electromagnetic radiation, gas outflows and ionized plasma jets leads to feedback and affects the growth of the SMBH (Ferrarese and Ford, 2005). There is a synergistic relation between SMBH gas accretion, outflows and the evolution of galaxies.

The AGN, which appears as a nuclear point source, emits radiation over the whole electromagnetic spectrum and in some cases can outshine the entire galaxy. The standard model of an AGN is comprised of four main components in addition to the SMBH; the accretion disk, the dusty torus surrounding the disk, the broad emission line region (BLR) and the narrow emission line region (NLR). The gas inflow to the SMBH is governed by the accretion disk and it thus forms the ‘engine’ of the AGN converting the gravitational potential energy of the in-falling matter into radiation with a
Background: Binary supermassive black holes and gravitational recoil

Figure 1.2: A schematic illustration of the AGN unification model (not to scale; adapted from Fig. 1 from Urry and Padovani (1995)). This diagram shows the different classifications of the AGN depending on the viewing angle. FSRQ: Flat Spectrum Radio Quasar; SSRQ: Steep Spectrum Radio Quasar; NLRG: Narrow Line Radio Galaxy; QSO: Quasi Stellar Object; FR I & II: Fanaroff-Riley Class I and II.

The BLR is an ensemble of optically thick gas clouds photoionized by the extreme ultra-violet (EUV) continuum of the accretion disk. It emits broad emission lines due to the Doppler shifts caused by the motions of the emitting clouds in the gravitational potential of the SMBH. The BLR extends up to a few parsecs for the most luminous AGN with the size scaling as $L^{0.5}$ (where L is the luminosity of the AGN) (Bentz et al., 2013).

A clumpy distribution of dusty molecular gas clouds surrounds the ac-
Background: Binary supermassive black holes and gravitational recoil

The accretion disk in a toroidal form and thus, obscures the BLR and the accretion disk. The inner radius of the torus is set by dust sublimation. The dust is heated by the accretion disk UV/optical continuum and it produces IR radiation in most cases (Barvainis, 1987; Almeyda, 2017). The NLR consists of low velocity, low density gas clouds, which are also photoionized by the AGN. These clouds emit narrow emission lines and the NLR extends beyond the torus up to a few kpcs. Urry and Padovani (1995) discuss the different components of an AGN as shown in Figure 1.1.

AGN unification models are used to discuss the origin and properties of the different components of an AGN as well as the classifications used to describe AGN. Recent discussions of the unification model can be found in Ho (2008) and Netzer (2015). According to unified models, the orientation of the torus relative to the observer determines whether or not the BLR (and accretion disk) is obscured as in Type II (edge on) or unobscured as in Type I (face on). We can broadly categorize AGN into radio loud or radio quiet AGN. Radio loud AGN have powerful jets. These jets are often observed to be one-sided due to relativistic beaming. When the viewing angle is close to the jet axis they are known as quasars. If it is along the jet axis, they are called blazars and if it is perpendicular to the jet axis, they are just known as radio galaxies. The central source powers the radio jet and radio emission can also be observed from the radio lobes. Depending on the viewing angle we see either the compact core and the jets or just the lobes. Figure 1.2 shows the different classifications an AGN can have depending on the orientation in which it is observed.

1.2.2 Galaxy mergers and the formation of binary supermassive black holes

Galaxy mergers are believed to play an important role in galaxy evolution. Dark matter hierarchical structure growth simulations (Di Matteo et al. (2005); Vogelsberger et al. (2014); Genel et al. (2014)) predict that galaxies evolve through gas-rich mergers which trigger massive starbursts and quasars. Energy input from quasars regulates the growth and activity of SMBHs. Energy released by the quasar or supernovae drives winds which eventually disperse the remaining gas leading to the ‘red and dead’ early type galaxies (Cattaneo et al., 2009). There is compelling evidence that every large galaxy has an SMBH at its center Ho (2008). While actively
accreting, the SMBH appears as (and can be identified as) an Active Galactic Nucleus (AGN). Given that both galaxies contain a SMBH, during a major merger the two SMBHs are expected to form a binary SMBH system (Begelman et al., 1980) which eventually coalesces. The inspiral (decay of orbits of the two SMBH) at large distances is initially driven by dynamical friction (gravitational ‘drag’ due to stars). When the binary separation is equivalent to the gravitational influence radius of the larger SMBH, it undergoes further tightening due to slingshot interactions with stars, which are ejected from the center (Merritt and Milosavljević, 2005; Mayer et al., 2007a). When the separation between the binary SMBH is small enough for gravitational wave emission to become significant, they efficiently carry away the remaining angular momentum and causing the binary to coalesce on a short timescale.

1.2.3 Gravitational wave emission and coalescence

The coalescence of a binary SMBH following a major merger is driven by the emission of gravitational waves. In general, the gravitational wave emission is anisotropic. Numerical relativity simulations of the orbits of spinning SMBH (Campanelli et al., 2006; Lousto et al., 2010) show that this anisotropy can provide a kick velocity to the merged SMBH.

The kick velocities achieved depend on a number of parameters including the SMBH mass ratio as well as the initial orbital and spin configurations of the binary. The kick velocity is higher for higher mass ratios and non-aligned spin configurations. Kick velocity distributions have been obtained for ranges of spin magnitude and orientation derived from accretion simulations (Lousto et al., 2012) (Figure 1.3). Recois of almost 4000\(kms^{-1}\) can be obtained when the spins are aligned with the direction of the orbital plane (Lousto et al., 2010; Campanelli et al., 2007; Lousto and Zlochower, 2011; Lousto et al., 2012; González et al., 2007; Tichy and Marionetti, 2007). Some studies (Lousto and Zlochower, 2011) have shown that partially aligned spin configurations can produce higher kick velocities up to 5000\(kms^{-1}\). However, these extreme recoil velocities are relatively rare. The large majority of kicks have velocities that are below 1000\(kms^{-1}\).

Numerical relativity simulations of a binary SMBH shows that the time it takes for the binary pair of BHs to coalesce due to anisotropic radiation of gravitational waves is dependent on the mass ratio of the two SMBH. It
Figure 1.3: Plot from Lousto et al. (2012) Probability distribution of recoil velocities ($kms^{-1}$) along the line of sight for spin magnitude and direction distributions predicted by accretion simulations. $\gamma$ is the index for the equation of state is given by (Loeb, 2007; Goodman and Tan, 2004),

$$t_{gw} = 2 \times 10^6 \left( \frac{M}{4\mu} \right) a_3^4 M^7 \text{ yr}$$

where $M_1$ and $M_2$ are the masses of the two SMBHs, $\mu$ is the reduced mass of the system ($M_1 M_2 / M$) and the total mass of the system is given by $M = M_1 + M_2$, $a_3$ gives the length in terms of the Schwarzschild radius ($r = 2GM/c^2$)

### 1.2.4 Gravitational recoil

**Displaced SMBH**

In extreme cases the merged SMBH can be ejected from the host galaxy (Merritt et al., 2004). But a large kick that does not exceed the escape velocity causes the SMBH to undergo oscillations in the potential of the galaxy. The post recoil oscillation timescale depends on several initial conditions
Background: Binary supermassive black holes and gravitational recoil

Figure 1.4: Snapshots from the Gualandris and Merritt (2008) simulations of the post recoil trajectory of the oscillating SMBH following coalescence in a model galaxy. The black dot in all the panels shows the position of the SMBH at different times. Times are $t = 2.1875; 2.21875; 2.25; \ldots, 2.46875$, increasing from top left to bottom right. The contours show the stellar density distribution in the galaxy and the cross approximately represents the position of the stellar center. The total elapsed time in this snapshot of the simulation is approximately half an oscillation period of the recoiling BH in phase II.

including the gas content of the galaxy (Blecha et al., 2016) and the kick velocity received by the merged SMBH. Gualandris and Merritt (2008) have identified three dynamical phases for large scale oscillations for displaced
SMBH with kicks greater than $\sim 10^2$ km s$^{-1}$. Their n-body simulations have been carried out for gas poor galaxies. In ‘Phase I’, the SMBH undergoes harmonic oscillations that are damped fairly quickly due to dynamical friction ($\sim 10^7$ yrs). The amplitudes of these oscillations are greater than the galaxy core radius. This is followed by ‘Phase II’ in which long lived oscillations within the core of the galaxy gradually decay in amplitude from 100 to $\sim 10$ pc and last for $\sim 1$Gyr (Gualandris and Merritt, 2008). For gas-poor systems the oscillations can persist for several Gyrs (Blecha et al., 2016). Figure 1.4 shows snapshots from the Gualandris and Merritt (2008) simulations illustrating the evolution of the oscillation amplitudes through Phase II.

Several different observational signatures exist for displaced SMBHs (Loeb, 2007) if they continue to accrete. Bondi accretion (Edgar, 2004), that is, spherical accretion onto a compact object as the object moves through the interstellar medium (ISM), is one of the potential fueling mechanisms for AGN. The rate of accretion of interstellar gas onto the SMBH as it moves through the ISM depends on the recoil velocity and is given by,

$$\dot{M}_B = 7 \times 10^{-7} n_0 M_7^2 v_8^{-3} M_{\odot}{\text{yr}}^{-1}$$  \hspace{1cm} (1.2)$$

where $M_7$ is the BH mass in units of $10^{-7}$ M$_{\odot}$, $v_8$ is the speed of the SMBH in units of $10^8$ cms$^{-1} = 10^3$ kms$^{-1}$ and $n_0$ is the interstellar medium (ISM) density in units of 1 cm$^{-3}$.

Depending on the recoil velocity received by the SMBH, the BLR can retain material that is most tightly bound to it including surrounding gas and stars. After the recoil, the accretion disk and a portion of the BLR remain attached to the coalesced BH and therefore the displaced SMBH remains visible as an AGN which can be observed as an optical or infrared (IR) source. The radius within which the material remains with the recoiling SMBH is given by,

$$R_{\text{out}} \sim \left(\frac{GM}{v_{ej}^2}\right) \sim 45v_8^{-2}$$  \hspace{1cm} (1.3)$$

where $v_{ej}$ is the ejection (or recoil) velocity of the SMBH. This is the
radius at which the Keplerian velocity is equal to the kick velocity.

The lifetime of the retained disk (accretion lifetime: time taken by the
disk to be consumed by the SMBH) is given by,

\[
t_{\text{disk}} \sim 8.4 \times 10^6 \alpha^{-0/8} \eta^{0.4} M_7^{1.2} v_8^{-1.8} \text{ yr}
\]

where \( \alpha^{-1} \) is the viscosity parameter as scaled to the characteristic value
of 0.1, \( \eta = (\epsilon/0.1)(L/L_E) \). The radiative efficiency is given by \( \epsilon \) and the disk
luminosity \( L \) is in terms of the Eddington limit \( L_E = 1.4 \times 10^{45} M_7 \text{ erg s}^{-1} \)
in the case where the \( \alpha \) disk extends to the last stable orbit around a single
SMBH.

We see that \( t_{\text{disk}} \) scales with the mass of the merged SMBH and is in-
versely proportional to the recoil velocity. Smaller kick velocities allow more
material (BLR) around the SMBH to remain attached to the BH after the
kick. This increases the disk lifetime. For a BH mass of \( M = 10^9 M_\odot \) and
velocity of \( \sim 400 \text{ kms}^{-1} \), the \( t_{\text{disk}} \sim 10^9 \text{ yr} \) which is comparable to the
timescale of the Phase II oscillations. Thus to have a \( t_{\text{disk}} \) comparable to the
timescale of the Phase II oscillations we need to have a combination
of velocities high enough to produce oscillations and large SMBH masses.
Typical values of the velocity range from \( \sim 100 \text{ km s}^{-1} - 1000 \text{ km s}^{-1} \). Other-
wise, an AGN can only be observed if Bondi accretion can provide sufficient
fuel. This produces a luminosity of \( L \sim \eta \dot{M} c^2 \sim 10^{39} \text{ erg s}^{-1} \) (where \( \eta
= 0.1 \) and \( \dot{M} \) is from equation 1.2) for a BH mass of \( M_7 \) while the typical
luminosity for an AGN is \( L \sim 10^{42-44} \text{ erg s}^{-1} \) (Woo and Urry, 2002). The
galaxies in the study discussed in this dissertation have AGN with relatively
low luminosities with \( L \sim 10^{40-42} \text{ erg s}^{-1} \). To identify a displaced SMBH,
its needs to be able to be seen as an AGN and must thus have luminosities
comparable to an AGN. Thus for Bondi accretion to act as the fuel for an
AGN, the SMBH mass needs to be greater than \( M \sim 10^{8-9} M_\odot \).

The predicted core oscillation damping timescale is comparable to the
time between galaxy mergers. The local inferred galaxy merger rate has
been found to be within a range of \( 1 \text{ Gyr}^{-1} \) (Hopkins et al. (2010)) to
\( \sim 0.12 \text{ Gyr}^{-1} \) (Rodrigues et al. (2018)). Major galactic mergers are theorized
to lead to the formation of ellipticals (Toomre and Toomre, 1972; Mihos and
Hernquist, 1996) as well as local disks Rodionov et al. (2017)). The evolution
of galaxy mergers and the merger rate also depends on the gas content of the host galaxies (Hammer et al., 2005; Robertson et al., 2006; Hopkins et al., 2009; Athanassoula et al., 2016; Sparre and Springel, 2016). The empirically derived merger rate is affected by the sample of the galaxies used as well as the method used to extract the merger rate. Thus, the merger rate is sample biased as well as biased towards the technique used to measure the rate.

The time scale over which the accretion disk can still fuel the SMBH even after receiving the recoil kick is also comparable to $\sim 1 \text{Gyr}$ (Loeb, 2007) given that $v_8 < 1$ and $M_{BH} \sim 10^9 M_\odot$. Thus, the SMBH can be observable as an offset AGN up to $\sim 1 \text{Gyr}$ after coalescence, with a displacement $\sim 10$-100 pc, depending on time elapsed after coalescence and position in the oscillation (Merritt et al., 2009). Therefore, we expect to see recoiling SMBHs in the nearby universe in galaxies that have undergone mergers in the last $\sim$few Gyrs. The observed incidence of recoiling SMBHs will help put a constraint on the galaxy merger rate.

The stars near the SMBH that have orbital velocities greater than the kick velocity also remain attached to the SMBH after the kick. This is referred to as a ‘hypercompact stellar system’ and must have a high internal velocity distribution (Merritt et al., 2009). ‘Phase III’ is characterized by Brownian motion which signifies that the SMBH is now in thermal equilibrium with the surrounding stars.

### 1.3 Identifying recoiling SMBH

So far we have detected gravitational waves from stellar mass binary black holes (Abbott et al., 2016) but the gravitational wave signatures from coalescing SMBHs cannot be detected by LIGO because they fall out of the range of frequencies that can be observed by LIGO. Pulsar timing arrays may also in the future to detect gravitational wave signatures from SMBH coalescences depending on the frequency emitted (Rasskazov and Merritt, 2016). Thus, currently we have to look at alternate detection methods for recoiling SMBH until e-LISA is launched; such as their electromagnetic signatures. LISA will be able to detect gravitational waves from binary SMBH coalescence.

Recoiling SMBH (AGN) can be identified from a large spatial offset
Identifying recoiling SMBH

and/or Doppler shift, but only during the first $\sim 10^7$ yrs (when the recoil is in Phase I), or over a much longer timescale by a small offset (or Doppler shift). In the first case, recoil signatures are rare but in principle can be observed at larger cosmological distances. In the second, the signatures should be fairly common but are only observable in nearby galaxies since it is very difficult to distinguish them from normal gas motions.

Figure 1.5: This plot shows the 1-pixel scale displacement as a function of redshift. The blue line represents a plate scale of $0.13''$/pixel (NICMOS-3, WFC3/IR) and the green line represents a plate scale of $0.05''$ per pixel for HST cameras (NICMOS, WFPC2-PC, and ACS).

1.3.1 Spatial Offset

During the post recoil oscillations the SMBH will appear to be displaced from the center of the galaxy when viewed from certain angles provided that the recoil velocity does not coincide with the line of sight. The SMBH has the largest recoil velocities during the Phase I oscillations which are relatively short lived ($\sim 10^7$ yrs). The lower end of the average time between mergers ($\sim 1 - 10$ Gyr (Hopkins et al., 2010; Rodrigues et al., 2018) see above for a brief discussion) is comparable to the duration of the Phase II oscillations, which is why displaced SMBHs are expected to be seen in nearby early
Identifying recoiling SMBH
type galaxies depending on the phase of oscillation and direction relative to the observer. Images taken by the Hubble Space Telescope (HST) can be used to find parsec scale displacements in galaxies with $z < 0.5$. Lena et al. (2014) used images from HST to find evidence of displacements in 14 nearby galaxies, 6 of which were deemed to be robust cases.

The Phase II oscillations last for $\sim 1$Gyr and have an amplitude range of 10-100pc. Lousto et al. (2012)’s simulations of kick velocity distributions show that large recoils are much rarer than the relatively smaller recoils. We have to sweep a much larger volume of space to find such displacements. Significant displacements can only be detected in galaxies that are in either Phase I or II of the post recoil trajectory. We are also limited by distance because we will need larger displacements in galaxies with large redshifts for them to be detectable by our current telescopes with their corresponding resolution. Figure 1.5 shows the resolvable (one HST camera pixel) distance as a function of redshift. It shows the distance that is equivalent to one pixel (for an HST camera) at the given redshift. It is possible to detect sub-pixel displacements by careful analysis of HST images.

1.3.2 Velocity Offset

The kicked SMBH retains some of the gas surrounding it if the kick velocity is not too high. A second method of detecting the displaced SMBH is by analyzing the Doppler shifts of emission lines from the retained gas showing a relative velocity between the SMBH and the host galaxy. For example, if part of the BLR is retained, the broad Balmer lines will thus, appear to be shifted with respect to the narrow lines (Bonning et al., 2007). (Refer to section 1.3.3 for further details of previous work done using this method for other candidates).

This has been observed in the case of E1821+643 (Robinson et al., 2010) (Refer to chapter 4 for more details on the object and its observations). Apart from gravitational recoil, kinematics of gas outflows in the BLR and the NLR can also cause such velocity offsets (Bonning et al., 2007).

Observations to detect a recoil driven velocity offset have to be made before the resultant oscillations have damped. Large kicks are rare and therefore few candidates for recoiling blackholes have been observed using velocity offsets.
1.3.3 Previous work

There have been several attempts to search for recoiling SMBH. Loeb (2007) has described the observational signatures of an SMBH that is ejected from the host galaxy following a major merger. Loeb’s study also presents estimates of the amount of material that stays with the kicked SMBH following coalescence (discussed above). In general the accretion disk and the BLR remain with the kicked SMBH and the NLR is left behind depending on the kick velocity.

Lena et al. (2014) conducted a systematic search of 14 nearby core elliptical galaxies and found significant spatial offsets in 6 galaxies. This dissertation follows the method described in Lena et al. (2014)’s work and expands the study to a much larger sample (see chapters 2 and 3 for more details).

The following searches are based on Doppler shift as a signpost of a recoiling SMBH. Bonning et al. (2007) also conducted a study to search for recoiling SMBH in the SDSS quasar database (in DR5) for QSOs (Quasi stellar objects) that have measurable H\(\beta\) and [OIII] emission lines. But they did not find any convincing evidence for recoiling SMBH with accretion disks. Eracleous et al. (2012) conducted a survey of \(z \leq 0.7\) SDSS quasars to search for recoiling SMBH using spectroscopic principle component analysis in 88 quasars with H\(\beta\) emission lines. They found implied accelerations in 14 candidates.

Kim et al. (2017) have conducted a systematic search for recoiling SMBH by crossmatching SDSS data with X-ray data from the Chandra X-ray telescope and have identified CXO J101527.2+625911 as a recoil candidate with an offset of 1.26 ± 0.05 kpc.

A number of other recoil candidates have also been reported in the literature. Batcheldor et al. (2010) found evidence of a spatial displacement between the position of the AGN point source and the (photo) center of the galaxy in the nearby giant elliptical M87. They also pointed out that asymmetric jet power is also a possible mechanism for the displacement. CID - 42 is a recoil candidate that has been studied several times since it shows both spatial and velocity offsets (Blecha et al. (2013); Novak et al. (2015); Civano et al. (2010, 2012). Jonker et al. (2010) report a candidate recoiling SMBH identified as the X-ray source CXOJ122518.6+144545 which has an offset of 3.6 arcsec (3.2 kpc) with respect to its host galaxy. Chiaberge et al.
(2017) have presented the properties of the radio loud quasar 3C 186 which shows a spatial offset of $\sim 11\text{kpc}$. Spectroscopic observations also show a velocity offset between the BLR and the NLR.

Komossa et al. (2008) studied the emission lines in SDSS J0927+2943 where the BLR is blue shifted with respect to the NLR suggesting the presence of a recoiling SMBH. NGC 3115 is another recoil candidate which has spectroscopic and radio data showing a spatial offset of $14.3\text{pc}$ (Menezes et al. (2014); Jones et al. (2019)). Shields et al. (2009) has discussed the velocity shift in the broad emission lines for the quasar SDSS J105041.35+345631.3 as evidence for the quasar being a recoil candidate. Steinhardt et al. (2012) discusses the quasar SDSS 0956+5128 as a recoil candidate with extreme velocity offsets ($1200\text{ km s}^{-1}$). Kalfountzou et al. (2017) discuss spectroscopic observations of the kiloparsec scale triple SMBH system (SDSSJ1056+5516) which show a velocity offset.

Even though there have been several searches (as mentioned above) to look for spatial and velocity offsets, so far there has not been a systematic search for Phase II type residual displacements (within $\sim 100\text{ pc}$) as a signpost of a gravitational recoil on a scale larger than Lena et al. (2014).

1.4 Chapter synopsis

This dissertation presents an observational attempt to detect candidate recoiling supermassive black holes in the nearby universe. This study will help us understand the nature of these events as well as help us put better constraints on the both SMBH merger rate as well as galactic merger rates.

Chapters 2 and 3 discusses the statistical search for recoiling SMBH within a redshift of 0.3. This study searched for the existence of spatial offsets between the AGN and the galaxy photocenter, as signposts of gravitational recoil. Chapter 2 describes the methods used to conduct a photometric analysis of 100 nearby elliptical galaxies using images from the Hubble Space Telescope including sample selection, image processing pipeline, expected outputs, errors and contaminants.

Chapter 3 describes the criterion used to determine when a displacement is considered significant and presents the results of the analysis discussed in chapter 2. It also contains discussion of individual candidates and the ‘robustness’ of displacements as well as comparison of results for different
Chapter synopsis

wavelengths.

Chapter 4 discusses a previously identified gravitational recoil candidate the quasar E1821+643. Building on a spectropolarimetry study where Doppler shifts were found between the broad and narrow lines, this work expands the study to include, spectroastrometry and HST image analysis to map the distribution of the OIII emission. Spectroastrometric measurements from Gemini long slit observations indicate a spatial displacement. The HST observations were also combined with Gemini data to simulate spectroastrometric observations that indicate a spatial displacement between the quasar nucleus and the NLR. This shows that the displacement can’t be explained by spatial distribution of the [OIII] emission alone.

Finally, Chapter 5 summarizes the conclusions for both the projects as well as the science questions which formed the motivation for this work. This chapter also presents the prospects for future work in relation to the results of this work and some open questions that remain.
As described in chapter 1, during the phase II oscillations, the recoiling SMBH oscillates in the host galaxy for $\sim 1Gyr$ with amplitudes from $\sim 10 - 100$ pc. During this time, the SMBH can be identified by a spatial offset between the position of the SGN and the photocenter of the galaxy. This chapter describes the search for recoiling SMBH in nearby elliptical galaxies by analyzing spatial offsets between the position of the SMBH as traced by the AGN and the center of the galaxy. Section 2.1 describes the previous work that has been done to find such recoiling SMBH. Section 2.2 describes the sample used to find such offsets in this work. Section 2.3 describes the HST image analysis as well as the details of the error analysis.

2.1 Previous work

Batcheldor et al. (2010) conducted an isophotal analysis of M87 which revealed a significant displacement (of 6.8 ± 0.8pc) between the photocenter of the galaxy and the AGN position. This displacement could be either a result of a recoiling SMBH in M87 or a sustained asymmetry in the power of the jet/counter-jet. This was the first attempt to find Phase II recoil oscillations using isophotal analysis.

Lena et al. (2014) conducted an analysis of 14 nearby elliptical galaxies using Hubble legacy archival data to look for spatial offsets between the
center of the galaxy and the position of the AGN. All 14 galaxies were carefully chosen to have an AGN and to be core ellipticals. Core elliptical galaxies have a light profile that flattens towards the center of the galaxy indicating a stellar mass deficit. This is believed to be due to the formation of an SMBH binary after a galactic merger. Following the formation of an SMBH binary, 3-body interactions with stars in the center of the galaxy lead to ejections of the stars causing a mass deficit (Faber et al., 1997; Merritt and Milosavljević, 2005; Kormendy and Bender, 2009; Thomas et al., 2014, 2016). On the other hand, in galaxies which do not exhibit a core, the light profile continues to rise towards the center. Such galaxies are often referred to as power-law galaxies.

Lena et al. (2014) found evidence for small displacements ($\leq 10\text{pc}$) in 10 of the 14 galaxies including 6 cases considered to be ‘robust’ (see section 3.1.3 for a discussion of the criterion used to determine robustness). They also found approximate alignments between the displacement vector and the radio source axis of 4 of the candidate galaxies that had FR I or FR I like radio sources with powerful well-defined kiloparsec scale radio jets. This suggests a correlation between the radio axis and the recoiling SMBH. Thus asymmetric jet power may be one of the mechanisms responsible for the observed displacements.

Lena et al. (2014) also performed Monte Carlo simulations to compute the probabilities of observing a displacement larger than those measured in the sample galaxies. The simulations were performed for displacements arising from a kick large enough to move the SMBH beyond the core radius of the galaxy. It was also assumed that the galaxy is observed at a random time since the last time it went though a merger, and that recoil kicks have random directions. The probabilities were calculated for two different galaxy merger rates as obtained from the merger rate models of Hopkins et al. (2010) for redshifts $z < 1$. The adopted time between galaxy mergers were $t_m = 5.0\text{Gyr}$ and $t_m = 0.4\text{Gyr}$ for galaxy masses $\log (M_{\text{gal}}/M_\odot) > 11$ and $\log (M_{\text{gal}}/M_\odot) > 12$ respectively. The assumed values of $t_m$ lead to a high probability that larger displacements should have been observed which is not consistent with the observed displacements in Lena et al. (2014). The observed displacements suggest that the merger rate should be much smaller than those adopted. Their simulations (with their measured displacements) suggest a $t_m \geq 30 - 40\text{ Gyr}$ which corresponds to a merger rate of $\sim 0.03$
mergers Gyr$^{-1}$ for a 50% chance of not observing a displacement.

2.2 Sample selection and classification

Lena et al. (2014) used a sample of 14 nearby elliptical core galaxies for their study. The main motivation of this work is to expand the sample of galaxies used in Lena et al. (2014) to include a much larger sample of nearby early-type galaxies. Lena et al. (2014) only included core elliptical galaxies in their sample but we expanded our sample to include both core as well as power law ellipticals. Core elliptical galaxies have a light profile that flattens towards the center of the galaxy (as described in the previous section). Since this is believed to be due to the formation of a SMBH binary after a galactic merger, we expect that recoiling SMBH will be preferentially found in core, as compared to power-law galaxies. The sample selected for this work were chosen from galaxies for which archival HST images were available. We also limited the sample to nearby galaxies (z<0.4). The redshift limit is based on the resolution of HST combined with the redshifts from the parent surveys (discussed below). Only galaxies that have evidence of AGN activity were included in the sample. The sample was selected to include approximately equal numbers of core and power-law galaxies. Our sample was selected from the following earlier surveys that studied nearby active galactic nuclei, radio galaxies and BL Lac host galaxies.

Capetti and Balmaverde (2005) is a study of the connection between the multiwavelength properties of AGN in nearby early-type galaxies with z<0.1 and the characteristics of their hosts. It is based on a radio-flux limited sample of nearby early-type galaxies.

Martel et al. (1999) studied 46 3CR radio galaxies with z<0.1 with the WFPC2 camera. This was the fifth and last of a series of papers describing the properties of 252 radio galaxies observed in the R band (F702W). However the galaxies from their earlier papers have redshift higher than our cut off.

Madrid et al. (2006) describes an HST snapshot survey of 3CR radio galaxies using NICMOS imaging to study galactic morphology. This study contains 69 radio galaxies with z<0.3.

Falomo et al. (2000) is a study of 30 BL Lac host galaxies using WFPC2. All these galaxies have a redshift of z < 0.2. This survey was conducted to
study the morphological features in BL Lac galaxies to explore the presence or absence of external gravitational interactions.

Capetti et al. (2009) is a study of 63 early type radio galaxies. These were selected from an HST/ACS survey of Virgo Cluster galaxies Côté et al. (2004). This study was conducted to investigate the origin of the radio emission in the galaxies and study the correlation between the host properties and radio and optical luminosities.

For this study, all available ACS, WFPC2, NICMOS and WFC3/UVIS and WFC3/IR images of the galaxies included in the works listed above were downloaded from the Hubble Legacy Archive (HLA). Whenever possible multiple optical & NIR images were obtained for each galaxy in different filters.

2.2.1 Sample Classification

Figure 2.1: An example of the different types of galaxy structure according to the classification scheme used. CI: Class I; C II-1: Structure 1; C II-2: Structure 2; C II-3: Structure 3; CIII: Class III and C IV: Class IV. The contrast in the images has been adjusted so as to highlight the particular features in them. For the sample used in our study, only galaxies from C I and C II-1 have been used.
Since we only wanted to use the galaxies that were suitable for isophotal analysis, all the galaxies in the sample have been visually classified according to the features in their images.

The galaxies from the studies listed above were visually classified based on the presence of irregular or distorting morphological features: Regulars (Class I), Structures (Class II), Strong Point Source (Class III) and Irregulars (Class IV). The classification Regular includes galaxies with giving a smooth light distribution and only weak small scale distorting features. The Structures are galaxies that have varying degrees of morphological sub-structures ranging from easily maskable dust features to prominent dust lanes and large scale dust structures, interacting galaxies and so on. The Strong Point Source class includes galaxies that have a very bright central point source which dominates the galaxy and will have to be subtracted before any analysis can be performed. The final class consists of highly irregular galaxies including interacting galaxies, those with extremely saturated nuclei or which are highly obscured.

For the sample used in our study we only used galaxies with a relatively smooth distribution (i.e., mostly Regulars and some Structures). Galaxies with un-maskable highly obscuring structures, large scale structures, extremely strong point sources and interacting galaxies were discarded from analysis. Out of $\sim300$ galaxies, 96 galaxies were chosen in the final sample used in this work. This includes 51 core and 45 power-law galaxies.

In addition to archival images we also obtained new infrared images of 5 galaxies using HST WFC3/IR in the F110W and F160W filters (HST cycle 25 program GO15082). These were identified as showing significant displacements between the galaxy photocenter and AGN position in optical HST images but did not have archival images in IR filters. The ability to analyze the same galaxy in multiple filters provides independent measurements of any displacement and in the NIR, in particular, the effects of obscuring dust features are minimized.

2.3 HST Image Analysis

Figure 2.2 shows a cartoon of an elliptical galaxy. The contours represent the isophotes of the galaxy. In the analysis method adapted for the study, we model the isophotes of the galaxy which are then used to find a flux
weighted average photocenter of the galaxy. This center is then compared to the position of the AGN to obtain a spatial offset between the two.

To measure a spatial offset between the photocenter of the galaxy and the position of the AGN, a pipeline was developed to construct a photometric model of the galaxy and find its photocenter as well as the AGN position. The pipeline was developed in pyraf as a semi-interactive script.

As in Lena et al. (2014), we used multiple images of the same object in both optical and IR filters (where available) to look for displacements in different wavebands.

To test the accuracy and precision of my method, artificial galaxies were also created using Galfit with varying parameters (as discussed in section 2.3.2).

2.3.1 Galaxy Modeling

Figure 2.2: A cartoon illustrating the the 2D-ellipse fitting. The black ellipses represent isophotes tracing the 2-D light distribution of the galaxy. The red filled circle denotes the flux weighted average position of the photocenter of the galaxy. The green filled circle shows the position of the central AGN point source. This cartoon shows a highly exaggerated version of the expected spatial displacement between the photocenter and the AGN point source.
The pipeline (figure 2.3) was written in *pyraf* (de La Peña et al., 2001) and invokes several tasks to model the surface brightness distribution of any given galaxy and hence, determine the flux weighted photocenter of the galaxy. To find the photocenter of the galaxy, the *IRAF* task *Ellipse* (Busko, 1996) is used to fit elliptical isophotes to the image to obtain a model for
the surface brightness distribution of the galaxy. The elliptical isophotes are fitted to the image as a function of the semi-major axis. **Ellipse** requires a number of initial guesses to run. These include the coordinates of the center of the galaxy (\(x\) and \(y\) in pixels), the maximum and minimum semi-major axis, the ellipticity and position angle of the ellipses, the maximum semi-major axis for the iterative mode and the step (semi major axis in pixels). The initial guesses for the maximum and minimum semi-major axis depend on the light distribution, the signal to noise ratio and the flux to background ratio for the galaxy. For the sample of 96 galaxies discussed in this dissertation, the initial guesses were determined by eye. The inner and outer semi-major axes were visually determined. If a nuclear obscuring structure was present, the inner semi-major axis was set to exclude the structure. Otherwise, the inner semi-major axis was determined such that it excludes the PSF from the analysis. The outer semi-major axis was typically set to the point where the signal to noise ratio (SNR) of the galaxy was comparable to the background SNR.

Several types of ‘distortions’ are present in almost every image. The pipeline creates a first bad pixel mask using the *weight* image (exposure time map), that is obtained from the original image (as downloaded from the HST archive), to mask out the image defects and photometric irregularities in the original image in order to minimize distortions. This includes cosmic rays, bad pixels, null pixels and other image defects. Throughout the pipeline, when needed, additional masks are created to mask out other outstanding structures in the image including (but not limited to), central dust lanes, jet like structures, background stars and other dust features.

The semi-interactive code requires a set of initial guesses for the basic **Ellipse** parameters. The model and residual are then manually evaluated and new initial guesses are provided if needed. In some cases where there is substantial interference in the central region of the galaxy either due to a dust lane or complicated galactic structure, the central region is completely masked and the pipeline is run again on the unobscured portions of the light distribution of the galaxy. Each mask and the resultant **Ellipse** model is evaluated by eye to check for irregularities.

The pipeline includes an iterative procedure to refine the mask. The residual image from the initial **Ellipse** fit is combined with the original badpixel mask to create an updated mask. This process is repeated until
the condition is met and a smooth fit is obtained. It only takes an average of 2-3 iterations to obtain a satisfactory fit that lies within our 10% tolerance level.

On completion, the pipeline returns values for the semi-major axis, central x and y coordinates, ellipticity, position angle, mean isophotal intensity and the total flux enclosed by each elliptical isophote. The photocenter is defined as the flux weighted average (using equation 2.1) of the x and y coordinates of the centers of each ellipse.

\[(x_{pc}, y_{pc}) = \left( \frac{\sum_i x_i j_i}{\sum_i j_i}, \frac{\sum_i y_i j_i}{\sum_i j_i} \right) \tag{2.1} \]

where \(x_i \) and \(y_i \) are the values of the \(x\) and \(y\) coordinates of the centers for each isophote. \(j_i \) is the flux within each isophote. The errors obtained for each of the isophotes in \(x_i \) and \(y_i \) as returned by \texttt{Ellipse} are \(\sim \frac{1}{10}\) pixel which translates to approximately a 10% error in angular distance depending on the camera used to obtain the image. (Refer section 2.3.2 for details on error/precision analysis.)

It is assumed that the position of the SMBH is traced/located by the point-like source near the center of each galaxy. This is determined as follows. First, a residual map was created by subtracting a median smoothed image from the original image. The AGN point source usually shows up prominently in the residual image. The \texttt{IRAF} function \texttt{imexamine} was used to fit 2-D Gaussian profiles to marginal distributions of the point source in the residual map to obtain the \(x\) and \(y\) coordinates of the position of the SMBH.

### 2.3.2 Error analysis

The final error on the position of the photocenter is the combination of the errors on the mean isophotal center and the uncertainties on the position of the AGN. Since we are using the errors as returned by \texttt{Ellipse} we need to make sure that these errors are reasonable. \texttt{Ellipse} returns the errors on each isophote for each \texttt{Ellipse} model. We have fit \texttt{GALFIT} (Peng et al., 2002) models for 3 galaxies namely, 3c029, NGC4278 and NGC4261 (chosen randomly). These galaxies were modeled in \texttt{GALFIT} using \textit{Sersic} profiles. (Galfit is a 2-D image decomposition program which fits analytical func-
HST Image Analysis

Figure 2.4: Left: Error distribution for x coordinate. Right: Error distribution for y coordinate. For both plots, the Blue histogram shows the distribution of the True errors (defined as the difference between the known photocenter of the galaxy as obtained from GALFIT and the position of the photocenter for each isophote as returned by Ellipse). The Ellipse errors are seen to be broadly consistent with the True errors. This data was derived by applying the Ellipse fitting pipeline to synthetic galaxy models produced with Galfit for HST images of 3c029, NGC4278 and NGC4261 (as described in the text).

We also used a PSF for each image that was obtained using the Tiny Tim online program (Krist, 1993). We thus have the centers of light of these model galaxies as returned by their Sersic profiles in the GALFIT models. We classify the True error as the difference between the center co-ordinates of the Sersic profile of the GALFIT model and the center of each of the fitted isophotes as returned by the Ellipse model. The Ellipse errors are simply the errors on the centers of each of the fitted isophotes as returned by Ellipse. We have created 4 images for each of the 3 galaxies. Each of the 4 images combines the GALFIT model with 0.5, 1, 1.5 and 2 times the residual as obtained from GALFIT. This allows us to test the pipeline for varying noise levels. We then run Ellipse on these combined images to obtain the error distribution. The distribution resembles a half Gaussian. A conservative estimate of the errors can be obtained from this distribution.
For the purpose of this paper we assume the error to be approximately 0.2 - 0.3 pixels as a conservative estimate. We also see that the Ellipse errors are comparable to the True errors obtained from the Galfit models (Figure 2.4. This demonstrates that errors obtained from the pipeline we developed are indeed reasonable. These error distributions are similar to the errors in Batcheldor et al. (2010) and Lena et al. (2014).

Apart from the error on the photocenter position, we also need to analyze the error on the position of the point source.

We have improved the error analysis by analyzing synthetic galaxies which were created using Galfit models of NGC4261.

![Figure 2.5: Left: Galfit model of NGC 4261, middle: Composite of Galfit model and residual image obtained from Galfit analysis, right: Ellipse model of composite image](image)

The effect of noisy data on the recovery of the SMBH position was analyzed by using composite images of a synthetic galaxy (NGC 4261) with externally added noise. The ‘external’ noise used in the model is the residual obtained after the GALFIT model is subtracted from the original galaxy. The synthetic galaxy was studied with various levels of noise added to it to check for accuracy of the pipeline. The pipeline works efficiently (errors within $\sim 0.3$ pixels) to recover the desired results/offsets for up to 2 times the original noise added back into the galaxy model (as seen in Figure 2.5).

Another uncertainty is in the position of the AGN. The unsharp masking procedure can be affected by the presence of contaminants like dust lanes that go through the center of the galaxy. Some galaxies have an extended central source instead of a point source. Others have bad pixels near the
position of the AGN. Plate scale differences between different cameras can also affect the precision of the AGN position. Low brightness AGN can also be difficult to identify using the unsharp masking process.

In order to test the recoverability of the AGN position depending on the quality of the point source we also injected a synthetic galaxy with a fake point source with a known displacement to try to recover this displacement. The fake point source is added using mkobjects in IRAF which creates a gaussian point source in the image at a specified location with the specified intensity which is matched for an average AGN in our sample. The point source intensity was varied relative to the galaxy surface brightness. We also tested instances of a diffuse source. Our pipeline successfully recovers the fake point source accurately (errors within \(\sim 0.3\) pixels) in most cases. However, when the artificial source was diffuse or when the intensity of the source was comparable to the flux of the host galaxy in it’s immediate vicinity, the pipeline was unable to recover the point source accurately.

### 2.3.3 Examples

Fig 2.6 shows an example of the results from the photometric analysis and the process to find the point source position. On the left is the original HST image of the galaxy 3C076.1. On the right, the top row shows the products of the \texttt{Ellipse} fitting model to find the photocenter of the galaxy and the bottom row shows the median smoothed and the unsharp masked images used to obtain the position of the AGN. The top row left panel shows the model of the galaxy as created by \texttt{Ellipse} by fitting the 2D-light distribution with isophotes. In this image the central region is masked up to a semi-major axis of \(\sim 20\) pixels in order to exclude the region that includes the dust lane. This region is visible in the top right panel which is the final residual image after subtraction of the model from the original image. The bottom left panel is the median smoothed image which is subtracted from the original image to obtain the residual as shown in the bottom right image. The unsharp masked image highlights the position of the AGN point source.

Figures 2.7 and 2.8 are two examples of galaxies for which the isophotal analysis was performed. 3C076.1 is a galaxy that shows a significant displacement in both \(x\) \((-23.22\,\text{mas})\) and \(y\) \((-40.57\,\text{mas})\) coordinates. This corresponds to a radial displacement of \(\sim 46.74\,\text{mas} \,(\text{pc})\) with a conservative error of \(\sim 20\%\). The second galaxy, NGC4623 does not have a significant
Figure 2.6: An example illustrating the methods used in modeling the galaxy light distribution and measuring the point source position. The galaxy is 3c076.1. The top two images show the isophotal model created by Ellipse and the resulting residual image. The bottom two images show the median smoothed image and its residual which highlights the position of the AGN point source.
Figure 2.7: Results of the isophotal analysis of a WFPC2/F555W image of 3C076.1 which shows a significant displacement. For all the plots, the **Red Star** denotes the position of the flux weighted average galaxy photo center and the **Green Star** denotes the position of the AGN point source as obtained from the median smoothed image. **Top Row:** The left-most panel shows the original image, the middle panel is the isophotal model created by the pipeline and the third panel is the residual image. **Middle Row:** The left-most panel shows the azimuthally averaged surface brightness profile in counts s$^{-1}$. The next two panels show the distribution of the $x$ and $y$ coordinates of the isophotal centers as a function of the semi major axis. **Bottom Row:** The left-most panel shows the distribution of the $x$ and $y$ coordinates of the position of the center of each isophote as produced by the Ellipse fit. The next two panels show the histograms of the distribution of the isophotal centers. The errors on individual data points are on the order of $\sim 0.1 - 0.2$ pixels.
Figure 2.8: This is an example of a Galaxy NGC4623 that does not show a significant displacement. The legend is the same as Fig 8.
displacement in either $x$ or $y$ coordinate.

Two of the galaxies in our sample (NGC1399 and NGC5419) were also included in Lena et al. (2014)’s sample galaxies. Lena et al. (2014) found no significant displacements in NGC 1399 and a dual nucleus in NGC 5419. Our results are consistent with theirs.
This chapter presents the results, discussions and conclusions for the search for recoiling SMBH in nearby elliptical galaxies as described in chapter 2.

Section 3.1.1 describes the method used to determine the significance of the measured displacements. Section 3.1.3 describes all the results of the search for spatial offsets in nearby elliptical galaxies using HST image analysis including the list of the recoil candidates obtained through this study. Section 3.2 discusses the candidates and the various inferences derived from the results. This section also discusses the alternate mechanisms that could cause the observed spatial offsets even in the context of the galaxies and their corresponding measured offsets. Section 3.3 describes the final conclusions obtained from the search for recoil candidates. Section 3.4 lists the notes on individual candidates and comments on the robustness of the observed spatial offset.

3.1 Results

Multi-wavelength analysis of galaxies using images obtained with different cameras and filter combinations allows us to obtain multiple independent measurements of the displacements, increasing confidence in the evidence for a real displacement (if they agree across multiple filters). The methods
Results

described in 2 were applied to multiple images of each galaxy in all available filters (like F555W, F814W, F160W etc.) and multiple cameras (e.g. WFPC2, NICMOS, ACS and WFC3) in the HST archive, to confirm the offsets at different wavelengths. IR images are particularly useful in analyzing galaxies with dust and other obscuring features near the SMBH which can interfere with the accurate measurement of the AGN position. We have also obtained new HST images using the WFC3/IR for 5 of the candidates that do not have any HST/IR archival images namely: M89, NGC3998, NGC4473, NGC5419 and NGC5920.

3.1.1 Robustness of measured offsets

As discussed in chapter 2, there are several uncertainties in measuring the offset between the photocenter of the galaxy and the position of the AGN. Both the positions are affected by morphological features in the galaxy (such as isophotal twisting, dust structures, etc).

We cannot rely solely on the combined errors as described in section 2.3.2 since they only quantify the errors on the isophotal analysis and the AGN position. The positional errors do not account for systematic uncertainties on the photocenter and AGN position. To evaluate these we have examined the distribution of $x$ and $y$ coordinates of the isophote centers as returned by Ellipse. Since these distributions are not Gaussian we quantify the resultant confidence level of detection of a displacement using the Inter Quartile Range (IQR) of each coordinate, that is, the difference between the upper and lower quartiles of the distribution in each case. The IQR allows us to effectively combine the errors on the isophotes as well as on the AGN center to quantify the significance of the measured displacement. This method has been adapted from Lena et al. (2014). Each displacement is assigned a significance category (‘null’, ‘low’, ‘intermediate’ and ‘high’) depending on its magnitude in relation to the IQR as follows:

- null: $\Delta x, \Delta y < 0.8$ IQR
- low: $0.8$ IQR $\leq \Delta x, \Delta y < 1.6$ IQR
- intermediate: $1.6$ IQR $\leq \Delta x, \Delta y < 2.4$ IQR
- high: $2.4$ IQR $\leq \Delta x, \Delta y$
Figure 3.1: The distribution of the $x$ and $y$ displacements, normalized by the IQR for all the objects in multiple filters. The lines represent the approximate 3-sigma threshold used to separate the ‘high’ confidence displacements from the sample. The large red dots represent the 18 selected candidates as having 'high' or 'intermediate' significance in $x$ or $y$, in at least one image, but for these galaxies, results from all analyzed images are plotted here. The small yellow dots represent the rest of the sample that did not have significant displacements.
Results

Here the threshold value of 0.8 IQR is approximately equal to 1σ for a Gaussian distribution. For a perfectly smooth galaxy with regular elliptical isophotes, we expect that the distribution of isophote center coordinates in \( x \) or \( y \) will be a Gaussian whose width reflects the statistical uncertainty determined in Chapter 2, i.e., \( \sigma \approx 0.2 \) pixels. A non-zero normalized displacement relative to the IQR indicates that the AGN center is not aligned with the photometric center of the galaxy. The magnitude of the normalized displacement is indicative of how significant the displacement is (as described above). Normalizing the \( \Delta x \) and \( \Delta y \) with respect to the IQR allows us to quantify the significance of the displacement by identifying offsets that may be spurious due to image irregularities as discussed above.

Based on the above mentioned displacement categories, a first cut of candidates was obtained. Out of 96 galaxies, 18 galaxies show a significant displacement (17 with ‘high’ significance displacements and 1 with an ‘intermediate’ significance displacement) in at least one of the \( x \) or \( y \) co-ordinates in at least one of its analyzed images.

3.1.2 HST image analysis results

The results of this study are summarized in tables 3.1 and 3.2. All the individual \( x \) and \( y \) coordinate displacements are measured as: Displacement = AGN position - flux weighted average photocenter position. Out of 96 galaxies in the sample analyzed, 18 galaxies show a significant displacement (‘high’ significance displacement category with respect to the normalized IQR as described in the previous section and one with an ‘intermediate’ significance category that was chosen due to the IQR being close the the threshold between ‘high’ and ‘intermediate’ significance). Of these 18 galaxies, 14 galaxies are core ellipticals and 4 are power law galaxies. Table 3.3 also lists the position angles (PAs) of the displacement vector, galactic dust lanes and the radio jet axis, for comparison. The displacements in \( x \) and \( y \) were combined to obtain a radial displacement:

\[
r = \sqrt{(\Delta x^2 + \Delta y^2)}
\]

(3.1)

Out of the 18 candidates mentioned, 17 show a ‘High’ significance displacement in at least one of either the \( x \) or \( y \) coordinate. The remaining
Figure 3.2: The distribution of the linear displacements in parsecs with respect to redshift for all images of the candidate galaxies. The lines represent the equivalent of 0.3 HST pixel for two different plate scales. The green line represents a plate scale of 0.05” per pixel (WFPC2/PC, NICMOS 1 and 2 and ACS). The black line represents a plate scale of 0.13” per pixel (WFC3/IR and NICMOS3). The colored circles with smaller size correspond to a plate scale of 0.05”/pixel and the larger circles correspond to a plate scale of 0.13”/pixel. The colors of the circles correspond to displacements measured from IR (red) or optical (blue) images. The data points outlined in a secondary black circle represent the displacements with low confidence (< 2.4 IQR).
Results

Figure 3.3: Distribution of radial displacements for the candidates in multiple filters. The red-shaded histogram represents the core galaxies and the blue-shaded histogram represents the power-law galaxies. The top panel shows the displacements for the optical filters and the bottom plot shows the displacements in the infra-red filters.
Results

Table 3.1: Measured displacements for recoil candidates. This table also includes the the IQR values for the $x$ and $y$ coordinates and the significance of the measured displacement. A detailed description of the dual nuclei is given in table 3.2

Table 3.2: Measured displacements for dual nucleus galaxies. Where the offset is absent, the image did not yield a resolvable dual nucleus. ptc = photocenter.
### Results for recoil candidates: Position angles

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Table 3.3: Measured position angles for recoil candidates. This table also includes the relevant jet axis and dustlane axis in degrees from East.
Results

galaxy shows an ‘Intermediate’ significance displacement in both the $x$ and $y$ coordinates. The radial displacements were found to range from $\sim 2\text{pc}$ to $\sim 130\text{pc}$.

Figure 3.1 shows the distribution of the IQR - normalized displacements for the entire sample. The large red filled circles show the candidates listed in tables 3.1 and 3.2. We see that for most of the candidates at least the $x$ or $y$ coordinate displacement lies above the threshold which corresponds to $3\sigma$. For some galaxies, measurements from different filters yield non-significant displacements. Most of the non-detections lie within the $3\sigma$ box as shown by small yellow dots. The ones that lie outside the box correspond to images with heavy obscuring structures which give rise to spurious detections and are discarded from the candidates list.

It is important to critically analyze images in multiple filters before determining whether or not the measured spatial offset is real or spurious. Multifilter analysis revealed that out of the 18 candidates only about half have consistent displacements in multiple filters making them stronger candidates. The presence of obscuring features in some galaxies can be the cause of a lower confidence in the existence of a real displacement.

Figure 3.2 shows the radial displacement for the 18 candidates in images from different filters as a function of redshift. The two lines correspond to the distance equivalent to 0.3 pixels for the 2 different plate scales of the HST images used in this work which is approximately the estimated uncertainty in the photocenter analysis. As expected, only higher displacements are observed at higher redshifts. HST’s WFC3 and NICMOS 3 have a plate scale of 0.13 arcsec per pixel while ACS, WFPC2/PC, and NICMOS 1 and 2 have a plate scale of 0.05 arcsec per pixel. In the case of 3 of the candidates NGC4473, NGC5419 and NGC4486b, this causes a disparity between the results obtained from images taken from different filters/cameras (see discussion). The circled points in figure 3.2 correspond to the results where the detection of an offset was not significant. Multi-filter analysis is used to reveal the significance of an offset measured across different filters. If the offset is consistent across multiple filters, the displacement is considered to be robust. In many cases, the IR offset is smaller than the optical offset. In some cases this is caused by the presence of a nuclear dust lane that can obscure the AGN and lead to an error in the exact measurement of the AGN position. Displacements were not confirmed for all the objects in all
wavelengths. Even though most points lie above the corresponding threshold lines as would be expected, several lie below it. Most of the points that lie below the respective detection threshold are considered to be uncertain.

Figure 3.3 show the distribution of the radial displacements for the 18 candidates in optical and IR filters. 14 candidates were core elliptical galaxies while 4 were power-law galaxies. Thus it is found that a majority of the displacements are found in core rather than cuspy galaxies out of the candidates for recoil. Though most of the displacements are less than 50 pc there are some galaxies with displacements up to $\sim 130$ pc (however, it was found that the large displacements had low significance).

### 3.1.3 Displaced SMBH candidates

Out of the 96 galaxies that were analyzed, a significant displacement was measured in 18 galaxies in at least one filter. Figure 3.11 presents an example of a galaxy for which a significant displacement was measured and Figure 2.8 presents the results for a galaxy that does not show a significant displacement. In the case of most candidates we find that there is little spread in the distribution of the photocenter of individual isophotes. The presence of central dust lanes and other obscuring nuclear structures can cause distortions in the light profile of the galaxy as can be seen in the form of a bump seen in Figure 3.11. In the case of Figures 3.11 we see that there is a clear spatial offset between the cluster of isophotal centers and the position of the AGN. Out of the candidates, 14 galaxies are core ellipticals and 4 are power law galaxies. (Please refer to section 3.4 for more details on the candidates).

### 3.2 Discussion

In this section, we shall be discussing the gravitational recoil candidates obtained from our study and their statistical implications.

Candidates are considered robust if the multifilter analysis reveals consistent displacements across different filters. In case multiple filters are not present for a candidate, the displacement must be significant (as discussed above).
3.2.1 Nuclear point sources and evidence of AGN activity

Our sample of 96 galaxies were selected from previous studies of radio selected galaxies. The presence of an AGN in the candidates obtained was identified by looking for X-ray point sources, broad emission lines and radio jet activity. Details for nuclear activity for each candidate has been discussed in section 3.4. Out of the 18 recoil candidates, only two (M85 and M105) have ambiguous nuclei.

3.2.2 Factors affecting displacement

Out of the 18 candidates, 10 show a significant nuclear structure that can be attributed to dust (details on individual objects are discussed in section 3.4). Though this region is masked out in the ellipse fitting pipeline and should not affect the photocenter detection, it causes an additional uncertainty in the position of the nuclear point source. The direction of the displacement relative to the dust lane provides an indication that dust obscuration may affect the results. If the displacement is approximately perpendicular to the dust lane in an image, this increases the probability of a ‘spurious’ displacement being caused due to the presence of the dust lane. Multifilter analysis can reduce the effect of the dust structure by using IR images. 9 of the 10 candidates with a nuclear dust structure have NIR images. In most NIR images, the effect of the dust structure is greatly reduced allowing for a more precise location of the AGN position. However, if the AGN point source is strong and not obscured by the dust structure (as in the case of NGC3557), a precise position for the AGN can be obtained. In the case of 3C430, even the IR image shows heavy obscuration due to the central dust lane, but the point source is not obscured anymore. For 3C076.1, on the other hand, the effect of the nuclear dust structure is greatly reduced in the IR image which yields a more accurate displacement.

Other factors affecting displacements include a diffuse nucleus and knots in the jet which could be mistaken for a displaced AGN (López-Navas and Prieto, 2018; Batcheldor et al., 2010). However, for our candidates that have a jet, we do not see optically strong and resolvable knots. M85 and M105, both have a diffuse nucleus. In these cases we cannot confirm the presence of an AGN and thus cannot confirm them as recoil candidates. The presence of knots in the jet accompanying the AGN could be mistaken for a displaced
SMBH. Knots arise from optical synchrotron radiation from the jets.

### 3.2.3 Dual nucleus candidates

Three of the galaxies, NGC4486b, NGC4473 and NGC5419 have a potential dual nucleus structure. NGC5419 has a distinct secondary point source in the North-west direction (approximately 150 degrees) to the primary source (which is visible in the optical images). NGC4473 and NGC4486b have a dumbbell shaped nuclear structure that is not entirely resolved in any image but the dumbbell structure is prominently visible in most filters. The dumbbell structure is not visible in the WFC3 IR images due to the plate scale being larger but it is still visible as an elongated feature instead of a simple point source. This leads us to infer that there may be a dual source at the center of each of these three galaxies. The dual nucleus of NGC 4486b was studied by Lauer (1985) where they found a 12pc separation between the two nuclei. We have recovered a similar separation. NGC5419 has also been previously identified as a dual nucleus (Lena et al., 2014). NGC4473 has not been previously reported to be a dual nucleus (as far as we know). Please refer to section 3.4 for further discussion of all the candidates and their corresponding displacements. Figure 3.4 shows the dual nature for these objects.

The nuclear dumbbell structure is not due to dust extinction (in NGC4473) since we have analyzed both IR and optical images and the light profiles though the dumbbell structure appears in both images. One of the other possibilities is the presence of a stellar disk in the nuclear region (Combes et al., 1990; Portail et al., 2015). We need to investigate these objects more in order to make further inferences on their nature.

### 3.2.4 Robust candidates

After analyzing all the available images in the HST archive for the 18 candidates, a further selection of robust candidates was made based on the following criterion.

- The AGN point source is well defined in the image.
- There is clear evidence for nuclear AGN activity.
Discussion

Figure 3.4: Dual nucleus candidates. Left: NGC4473 WFPC2 F555W. Middle: NGC4486b NIC F160W. Right: NGC5419 WFPC2 F555W

Figure 3.5: The algorithm used to determine which galaxies are considered to be robust recoil candidates, dual nuclei or discarded as candidates
Discussion

- Consistent displacement (within error) exists across multiple filters with comparable amplitudes and displacement vector.

- If there is a discrepancy in the displacements between different filters, it can be easily explained due to image artifacts or obscuring features; e.g. dust lanes which are visible in optical images but not in the IR images.

- If multiple images do not exist in the HST archive, the displacement in the one available and analyzed image produces a ‘high’ significance displacement.

- A candidate is considered as a dual nucleus is there is evidence of dual nuclei in the images analyzed for that candidate.

This criteria is demonstrated in the form of a flowchart in Figure 3.5. Based on these criteria, the following 6 candidates were chosen as the most robust recoil candidates: 3C353, 3C430, 3C076.1, M49, NGC3245 and NGC3557. Apart from the 6 recoil candidates, NGC4473, NGC4486b and NGC5419 were considered to be dual nuclei (as discussed in section 3.2.3).

3.2.5 Alternate displacement mechanisms

Lena et al. (2014) (and the references within) discusses these alternate displacement mechanisms. Although an offset AGN may be a signpost of a recoiling SMBH, there are several other mechanisms that can cause the SMBH to be displaced from the center of the galaxy by distances comparable to our measured offsets (∼10pc) (Batcheldor et al., 2010).

Asymmetric jets

If the jets from the SMBH are intrinsically asymmetric, the resulting net thrust can cause a displacement in the position of the SMBH from the equilibrium position (Shklovsky, 1982; Saslaw and Whittle, 1988). The presence of strong magnetic fields (∼10³ G) gives rise to jets in AGN. Magnetically driven jets of unequal strengths can arise out of the disk due to certain configurations of the dipole and quadrupole components (Kornreich and Lovelace, 2008; Wang et al., 1992). This can give rise to one side with a dominant jet. Kornreich and Lovelace (2008) considers the influence of a
Discussion

one-sided jet that maintains its force on the BH for a time on the order of the Salpeter (1994) time. They find that the acceleration of the BH is

\begin{equation}
  a_{BH} \approx 2.1 \times 10^{-6} f_{jet} \dot{m} \text{ cm s}^{-2}
\end{equation}

where \(\dot{m} \equiv \dot{M}/\dot{M}_{Edd}\), \(\dot{M}\) is the mass acceleration rate,

\begin{equation}
  \dot{M}_{Edd} = L_{Edd}/(\epsilon c^2) \approx 2.2(M_{BH}/10^8 M_\odot) M_\odot \text{yr}^{-1}
\end{equation}

Equation 3.3 gives the Eddington accretion rate and \(f_{jet} = L_{jet}/L_a\) where \(L_a\) is the accretion luminosity and \(L_{jet}\) is the jet luminosity. This equation can be used to derive the displacement of the SMBH due to asymmetric jet power. Batcheldor et al. (2010) discuss the displacement in the position of the SMBH in M87 as being a result of the jet power asymmetry. In M87 they found that the observed displacement could be explained by a jet power asymmetry of \(\sim 3%\) of the accretion luminosity.

From the candidates found in this study, 3C076.1, 3C353 and 3C430 show a displacement vector which is approximately aligned with the jet axis. This makes them strong candidates for an asymmetric jet power induced offset.

**Stalled SMBH binaries**

Binaries stall at the ‘hard binary separation’ which is given by

\begin{equation}
  a_h = \frac{G \mu}{4 \sigma^2} = \frac{M_2 r_h}{M_{12} 4}
\end{equation}

\begin{equation}
  \approx 0.27 (1 + q)^{-1} \left( \frac{M_2}{1 \times 10^7 M_\odot} \right) \left( \frac{\sigma}{200 \text{km s}^{-1}} \right)^{-2} \text{ pc}
\end{equation}

where \(r_h = GM_1/\sigma^2\) is the influence radius of the larger SMBH, \(M_1\) and \(M_2\) are the two masses of the BHB, \(M_1 + M_2 = M_{12}\), \(\sigma\) is the field star velocity dispersion and \(\mu\) is the reduced mass of the BHB (Merritt, 2013). This happens due to the lack of interacting stars. As discussed in chapter 1, after a galactic merger, the two SMBH form a binary at the center of the merged galaxy and undergo 3-body interactions with stars clearing out the center of the galaxy. This causes the light profile of the galaxy to flatten off towards the center of the galaxy. The 3-body interactions and subsequent
kicking out of the third body (the star), causes the binary to tighten and eventually coalesce. If an insufficient number of 3-body interactions take place, instead of the binary hardening and eventually coalescing, the evolution of this binary pair effectively stalls. This is the so-called ‘final-parsec problem’ (Merritt and Milosavljević, 2005). Thus if the center of mass of the binary lies near or at the position of the photocenter of the galaxy the AGN will appear to be displaced from the center and produce results similar to the results expected for recoiling SMBH. This is expected if the secondary is accreting. Recent work on triaxial and gas rich systems suggests that the binary can continue to tighten and does not produce a stalled SMBH binary (Vasiliev et al., 2015). The presence of gas in a system has been argued to be a factor in avoiding the stalling of an SMBH binary (Escala et al., 2005; Mayer et al., 2007b; Cuadra et al., 2009). N-body simulations have found that the presence of centrophilic orbits can lead to efficient evolution and decay of the binary orbit (Khan et al., 2011; Preto et al., 2011; Gualandris and Merritt, 2012). However, these simulations do not have the sub-parsec scale resolution required to probe the final stages of the binary’s evolution.

Massive perturbers

A SMBH can undergo interactions with a number of massive perturbers including stellar mass SMBH, giant molecular clusters and globular clusters. The masses of these perturbers can range up to \( \sim 1 \times 10^7 M_\odot \). These perturbers can cause the SMBH to undergo brownian motion in the gravitational potential of the galaxy. The displacements estimated by Merritt (2013) are between 0.01 \( r_c \) and 0.1 \( r_c \) where \( r_c \) is the core radius of the galaxy. Typical core radii of \( \sim 1 \) kpc are expected in nearby elliptical galaxies (Lauer, 1985; Casertano and Hut, 1985). A displacement on the order of 0.01 \( r_c \) is expected as a result of Brownian motion in a typical SMBH of \( 10^9 M_\odot \). All the observed displacements for the candidates discussed in this dissertation have an offset that lies within the core radius of their host galaxies.

Antonini and Merritt (2012) discuss how a population of giant perturbers like giant molecular clouds can affect the motion of the SMBH. It is seen that because dynamical friction has a relatively low efficiency in low density cores, the formation of stalled massive objects is preferred in the cores of giant ellipticals. This suggests that massive perturbers cannot be overlooked...
as a possible mechanism for producing displacements in the position of the AGN with respect to the position of the photocenter of the galaxy.

### 3.2.6 Distinguishing possible displacement mechanisms

It is possible to statistically determine which scenario is more likely by analyzing the relationships between the displacement vectors and various properties of the host galaxy. For example, looking for a correlation between the radio jet axis and the direction of the displacement will help distinguish between gravitational recoil and other mechanisms like asymmetric jets or massive perturbers. A tight correlation would suggest that the displacements are mainly due to jet acceleration. On the other hand, we expect a looser correlation if gravitational recoil is the primary displacement mechanism (Lena et al., 2014). Displacements caused by a massive perturber should show no correlation between the jet position angle and the displacement axis. Finally, an anticorrelation with jet direction might be expected if the displacements result from stalled SMBH binaries (assuming that the spin and orbital angular momenta are correlated). Similarly, a greater incidence of displacements in core galaxies, as already indicated in this study, favors either stalled binaries or gravitational recoil, since the 'core' is thought to be related to the formation of an SMBH binary.

3C098, 3C076.1, 3C353, 3C430, M49 and NGC5920 (3c318.1) have powerful radio jets. For the galaxies 3C430, 3C353 and 3C076.1, the displacement is approximately along the axis of the radio jet (within PA \( \sim 10^\circ \)) suggesting that the displacement is possibly due to an asymmetric jet instead of a gravitational recoil. This however, does not rule out the recoil hypothesis.

### 3.2.7 Gravitational recoil candidates

The range of the displacements (3 - 130pc) is consistent with the range of expected offsets as predicted by Merritt and Milosavljević (2005); Gualandris and Merritt (2008) (\( \sim 10 - 100 \) pc). The range for the robust displacements was found to be 5 - 40 pc which is in the lower part of the range.

Significant displacements are found in \( \sim 20\% \) of the entire sample in at least one filter. Out of the 18 candidates, 14 are core elliptical galaxies and 4 are power-law galaxies. This is consistent with expectations since
we expect the SMBH binary to have formed in a core galaxy following a major merger (refer to Chapter 2). Of the 6 robust recoil candidates, 5 are found in core elliptical galaxies. Since the total sample used for this study is approximately equally split between core and power-law galaxies, the 5 robust core galaxies consist of about 10% of the core galaxy sample. All 3 dual nucleus candidates are also found in core galaxies.

Blecha et al. (2016) have conducted a series of simulations to predict the observability of recoiling SMBH. Their models take into account gas rich as well as dry mergers and different spin alignment configurations for the initial conditions. They found that spin alignment plays a significant role in suppressing recoils. For certain spin alignment configurations we should find a large number of recoiling SMBH in the nearby universe. Their predictions can be used in conjunction with our study to put better constraints on SMBH merger rates.

3.3 Summary and conclusions

We have analyzed HST archival and new images of 96 galaxies in the nearby universe to find instances where the central AGN is displaced from the center of the galaxy. We have found significant ($\geq 3\sigma$) displacements in at least one filter in 18 galaxies ranging from $\sim 2$pc to $\sim 130$pc. 14 of these galaxies are core ellipticals and 4 galaxies have a power-law light profile. These are considered to be candidates for hosting displaced SMBH.

6 of the 18 displaced SMBH candidates (3C353, 3C430, 3C076.1, M49, NGC 3245 and NGC 3557) are considered to have robust displacements of which 5 are core galaxies and NGC 3245 is a power law galaxy. The spatial offset for the 6 robust cases range from 5 - 40pc.

3 other galaxies (NGC 4473, NGC 4486b and NGC 5419) show evidence of a potential dual nucleus structure. Of these, NGC4473 is a new dual nucleus candidate, the other two have been studied before (see section 3.4 for notes on each galaxy. These galaxies need to be further studied to understand the nature of the dual nuclei.

The measured spatial offsets are possible signatures of gravitational recoil. The range of the recoil is consistent with the predictions of the amplitude of the Phase II oscillations from Merritt and Milosavljević (2005); Gualandris and Merritt (2008).
Apart from gravitational recoil, such spatial offsets can be caused by a few other methods. Five of the displaced SMBH candidates have a strong jet and in 3 cases (3c076.1, 3C353 and 3C430) the jet axis is approximately aligned to the displacement axis which suggests that asymmetric jet power could cause the spatial offset seen in those objects.

### 3.4 Notes on individual candidates

Tables 3.1 and 3.2 describe the results for the displaced SMBH candidates and the significance of the displacements. Table 3.3 lists the displacement vectors along with the position angle for the dustlanes, jets wherever present.

#### 3.4.1 3C098

This galaxy has been identified as hosting an AGN through detection of jets. It is an NLRG with a doubled FRII radio source and a jet connecting a compact core to the northern lobe. (Leahy et al., 1997; Baum et al., 1988). The powerful jet also has large scale lobes. It has a nuclear X-ray source whose spectrum can be modeled as a heavily absorbed power law (Evans et al., 2006). A point source, presumed to be the AGN, has been detected in HST NIR (NICMOS) images (Ramírez et al., 2014). Thus, for 3C098, there is optical (Seyfert 2 spectrum), radio (FR II source with core, jet, lobes) and X-ray (nuclear power law) evidence that it hosts an AGN, and the point source is detected in NIR HST images. This galaxy does not have a discernible dust structure. This galaxy has a powerful jet in approximately PA of 45°. The displacement (PA ∼ 70°) is not along the jet axis. But the results of the 2 filters (NIC2 110W and 160W) are only marginally consistent with each other (as seen in figure 3.6) and thus, do not identify as robust displacements.

#### 3.4.2 3C353

3C353 has powerful jets and is identified as an FR II radio galaxy through the structure of the lobes (Hardcastle et al., 1998; Kataoka et al., 2008) (PA ∼ 60°). There is evidence for both radio and X-ray activity from the nucleus, the jet and counter-jet, hotspots as well as one radio lobe. The AGN is detected as a strong X-ray source, with both the jet and counter-jet
Figure 3.6: The multifilter displacements for 3C 98. The error bars represent the IQR values in mas. The displacements shown in this plot are relative to the photocenter which is assumed to be at the origin in the plot.
Figure 3.7: As in Figure 2.7 for 3C 353 in NIC2 F160.
also detected in X-rays. Swain et al. (1998) presented detailed VLA images of the radio source showing the FR II double lobed structure, jet, counter jet and the compact core. Its optical spectrum is very red and exhibits weak emission lines characteristic of a LINER spectrum (Tadhunter et al., 1993; Simpson et al., 1996; Buttiglione et al., 2010). There are kpc scale offsets present between the intensity maxima between X-ray and radio observations. This core elliptical FR II galaxy has a central dust structure with a PA $\sim 120^\circ$ which is visible in the optical images but not in the IR. The overall isophotal analysis reveals minimal isophotal twisting in $x$ but a fair amount in $y$ axis as can be seen in figure 3.7. The IR image shows a significant displacement in $\sim 100^\circ$ which is coincident with the jet axis (PA $\sim 90^\circ$) suggesting that the displacement could be caused by the jet. Figure 3.8 shows that the the IR offset is consistent with the optical offsets and all the offsets are consistent approximately in direction. The IR image offset is not affected by the dust structure and thus is used as the robust offset.

### 3.4.3 3C430

3C430 is identified as an FRII classical double radio galaxy through the presence of powerful jet activity (Leahy and Williams, 1984) with PA $\sim 45^\circ$. This galaxy has a prominent nuclear dust structure (PA $\sim 112^\circ$). For the optical WFPC2 image the displacement is approximately perpendicular to the dust lane suggesting that the dust structure causes the large displacement. The IR image shows a smaller displacement ($\sim 227^\circ$) which is approximately along the direction of the jet axis (within $\sim 10^\circ$). Thus, jet acceleration is a possible cause of the observed displacement. The isophotal analysis reveals minimal isophotal twisting. Figure 3.10 shows that the optical and IR displacement are not consistent with each other. As mentioned above, this is probably caused by the prominent nuclear dust structure. The AGN is fairly unobscured in the IR image which shows a significant offset (Figure 3.10).

### 3.4.4 3C076.1

3C 76.1 is identified as an FR I radio galaxy with a powerful twin-jet (Leahy and Perley, 1991). This galaxy has a nuclear dust structure (PA $\sim 48^\circ$) which is not prominent in the IR image. There is some isophotal
Figure 3.8: The multifilter displacements for 3C 353. The error bars represent the IQR values in mas.
Notes on individual candidates

Figure 3.9: As in Figure 2.7 for 3C 430 in NIC2 F160.
Figure 3.10: The multifilter displacements for 3C 430. The error bars represent the IQR values in mas.
twisting with the isophotes being boxy towards the center of the galaxy. The displacement in the NIC2 IR image is smaller than in the WFPC2 optical image but still is very significant. The larger displacement in the optical image is probably due to the presence of the obscuring nuclear dust structure. The displacement (in the IR image) is in the direction of the jet axis (PA of jet is $\sim 135.2^\circ$ and PA of the displacement is $\sim 132^\circ$) which suggests that asymmetric jet power could have contributed in the displacement of the AGN. As can be seen in figure 3.11, both the offsets are approximately in the same direction. Figure 2.7 in chapter 2, shows the results for the NIR image which is not as affected by the dust lane and is considered to be a robust displacement.

![Multifilter Displacements for 3C 076.1](image.png)

Figure 3.11: The multifilter displacements for 3C 076.1. The error bars represent the IQR values in mas.

### 3.4.5 M49 (NGC4472)

M49 is identified as a Seyfert 2 and LINER AGN whose radio core has double sided jet activity (Ho and Ulvestad, 2001) (PA $\sim 80^\circ$). This galaxy
Figure 3.12: As in Figure 2.7 for M49 in WFC3 F160.
Notes on individual candidates

has a heavy nuclear dust structure (PA \( \sim 125^\circ \)) which causes the optical displacement to be distorted as a result of dust extinction. There is little to no isophotal twisting in this galaxy. The IR WFC3 displacements are consistent with each other in magnitude and are approximately in the same direction. Figure 3.12 shows the results for the WFC3 F160 image. The displacements are significant in the WFC3 IR images (as seen in Figure 3.13) and there does not seem to be a correlation with the jet or the dust lane axis. The NIC2 displacement is in approximately in the same direction as the WFC3 IR images but has a much larger displacement. The displacement is in PA \( \sim -10 \) to \(-40^\circ \) which is not coincident with the jet axis.

Figure 3.12: The multifilter displacements for M49.

3.4.6 M85

The nuclear source for this galaxy is slightly ambiguous. Sivakoff et al. (2003) suggest that the X-ray sources at the center could be either the AGN or just globular clusters. Gültekin et al. (2011) suggests that there might be a double nucleus in M85. This galaxy has a central elongated source that
appears to have a keyhole structure in the median subtracted image. The photocenter is in the center of the elongated structure that is seen in the WFPC2 and NICMOS images. The multifilter displacements are compared in figure 3.14. This galaxy is not considered to have a robust displacement.

Figure 3.14: The multifilter displacements for M85.

### 3.4.7 M89

This galaxy has been identified as having an AGN though X-ray observations (González-Martín et al., 2009). Malin and Carter (1983) have suggested that M89 could have jet activity from the structure of the shells (ripple effects in the morphological structure in the outer galaxy). This galaxy has a LINER spectrum and a strong X-ray point source with an absorbed powerlaw spectrum (Flohic et al., 2006). This galaxy has a variable nuclear point source (Maoz et al., 2005). This galaxy has a central nuclear dust structure (that is shaped like an arc that flattens at PA $\sim 90^\circ$) that is visible in the optical images but not in the IR images. The new HST images (WFC3 110/160w) show a small but still marginally significant displace-
Notes on individual candidates

Figure 3.15: The multifilter displacements for M89.
Figure 3.16: The multifilter displacements for M105.
Notes on individual candidates

The dust structure appears in a butterfly like structure in the WFPC2 image and is likely due to an image artifact. The multifilter displacements are compared in figure 3.15. This galaxy is not considered to have a robust displacement.

3.4.8 M105

The central source is identified as a radio loud AGN (Baldi and Capetti, 2009) but the nuclear source is diffuse. There is a big dust structure (PA \(\sim 120^\circ\)) in the center which is visible in the optical images but is not as prominent in the IR images. The displacements in the IR images while smaller than that optical are more believable due to low interference of the dust structure which affects the optical measured displacement. However, both the IR displacements are marginal as well as inconsistent with each other and thus cannot be considered to be a robust displacement. The multifilter displacements are compared in figure 3.16. This galaxy is not considered to have a robust displacement.

3.4.9 NGC3245

This power-law galaxy has a hard nuclear X-ray source near the optical nucleus (Filho et al., 2004; Capetti and Balmaverde, 2005; Capetti et al., 2009) which is a LINER nucleus Ho et al. (1997). This galaxy also has a boxy bulge (Hu, 2008). This power-law galaxy has a very prominent dust structure in the center (with PA \(\sim 167^\circ\)) which is prominent in both the optical and IR images. The displacement is affected by the dust lane in the optical image (PA \(\sim 116^\circ\)) but not in the IR image (PA \(\sim 106^\circ\)). The IR displacement is considered to be a robust displacement since the point source is not obscured by the dust structure and the dust structure is also masked out in the isophotal analysis greatly reducing it’s effect on the photocenter position. The multifilter displacements are compared in figure 3.18 and the results for the NIC2 F160 image are presented in figure 3.17.

3.4.10 NGC3557

This core elliptical galaxy has a prominent dust structure (PA \(\sim 90^\circ\)) in the center and was chosen from the radio selected galaxies in Capetti et al. (2009). This galaxy is a Flat Spectrum Radio Source (Healey et al. (2007))
Figure 3.17: As in Figure 2.7 for NGC 3245 in NIC2 F160.
and contains a jet (Liu and Xie (1992)). The central point source is very strong and is visible through the dust structure. The obtained displacement is considered robust since the point source itself is not obscured. The central dust structure is masked out in the isophotal analysis and thus it does not affect the position of the photocenter and is considered to be a robust displacement. However, there is no IR image available in the HST archive for this galaxy. An IR image will give us a better understanding of the central region of the galaxy that is affected by the dust structure. Since this galaxy only has one image in the HST Legacy Archive we do not have multifilter analysis for this galaxy. The results for the image in WFPC2 F555 are given in Figure 3.19.

### 3.4.11 NGC3998

This power-law galaxy has been identified to host an AGN though X-ray observations from González-Martín et al. (2009) as well as broad Hβ detections (Ho et al., 1997) in its LINER optical spectrum. This power-law galaxy
Figure 3.19: As in Figure 2.7 for NGC 3557 in WFPC2 F555.
Notes on individual candidates

has a very faint dust structure in the center (PA $\sim 90^\circ$). The WFC3 images show a directionally consistent (PA $\sim 170^\circ$) but marginally significant displacement in figure 3.20. There is almost no isophote twisting present in this galaxy. The dust structure could be the cause of the discrepancy in the measured displacements across the different optical and IR filters.

Figure 3.20: The multifilter displacements for the power law galaxy NGC3998.

3.4.12 NGC4143

This power-law galaxy shows no discernible dust lane in the center. The NICMOS image reveals a smaller displacement than the optical image. Both displacements are roughly in the same direction and are marginal as can be seen in figure 3.21. This galaxy shows broad H$\alpha$ line in the center revealing the presence of an AGN (Ho et al., 1997). This galaxy shows some isophotal twisting. The multifilter displacements are compared in figure 3.21.
Figure 3.21: The multifilter displacements for the power-law galaxy NGC 4143.
3.4.13 NGC4377

This galaxy is a part of the Virgo cluster and was chosen as a part of the radio selected galaxies in Capetti et al. (2009). X-ray sources have been detected from this galaxy Miller et al. (2015) and has been studied as a part of the AMUSE-Virgo survey (Gallo et al., 2010). This galaxy has a small nuclear dust structure. The displacement in the optical image is influenced by the presence of the central dust structure. The IR image does not show a significant displacement as can be seen in figure 3.22. This galaxy shows minimal isophotal twisting.

![Figure 3.22: The multifilter displacements for the core galaxy NGC 4377.](image)

3.4.14 NGC4452

This is an S0 power-law galaxy with no discernible dust structure. This galaxy was chosen as a part of the radio selected galaxies in Capetti et al. (2009) with X-ray detections (Miller et al., 2015). The central point source is prominent in all images. The ACS and the NICMOS images have fairly consistent direction of displacement. But both displacements are marginal.
Notes on individual candidates

as can be seen in figure 3.23.

![Figure 3.23: The multifilter displacements for the galaxy NGC 4452](image)

**3.4.15 NGC 4473**

NGC 4473 is a part of the VIRGO cluster and was chosen as a part of the radio selected galaxies in Capetti et al. (2009). X-ray sources have been detected in this galaxy (Plotkin et al. (2014); Miller et al. (2015)). There is some debate on whether or not this galaxy is a core elliptical Saglia et al. (2016); McConnell and Ma (2013). We find that the light profile of this galaxy resembles that of a core elliptical. This galaxy does not have a very discernible dust lane. The central region has a dumbbell shape suggesting the possibility of a double nucleus. This galaxy shows a double peaked structure in its stellar velocity distribution (Alabi et al., 2015; Kundu and Whitmore, 2001). This can be interpreted as a signature of a past merger. The photocenter lies in the middle of the dumbbell shape. The dumbbell shape is not resolvable in the new WFC3 HST images but the central region still appears to be elongated. As far as we know this galaxy has
Notes on individual candidates

Figure 3.24: As in Figure 2.7 for NGC 4473 in WFPC2 F814. Since this is a dual nucleus candidate, the two components of the dumbbell are shown by the two green stars.
Figure 3.25: The multifilter displacements for NGC4473. Since this is a dual nucleus candidate, the two points of the same color show the 2 components of the dumbbell with respect to the photocenter (at the origin) from the same image.
Notes on individual candidates

not been identified as a dual nucleus candidate before. Table 3.2 describes the individual observations and separations between the two nuclei. The two WFPC2 optical observations show a consistent separation of $\sim 16 - 18$ pc. The multifilter displacements are compared in figure 3.25. Figure 3.24 shows the results from the WFPC2 F814 image with the two components of the dumbbell highlighted with respect to the photocenter.

Figure 3.26: As in Figure 2.7 for NGC4486b in NIC1 F160.

3.4.16 NGC4486b

Kormendy et al. (1997) discusses spectroscopic evidence for an SMBH in the center of NGC4486b. This core galaxy does not have a central dust structure. The unsharp masked image reveals a dual nuclear structure as
identified in Lauer (1985) and a separation of $\sim 17$ pc is obtained which is approximately consistent with the Lauer (1985) inference of $\sim 12$ pc. The structure appears as dumbbell shape (PA $\sim 90^\circ$) with the two nuclei in the optical and NICMOS images. The photocenter lies approximately at the center of the dumbbell while the point source could be taken as either of the two dumbbells. Figure 3.27 shows the positions of the two nuclei for each of the IR and optical images. Figure 3.26 shows the results of the photometric analysis for NIC1 160W image.

Figure 3.27: The 2 nuclei for the IR and optical images of the core elliptical NGC4486b. The IR image provides a bigger separation between the two nuclei.

3.4.17 NGC5419

This galaxy is a bright and dominant galaxy in Abell S753 (Abell et al., 1989). This galaxy has also been discussed in Lena et al. (2014); Capetti
Notes on individual candidates

Figure 3.28: As in Figure 2.7 for NGC5419 in WFPC2 F555.
Notes on individual candidates

et al. (2005); Mazzalay et al. (2016) as a double nucleus candidate. This galaxy has been identified as hosting an AGN from radio observation (Goss et al., 1987; Subrahmanyan et al., 2003) and from hard X-ray observations from Balmaverde et al. (2006). This core galaxy (as identified first in Lauer et al. (2005)) does not have a central dust lane. The central source is revealed to be a dual point source. The separation between the two nuclei is about 5 pixels (∼ 83 pc) with a PA ∼ 162° relative to the photocenter (almost south of the photocenter). The photocenter coincides with the brighter of the two nuclei. The WFC3 images do not reveal a dual nucleus. This is a robust dual nucleus case as can be seen in figure 3.29 where the AGN in the optical image is offset compared to the photocenter.

Figure 3.29: The displacements for the core elliptical NGC5419. The green star represents the photocenter of the galaxy in the optical image and the blue star represents the position of the AGN. The dual nuclear structure is unresolvable in the IR images.
3.4.18 NGC5920

This is a core FR I type elliptical galaxy in Abel 2063B which shows evidence of radio jet activity (Madrid et al. (2006); Mazzotta et al. (2002)). Buttiglione et al. (2009) have conducted a spectroscopic survey of 3C objects including 3C318.1 (NGC5920). Massaro et al. (2015) discusses the X-ray observations from this AGN as well as from the neighboring knots in the jet and hotspots. There is a nuclear X-ray source associated with the radio core. Though a significant displacement is observed in the optical filter, we obtain a marginal significant displacement in the new HST IR images. Figure 3.30 shows the multifilter displacements for the galaxy NGC 5920.

Figure 3.30: The multifilter displacements for NGC5920
In this chapter I introduce the analysis of the quasar E1821+643. Section 4.1 outlines the properties of E1821+643 as well as the previous spectropolarimetry study conducted for the object. Section 4.2 describes the spectroastrometry analysis performed for the quasar using data from the Gemini telescope and the results showing a displacement in the [O\textsc{iii}] emission. Section 4.3 discusses the image analysis and results for the new HST images obtained for the quasar to understand the distribution of the [O\textsc{iii}] emission. Section 4.4 describes the spectroastrometry modeling used to test whether the measured [O\textsc{iii}] displacements in the Gemini data can be caused by an intrinsically asymmetric spatial distribution of [O\textsc{iii}] emission. Section 4.5 discusses the inferences drawn from the observations and their relation to whether the observed displacement was caused due to asymmetric [O\textsc{iii}] emission or whether the recoil hypothesis can hold true. Section 4.6 discusses the conclusions.

4.1 Introduction

E1821+643 is a radio-quiet QSO (RQQ) at a redshift of $z \approx 0.3$, and with an absolute magnitude of $M_V = -27.1$ (Pravdo and Marshall, 1984; Hutchings and Neff, 1991), it is one of the most luminous QSOs in the local universe. Although classified as an RQQ, it exhibits many similarities to
radio-loud quasars (RLQs), for example, Hutchings and Neff (1991) have found that the host galaxy is red, featureless and very large, with an estimated diameter of 75 kpc (∼ 24′′), which suggests an elliptical galaxy – however most RQQs are located in spiral galaxies. It has a huge extended emission line region (Fried, 1998), and is located at the center of a cooling flow (Russell et al., 2010), in a cluster of galaxies with an Abell richness class ≥ 2 (Lacy et al., 1992) – which again, is usually typical of RLQs. Russell et al. (2010) trace the Intra-Cluster Medium (ICM) gas down to ∼ 15 kpc from the nucleus – about the extent of the emission line nebula, and calculate that the QSO is currently accreting at 50% of the Eddington rate, but that the luminosity produced does not strongly couple to the ICM – i.e. it is unable to reheat the ICM to prevent the cooling flow. On the other hand, they cannot rule out mechanical and radiative feedback coupling to the “cold galaxy gas”.

In the radio, there is extended low-surface brightness emission well beyond the host galaxy (Blundell and Rawlings, 2001). On arcsecond scales, there is a ∼90° bend in the SW jet, which may be due to precession in a binary, as suggested by Blundell et al. (1996); Blundell and Rawlings (2001), but could also be explained by a spin flip following recoil after a binary supermassive black hole (SMBH) merger (Merritt and Ekers, 2002).

4.1.1 Spectropolarimetry: evidence for a recoil

Robinson et al. (2010) conducted spectropolarimetric observations of E1921+643 as a part of a project to characterize the polarization properties of the broad lines in AGN. They found that the broad Balmer lines are redshifted by ≈ 1000 km s⁻¹ with respect to the narrow lines and have high red asymmetric profiles. In polarized light, however, the broad lines are found to be equally blue shifted with corresponding highly blue asymmetric profiles (refer to figure 4.1). Robinson et al. (2010) explained these characteristics in terms of a scattering model where the broad line region moves away from the observer towards a scattering region in the host galaxy. With typical velocities achieved in the recoil hypothesis, the bulk of the broad line region remains bound to the recoiling SMBH. Thus, in direct light, the BLR appears to be red shifted with respected to the NLR. However, light from the BLR that is emitted toward the scattering region is scattered back towards the observer, becomes polarized and blue-shifted (as the source is moving...
Spectroastrometry towards the scattering screen as seen in figure 4.2).

This can be interpreted as gravitational recoil due to anisotropic emission of gravitational waves following the coalescence of a progenitor SMBH binary. An alternative interpretation is that the BLR forms part of a one-sided wind which could also produce the kind of polarization signature that is observed. However, no physical justification for the presence of a one-sided wind has been found.

Another alternative is that the BLR is associated with an active secondary in a binary system while the narrow lines would be attributed to the circumbinary disk (as argued in Bogdanović et al. (2009) and Dotti et al. (2009) for the recoil candidate SDSSJ092712.65+294344.0). The scattering within the accretion flow could cause the observed blue shift in polarized light. However, it is not clear whether the observed blue asymmetry in the polarized line profile could be reproduced without further modeling. The scattering geometry would produce polarization aligned with the axis of the radio jet which is contrary to the observations (Robinson et al., 2010).

In an effort to differentiate between interpretations, we have obtained high signal-to-noise spectra suitable for spectroastrometric analysis from the Gemini North telescope in Hawaii in order to look for a spatial offset, which was found. We describe the data reduction, analysis and results in section 4.2. We also obtained HST images to determine whether the spectroastrometric displacement was due to an asymmetric NLR by mapping the [OIII] distribution. The HST image analysis and results are discussed in section 4.3. We discuss the spectroastrometry modeling in section 4 followed by the conclusions in section 5.

4.2 Spectroastrometry

4.2.1 Observations and Data Reduction

Deep optical spectroscopy of E1821+643 was obtained to perform a spectroastrometric analysis of the emission lines (Bailey, 1998). Spectroastrometry is a technique to measure the relative spatial displacements across spectral features in a 2D spectrum like a long slit spectrum. This is done by measuring the centroid of the light profile along the slit at each wavelength. Any spatial asymmetry that coincides with a spectral feature like an emission line will tend to shift the centroid relative to the adjacent wavelengths.
Figure 4.1: Broad Hα line profiles of E1821+643 in total and polarized flux. In the top panel of the broad Hα emission the red line represents the redshifted (asymmetric towards the red) line profile in total flux (median velocity +1170 km/s) and the blue line represents the blueshifted (and asymmetric towards blue) line profile in polarized light. The bottom panel shows the two Gaussians fit to the flux profile. R1 (blue): $v = +470$ km/s with FWHM $\sim$ 3600 km/s. R2 (green): $v = +2100$ km/s with FWHM $\sim$ 7800 km/s. This plot has been taken from Robinson et al. (2010)
Figure 4.2: The scattering screen model that can be used to explain the polarization observations in the context of the recoil hypothesis. The bottom plots show the Gaussian fits to the polarized (scattered) view and direct view of the broad Hα lines. This plot has been taken from Robinson et al. (2010).
Spectroastrometry

The reduction of the spectroscopic observations and and spectroscopy were performed by Rachel Curran. The data for this project was obtained on the nights of 20100424 (target) and 20100323 (flux calibrations) using the Gemini Multi-Object Spectrograph (GMOS) on the Gemini North telescope in Hawaii. The R400 grating along with a 1” slitwidth was used. Two exposures were obtained at slit position angles of 0°, 90°, 180° and 270° each with an exposure time of 600s.

The Gemini: GMOS package within IRAF was used for the data reduction. Each 2D spectrum was corrected for bias, the flat-fielded sky subtracted, and wavelength and flux calibrated. The pairs of spectra obtained at PA = (0°, 180°) and (90°, 270°) were then combined to form single spectra in the North-South and East-West directions. 1D spectra were extracted from the combined spectra to sample the extended line emission (Fig. 4.3) in each direction at 1” increments, using 1” apertures. A spectrum of the nucleus was also extracted (using a 1” aperture) after combining the data from all four PAs (Fig. 4.5).

Spectroastrometry was carried out on the 2D spectra obtained at each PA using the following method. Gaussians were fitted to the spatial profile along column of pixels along the dispersion direction (see Fig. 4.4). The centroids were fit using a polynomial to remove curvature in the spectra. The spatial offsets at each wavelength were then calculated. The PA =180° data were then subtracted from the 0° data, and the 270° data were subtracted from the 90° data to remove any instrumental effects. The final result is a spectrum of the spatial displacements in, respectively, the North-South and East-West directions.

4.2.2 Testing recoil hypothesis

Spectroastrometry is a method that measures the relative spatial displacements of spectral features such as emission lines. This is done by obtaining the position of the source in the long slit 2-D spectrum as a function of wavelength. Any wavelength dependent asymmetries are highlighted in the resulting ‘displacement spectrum’. The spatial profile can be measured up to a precision of the order of milli-arcseconds.

In this case, we are looking for a displacement between the broad and lines in the spectrum of E1821+643. A displacement is expected in the recoil hypothesis, if the BLR remains bound to the SMBH. An offset of ≈40mas
Figure 4.3: A section of the 0° 2-dimensional spectra, showing the region of Hβ and O\textsc{iii} 4959 and 5007Å. The extended O\textsc{iii} can clearly be seen towards the north (bottom of the image). The chip-gap can also clearly be seen to the right of the O\textsc{iii} lines.
Figure 4.4: The spatial profile of the O\textsc{iii} $5007\text{	extperiodcentered} Å$ emission line (black). The red gaussian represents the fit to the spatial profile. The extent of the fit is truncated to the peak of the profile to prevent any extended emission from biasing the fit.
Figure 4.5: The spectrum of the nucleus of E1821+643 extracted from the combined 2D spectrum.

Figure 4.6: The displacement spectra derived from the Gemini long-slit observations. The dotted lines indicate the emission lines. The top panel is the total flux. The middle and bottom panel show the displacement spectra in the S-N and W-E direction respectively.
Spectroastrometry

Spectroastrometric displacements for [OIII] 4959

Figure 4.7: Displacement and flux profiles for [OIII] 4959. The top left and right panels show the offset of the [OIII] line in the W-E and N-S directions. The bottom left panel shows the flux for the [OIII] 4959 line. The bottom right panel shows the N-S and E-W offset components of the [OIII] 4959 line as color coded by wavelength.
Spectroastrometry

Spectroastrometric displacements for O[III] 5007

Figure 4.8: As in figure 4.7 for [OIII] 5007
was measured in the [O\textsc{iii}] $\lambda\lambda 4959,5007$ lines, relative to the broad H\textbeta{} line and the quasar continuum in approximately the North-West direction. This is demonstrated in figures 4.7, 4.8 and 4.6. Figure 4.6 shows the total displacement spectra in the N-S and E-W directions with the [O\textsc{iii}]-4959 and [O\textsc{iii}] 5007 and other lines highlighted. As mentioned above, a significant displacement is seen in the two [O\textsc{iii}] lines which are them represented in detail in figures 4.7 and 4.8.

This implies that the SMBH could be displaced in the opposite direction (South-East) which supports the recoil hypothesis. However, this spectroastrometric displacement could also result if the spatial distribution of the [O\textsc{iii}] emission is intrinsically asymmetric in nature.

4.2.3 Spectroastrometry results

Spectroastrometric analysis revealed that there are clear offsets in the [O\textsc{iii}] emission lines in the North-West direction (PA\sim$55^\circ$). However, the broad components of the H\alpha and H\textbeta{} lines do not show a significant offset. Small offsets are seen in the narrow components of these lines in the West direction.

The wings of the [O\textsc{iii}] lines show an interesting displacement signature. The blue wing of the [O\textsc{iii}] 5007Å line is displaced to the south, whereas the core of the line is displaced to the North-West. The red wing also has a slight displacement to the South. The [O\textsc{iii}] 4959Å line shows a similar structure, only with smaller displacements.

The broad lines are not displaced relative to the continuum. This is consistent with the quasar nucleus dominating the continuum. Thus, the displacement was only found in the narrow lines.

If it is assumed that the continuum and the broad emission lines represent the QSO and the narrow lines represent the galaxy (the gas producing the cores of the narrow lines lie beyond the radius where the kick velocity is equal to the Keplerian velocity), then this result is consistent with the hypothesis that the QSO is offset (and recoiling) in the South - East direction and the galaxy is to the North - West of the QSO. This interpretation is also consistent with the results of Robinson et al. (2010). They found that the BLR was redshifted with respect to the NLR in direct light and was blueshifted in polarized light.

Alternatively, a spectroastrometric offset could be produced if the spatial
distribution of [O\textsc{iii}] emission is intrinsically asymmetric with respect to the nucleus. For example, if there is a biconical wind emitting narrow lines, there will be approaching and receding components on opposite sides of the nucleus. Here, the displacement spectrum would produce blue- and redshifted displacements on opposite sides of the nucleus with respect to the continuum. If one side of the biconal wind is obscured, a one-directional displacement can be obtained.

4.2.4 Spectroastrometric continuum correction

In order to correct the measured displacements for continuum dilution, we follow the analysis in Porter et al. (2004), approximating the QSO and the host galaxy as point sources. Assuming that $f_\star$ (host galaxy flux) and $f_Q$ (quasar flux) vary slowly with $\lambda$, $f_{\star,j} \approx f_{\star,\text{star}}, f_{Q,j} \approx f_Q$, where $j$ is the pixel index in the spectral direction. Using eq. 4 in Porter et al. (2004),

$$\frac{\mu_j}{d} = \frac{f_{NL,j} + f_\star}{f_{NL,j} + f_\star + f_Q} - \frac{f_\star}{f_Q + f_\star}$$

(4.1)

where $\mu_j$ is the measured displacement, $f_{NL,j}$ is the narrow line flux, and $d$ is the actual displacement (in the same units as $\mu_j$).

We define

$$W_{NL,j} = \frac{f_{NL,j}}{F_C}$$

(4.2)

$$r_\star = \frac{f_\star}{F_C}$$

(4.3)

where $F_C$ is the continuum flux. By substitution in equation 4.1 we get,

$$\frac{\mu_j}{d} = \frac{W_{NL,j}}{W_{NL,j} + 1} (1 - r_\star)$$

(4.4)

Since

$$r_\star = \frac{f_\star}{F_C} \ll 1$$

(4.5)
HST image analysis

<table>
<thead>
<tr>
<th>Line</th>
<th>PA $\mu_{NS}$</th>
<th>$\mu_{EW}$</th>
<th>$d_{NS}$</th>
<th>$d_{EW}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>OIII 4959 Å</td>
<td>56.70</td>
<td>14.46</td>
<td>-20.53</td>
<td>89.03 ±6.72</td>
</tr>
<tr>
<td>OIII 5007 Å</td>
<td>56.26</td>
<td>28.88</td>
<td>-40.82</td>
<td>90.64 ±4.82</td>
</tr>
</tbody>
</table>

$d_{NS}$ and $d_{EW}$ are derived from $\mu_{NS}$ and $\mu_{EW}$ respectively by using equation 4.7 for the North-South and East-West direction.

\[ \frac{\mu_j}{d} = \frac{W_{NL,j}}{W_{NL,j} + 1} \] (4.6)

Hence

\[ \mu_j = \frac{W_{NL,j}}{W_{NL,j} + 1} d \] (4.7)

This model gives us a linear relationship between the the measured displacement and the ratio of the narrow line to continuum fluxes as given by $\frac{W_{NL,j}}{W_{NL,j} + 1}$. The slope of this relationship gives us $d$ which is the actual displacement between the two sources. The displacements were measured at the line peaks. This can be regarded as an upper limit to the displacement. The values for the two [OIII] lines are given in table 4.1. The corrected displacements are consistent in both lines (as is expected) $\sim$90 mas which is $\sim$400pc.

4.3 HST image analysis

4.3.1 Observations and point source subtraction

Understanding the morphology of the narrow line region on sub-arcsecond scales will help us in establishing whether the spectroastrometric displacements can be explained by asymmetric distribution of [OIII] emission caused by either partial extinction of a bi-polar outflow or superwind, or whether the results support the recoil hypothesis. We have obtained HST ACS images of the quasar E1821+643 using the proposal 13385 with Dr. Andrew Robinson as the PI. The [OIII] and H$\beta$ images were obtained with the ACS.
ramp filter FR656N; the continuum was imaged in the F647M medium band filter in order to map the [O\textsc{iii}] emission around the quasar and the host galaxy.

HST images were obtained in several ramp filters including [O\textsc{iii}] and H\textbeta{} (in the band FR656N) and the broad band continuum image (in band FR647M) as seen in figure 4.9. The data was pipeline processed with HST MultiDrizzle. Since the quasar dominates this galaxy, first a PSF subtraction was performed to remove most of the quasar light in order to effectively understand the distribution of the [O\textsc{iii}] emission alone. A standard star, GRW+70D5824 (obtained from the HST archive from the proposal ID: 9563 and imaged in the same filter FR656N) was used as a model for the PSF subtraction. This subtraction was performed both manually and using the Galfit software.

For the manual subtraction, the image of the standard star was scaled to match the nuclear point source in the FR656N [O\textsc{iii}] image. This scaling was obtained by matching the integrated flux (over a central aperture of 1 arcsec) for the two images. The star was then subtracted from the original image to reveal the distribution of the resolved [O\textsc{iii}] emission as seen in figure 4.10. The contribution of the [O\textsc{iii}] in the unresolved nucleus was obtained by comparing the strengths of the [O\textsc{iii}] to the continuum as obtained from the Gemini spectra (described in section 4.2). About \(\sim 20\%\) of the unresolved nuclear flux is [O\textsc{iii}] emission comes from the quasar. In the manual subtraction we also take into account the contribution of the [O\textsc{iii}] emission in the unresolved nucleus so as not to cause an over-subtraction of the [O\textsc{iii}] in the process of subtracting the quasar light, i.e. the point source template (the star) is flux-matched to the point source in the [O\textsc{iii}] image and then scaled by 80\% to account for the [O\textsc{iii}] contribution.

For the Galfit PSF subtraction, the standard star was used as the PSF model in the Galfit program to create a model (middle image in figure 4.11) which was then subtracted from the original to reveal the [O\textsc{iii}] distribution. The Sersic component is intended to model the galaxy light. Since the galactic component is negligible compared to the nucleus and the [O\textsc{iii}] emission, a galaxy component (Sersic) was not used in the Galfit model for the entire image but rather only confined to the nuclear region of the galaxy. A model was also made without using the Sersic component and it did not make a significant difference to the model and the residual [O\textsc{iii}]
4.3.2 Results of HST image analysis

Both the manual subtraction as well as the Galfit modeling produced similar distributions of the [O\textsc{iii}] emission after PSF subtraction as seen in figures 4.10 and 4.11. It is apparent from the residuals that the [O\textsc{iii}] emission is asymmetric with an excess in the North-West direction. There is a thick arc that extends up to $\sim 0.5 - 0.6$ arcseconds (2.3 - 2.7 kpc) from the center of the galaxy in the East - North - West direction. There is a secondary arc of clumpy [O\textsc{iii}] emission that extends up to $\sim 0.9 - 1.2$
Figure 4.11: PSF subtraction using Galfit. From left, the first panel shows the FR656N ramp filter [OIII], the middle panel shows the Galfit model and the last panel shows the Galfit residual showing the OIII asymmetry after subtraction of the point source. The direction is the same as in Figure 4.9.

arcseconds (4.1 - 5.5 kpc) in the North-East to North direction.

4.4 Spectroastrometry modeling

Since the spectroastrometry results obtained from the Gemini data revealed an offset in the [OIII] emission, it is necessary to test whether the asymmetric [OIII] emission (as seen in the HST image analysis in section 4.3) can be responsible for the observed displacement. We used HST [OIII] image combined with the spectra of the nucleus and extended [OIII] emission extracted from the Gemini data, to construct a simulated spectroastrometry observation, in order to determine if the asymmetric distribution of the [OIII] can account for the displacements measured from the Gemini data.

A three dimensional array was created by combining the FR656N [OIII] image with the Gemini spectra, where the third dimension is the wavelength. Each pixel of the image is assigned one of the spectra which is scaled to the pixel flux. For the unresolved nuclear region in the image, represented by point spread function (PSF) (~7 pixels radius which is approximately the size of the first airy ring, as denoted by the blue circle in Figure 4.13), the normalized nuclear spectrum was used. The optical spectrum was extracted from a 1 arcsec aperture which is three times bigger than the PSF. We estimate that 90% of the [OIII] emission in the extraction aperture is unresolved in the HST image (i.e., it comes from the central 7 pixels). The [OIII] and H$\beta$ narrow lines are fitted and subtracted from this spectrum. So, the nor-
Figure 4.12: Spectra used in the spectroastrometry modeling. The top panel shows the spectrum extracted from a 1 arcsec aperture centered on the nucleus. The [O\textsc{iii}] and narrow H\textbeta lines have been fitted and subtracted so that this spectrum just shows the quasar continuum and the broad emission lines. The middle panel shows the model fitted to the [O\textsc{iii}] lines. The bottom panel shows the spectrum extracted from an extended region outside the nucleus.
Figure 4.13: Approximate annuli used for the spectroastrometric simulations. The inner blue circle shows the nuclear region to enclose the PSF. The normalized [OIII] spectra is used for the annulus enclosed between the red and blue circle. The extended spectra is used for the region beyond the red circle.
Figure 4.14: Spectroastrometric analysis. The top and third panels show the reconstructed spectrum of the quasar extracted from the spectroastrometry modeling simulations. The second and bottom panels show the simulation of spectroastrometric displacement spectrum where you see the expected displacement. Second panel: the slit is along North-South Direction. Bottom panel: Slit is long West - East direction.
malized nuclear spectra that is used for the quasar nucleus was obtained by combining the subtracted nuclear spectrum (top panel of Figure 4.12) with 90% of the spectrum constructed from the fits to the [OIII] and narrow Hβ lines, to match the relative [OIII] line strength in the nucleus. The normalized [OIII] and Hβ spectrum (middle panel in Figure 4.12) was applied to a circle of ~ 30 pixels which is approximately equivalent to an aperture of 1 arcsec (excluding the nuclear region). This region (represented by the annulus between the red and blue circles in Figure 4.13) encompasses most of the extended [OIII] emission around the quasar. This also falls within the aperture of the Gemini observations (~ 1 arcsec). Finally, the extended [OIII] emission beyond the central arcsecond, (the region beyond the red circle in Figure 4.13) was represented by a spectrum extracted from a 1 arcsec aperture offset by 1 arcsec away from the nucleus (bottom panel in Figure 4.12). This spectrum is obtained from a distance 1 arcsec away from the nucleus and is resolved in the Gemini observations.

This data cube is convolved with a Gaussian profile representing the typical seeing conditions for the Gemini observations and a simulated 2-D long-slit spectrum is extracted both in the North-South and West-East directions. Spectroastrometric measurements were then performed just as for the original spectrum by fitting Gaussians along the spatial direction for each wavelength (figure 4.14). We obtain a relative displacement of ~ 5.5 - 9 mas for the [OIII] lines. This is much less than the displacement measured directly from the Gemini data which is ~ 40 - 60 mas. This result shows that the measured spectroastrometric displacement cannot be entirely explained by the asymmetric spatial distribution of the narrow line emission. This suggests that gravitational recoil can have caused the remaining displacement that was observed in the Gemini data.

4.5 Discussion

After subtracting the quasar point source, the resulting [OIII] emission distribution is visibly asymmetric in the East - North - West direction in a wide arc extending from the center to ~ 0.5". There is a secondary fainter region of extended [OIII] emission in the form of clumps at ~ 1" in the North to North-East direction.

The Gemini spectra reveals that there is an offset of upto ~ 90 mas
Conclusions

(after continuum correction) in the North-West direction and the analysis of the HST images also reveal that the $[\text{O} \text{III}]$ emission is asymmetric in approximately the North-West direction as can be seen in figures 4.10 and 4.11. This suggests that the displacement could be caused by the asymmetric $[\text{O} \text{III}]$ emission. No displacement is observed between the broad lines and the continuum. This is consistent with the continuum being dominated by the quasar nucleus.

The spectroastrometric simulations were conducted to analyze whether the $[\text{O} \text{III}]$ asymmetric emission could account for the entire offset as observed in the Gemini spectroastrometric data. The simulations revealed that the displacement obtained by combining the HST images with the Gemini Spectra is $\sim 25\%$ of the measured displacement so about 4 times smaller than the observed displacement. This suggests that the asymmetric $[\text{O} \text{III}]$ is not solely responsible for the observed displacement.

The quasar E1821+643 is a very strong point source which completely dominated the light of its host galaxy. As a result, we cannot use the method described in chapter 2 to determine the spatial offset of the AGN.

This result, combined with the spectropolarimetry, provides a convincing argument for the observed displacement being due to a recoiling SMBH. The spectroastrometry modeling, on the other hand, reveals that the observed displacement in the $[\text{O} \text{III}]$ lines can only be partly attributed to the asymmetric emission region. We propose that the recoil hypothesis accounts for the remaining displacement of $\sim 40 - 60$ mas ($\sim 0.18 - 0.27$ kpc) between the AGN and the center of the host galaxy. This is also consistent with the estimated displacement of $\sim 200$pc by Robinson et al. (2010). They also argued that the recoil velocity vector should be roughly aligned with the radio axis in the N-W direction which is consistent with our results.

The BLR does not show a displacement relative to the continuum. This is consistent with the recoil hypothesis which suggests that the BLR and accretion disk remain bound to the recoiling SMBH.

4.6 Conclusions

The spectropolarimetry results in Robinson et al. (2010) show that the broad Balmer lines are redshifted and red-asymmetric with respect to the narrow lines in direct light and are conversely blueshifted and blue-asymmetric
in polarized light. They propose that this could be due to a recoiling SMBH which is moving towards a scattering screen causing a redshift in normal light and a blue shift in polarized light.

Gemini spectroscopy was obtained to find the corresponding spatial displacement to the observed velocity offsets. The spectroastrometric analysis revealed a displacement ($\sim 40 - 60$ mas) in [O\textsc{iii}] lines in approximately the East - North - West direction (PA $\sim 55$ $^\circ$).

The HST images obtained for E1821+643 reveal that the [O\textsc{iii}] extended emission is asymmetric in the North-West direction which in turn can contribute to the observed spectroastrometric displacement. Another extended arc is seen at $\sim 1$" in the North to North-East direction.

However, the simulations combining the HST images with the Gemini spectroscopy reveal that the [O\textsc{iii}] contribution to the displacement is actually much smaller ($\sim 25\%$) than the observed displacement. This suggests that since asymmetric [O\textsc{iii}] distribution is not solely responsible for the displacement, it could result from a recoiling SMBH in the quasar E1821+643.
In this chapter I shall highlight the summary and conclusions of the two projects that I worked on. Section 5.1 provides a recap of the scientific motivation that lead to the work described in this dissertation. Section 5.2 provides a summary of the final results obtained through the two projects. Section 5.3 describes the new knowledge established by this work. Section 5.4 describes the future prospects for the field in context of the work described in this dissertation.

5.1 Recap of scientific motivation

Galaxy mergers lead to the formation of supermassive black hole (SMBH) binaries and general relativity (GR) predicts that they eventually coalesce through the emission of gravitational waves. As a result of anisotropic gravitational wave emission, the merged SMBH receives a recoil kick and subsequently oscillates in the galaxy for \( \sim 1 \text{Gyr} \) (Gualandris and Merritt, 2008, Blecha et al 2016). These events are a strong test of gravitational physics and the merger frequency of binary SMBH. Gravitational wave signatures from coalescing SMBH fall outside the frequency range of the Laser Interferometer Gravitational-Wave Observatory (LIGO/VIRGO) and have not yet been detected through Pulsar Timing Arrays (PTA). Planned space-based detectors like LISA may in the future (10-20 years), detect gravitational wave signatures from merging SMBH binaries. However, recoiling SMBH
can, in principle, be detected now via electromagnetic signatures. The recoil oscillations cause the SMBH to be displaced from the center of the host galaxy. Gravitationally recoiling SMBH can be detected as spatial offsets between the AGN and the center of the host galaxy in high resolution optical or infrared images, or by comparing the x-ray position of the AGN with the galaxy center (from optical images). Recoil candidates can be identified via Doppler shifting (relative velocity) of emission lines from the gas retained by the SMBH post recoil. The incidence of recoiling SMBH and their recoil amplitudes depends upon a combination of the kick (recoil) velocity distribution, post-recoil oscillation damping time and the galaxy merger rate. Displaced SMBH are observable signposts of the formation and subsequent coalescence of SMBH binaries. Galaxy evolution suggests that SMBH binaries should be common, but very few have been found so far. This may be because they stall (i.e. never reaching the separation at which gravitational wave emission becomes important), but are just hard to find, or because once formed they undergo coalescence quickly. Statistical analysis of SMBH displacements with respect to galaxy properties may provide insight into the stalled SMBH binary population, dependence on SMBH spins and the implications of SMBH recoil for the host galaxy. Thus, studying displaced/binary SMBH will help us understand both galaxy and SMBH binary evolution better. Constraining SMBH merger rates will also provide observational constraints on predictions for LISA detection rates.

5.2 Results from this dissertation

5.2.1 Search for gravitational recoil in nearby elliptical galaxies

We have conducted a search for spatially displaced SMBH (as a tracer for gravitational recoil) by analyzing both archival and new Hubble Space Telescope images. We find robust displacements in six galaxies of the sample of 96 total galaxies. Chapters 2 and 3 present the analysis of the entire sample and the candidate recoiling SMBHs obtained from the study. Chapter 3 also discusses whether the observed displacements can be explained by mechanisms other than gravitational recoil. 5 of the 6 galaxies (3C 76.1, 3C 353, 3C430, M49 and NGC 3557) are core elliptical galaxies. Core ellipticals are predicted to form after a major merger due to the formation of an
Results from this dissertation

SMBH binary in the merged system. NGC 3557 does not have a jet while the other four have prominent jet activity. The measured displacements in 3C 76.1, 3C353 and 3C430 show a correlation between the jet axis and the displacement vector. This suggests that asymmetric jet power could be the cause for the measured displacement in these three cases (Refer to chapter 3 for further details). This however, does not rule out the recoil hypothesis.

NGC 3245 is a power-law galaxy that shows a robust displacement. Gravitational recoil is an unlikely cause for this displacement. The measured offset could have resulted due to a different mechanism such as massive perturbers in the center of the galaxy (refer to section 3.2.5 for more details).

Out of the sample of 96 galaxies, 51 were core ellipticals and 45 were power-law galaxies. The robust displacements in core galaxies account for \( \sim 10\% \) of the core galaxy sample.

5.2.2 E1821+643

The quasar E1821+643 has been identified as a recoil candidate through spectropolarimetry observations (Robinson et al., 2010). This dissertation discusses the Gemini spectroastrometry and HST images analyses to study the observed offset in the context of gravitational recoil and alternate displacement mechanisms. The Gemini spectroastrometry data shows a large spatial offset (\( \sim 40 - 60\)mas) in the North-West direction. The HST images (taken in the continuum, H\( \beta \) and [OIII] filters) reveal an intrinsic asymmetry in the spatial distribution of the [OIII] emission over a thick arc of \( \sim 0.5 - 0.6 \) arcseconds (2.3 - 2.7 kpc) in the North-West direction as well as an extended [OIII] emission arc out at a distance of \( \sim 0.9 - 1.2 \) mas (4.1 - 5.5 kpc) from the nucleus in the North-East to North direction.

The HST image data was combined with the Gemini spectroscopy data to simulate spectroastrometric observations to evaluate whether the measured displacement in the Gemini data can be attributed solely to the asymmetric distribution of the [OIII] emission. The spectroastrometric simulations reveal that the asymmetric [OIII] only accounts for \( \sim 25\% \) of the observed displacement.

Thus, the spectroastrometric simulations reveal that the asymmetric distribution of the resolved [OIII] accounts for only a fraction (\( \sim 25\% \)) of the observed displacement. This leaves open the possibility that the quasar nu-
cleus and hence the SMBH is spatially offset from the center of the galaxy. This, together with the velocity offset reported by Robinson et al. (2010), strengthens the case for gravitational recoil of the SMBH in E1821+643.

5.3 New knowledge established

5.3.1 Recoil candidates

As referenced in section 1.3.3, several recoil candidates have been identified through both spatial offsets and velocity offsets. However only a few (~10) have been reported to have parsec-scale spatial offsets consistent with Phase II oscillation amplitudes (Batcheldor et al., 2010; Lena et al., 2014; Menezes et al., 2014; Jones et al., 2019). There are ~5 other recoil candidates with kilo-parsec scale offsets (discussed in section 1.3.3 as well as E1821+643 a new recoil candidate). These can be associated to the larger amplitude Phase I initial oscillations. In addition there are ~20 other recoil candidates discovered through velocity offsets (Bonning et al., 2007; Eracleous et al., 2012; Blecha et al., 2013; Novak et al., 2015; Civano et al., 2010, 2012; Komossa et al., 2008; Shields et al., 2009; Steinhardt et al., 2012; Kalfountzou et al., 2017).

Through this study, we have established that statistically, spatial offsets between the photocenter of a galaxy and the AGN are preferentially observed in core galaxies than power-law galaxies. This favors the gravitational recoil hypothesis since the core is thought to form due to the presence of an SMBH binary. We present 6 robust gravitational recoil candidates as well as 3 dual nucleus candidates. Out of the 3 dual nucleus candidates, NGC 4473 has not been identified as a dual nucleus candidate before this work.

We have also discussed 3 recoil candidates that have the displacement vector approximately in the direction of the jet axis. This follows the Batcheldor et al. (2010) discussion on M87 where the displacement vector and the jet axis also line up. In these cases, asymmetric jet power is a possible cause for the observed displacement.

5.3.2 Quasar: E1821+643

In the case of E1821+643, we have presented the results of the Gemini spectroastrometry analysis as well as the results of the HST image analysis.
Future prospects

The Gemini and HST data were obtained to detect a spatial displacement corresponding to the velocity offset measured from the spectropolarimetry. The HST imaging observations were obtained to determine if the spectroastrometric displacement was due to an asymmetric spatial distribution of the [OIII] emission. This provides another alternate displacement mechanism for observed velocity offsets apart from a gravitationally recoiling SMBH. However, the spectroastrometric simulations reveal that the asymmetric [OIII] only accounts for 25% of the measured displacement suggesting that the recoil hypothesis is still a compelling argument to explain the velocity offset.

5.4 Future prospects

5.4.1 Identifying more recoil candidates

In order to identify more recoil candidates we need to expand our sample search. A new sample of early-type galaxies can be obtained by cross matching the archival Chandra observations with archival high resolution images of the HST deep fields such as those obtained for the CANDELS, COSMOS, GEMS, etc surveys (Grogin et al., 2011; Scoville, 2007; Caldwell et al., 2008). JWST IR observations will help with identifying recoil offsets in elliptical galaxies since JWST will have an angular resolution of 0.031 - 0.06 arcsec (for NIRCam) (Wright et al., 2015). For lower redshift galaxies a new sample can be created by cross matching X-ray sources with the SDSS galaxy catalog. This will provide an X-ray selected sample where the X-ray observations can be used to confirm the presence of an AGN in the galaxies. This has been previously done by Kim et al. (2017) who have identified a recoil candidate (CXO J101527.2+625911) through by crossmatching SDSS data with X-ray data from the Chandra X-ray telescope. Spatial offsets in the HST images can be obtained by comparing the position of the AGN, as identified by a point source (that can be fit with a Gaussian) to the photocenter of the galaxy (obtained from isophotal analysis) as described in this dissertation. X-ray and optical data can be used to compare the position of the AGN to the center of the galaxy at larger redshifts than those discussed in this dissertation, to search for larger spatial displacements. GALFIT (Peng et al., 2002) can be used to model the galaxies in the higher redshift sample. Modeling the galactic parameters such as central surface brightness, core radius, Sersic index, stellar mass (from Near-IR), along with morpho-
logical characteristics like boxiness or diskyness will give a better insight into the properties of the galaxy in the context of the displacements.

5.4.2 Relevance to gravitational wave detectors

Much theoretical effort has been expended to estimate the detection rates of gravitational wave signals from SMBH binaries for both Pulsar Timing Arrays and the proposed space-based detector, LISA (e.g., Amaro-Seoane et al. (2012); Sesana et al. (2012); Babak et al. (2016)). However, these estimates are entirely based on theoretical models and simulations. Measuring the incidence of recoiling SMBH in massive elliptical galaxies will place an upper limit on the SMBH binary coalescence rate. This will provide an empirical date point, which can be compared with theoretical models to constrain the estimated detection rates for LISA. Identifying the incidence of the SMBH binaries and merger rates with redshift will help in understanding the evolution of SMBH binaries as well as characterizing the properties of the host galaxy population.

5.4.3 Relevance to galaxy evolution

The formation and merger of close black hole binary systems has profound consequences for our understanding of the structure and evolution of galactic nuclei. Once confirmed, recoiling black holes are signposts of supermassive black hole binary mergers which are predicted to be very luminous gravitational wave sources. Although SMBH binaries and binary coalescence events cannot currently be detected via their gravitational wave radiation it is important to search for their electromagnetic signatures. The statistical analysis of recoiling SMBH systems will give us a better understanding of evolution of galaxies as well as allow us to put better constraints on galaxy merger rates, arguably one of the more uncertain quantities that determines the number of displaced SMBH to be observed. We can also use the results to study the dependence on galactic properties, dependence on alignment of SMBH spins and the implications of SMBH recoil for the host galaxy.


Bibliography


Bibliography


Bibliography


Bibliography


Bibliography


Bibliography


Bibliography


Massaro, F., Harris, D. E., Liuzzo, E., Orienti, M., Paladino, R., Paggi, A., Tremblay, G. R., Wilkes, B. J., Kuraszkiewicz, J., Baum, S. A., and


Bibliography


Bibliography


Bibliography


