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Aspects of Supermassive Black Hole Growth in Nearby Active Galactic Nuclei

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ASPECTS OF SUPERMASSIVE BLACK HOLE GROWTH IN NEARBY ACTIVE GALACTIC NUCLEI

A Search for Recoiling Supermassive Black Holes
Gas Kinematics in the Circumnuclear Region of Two Seyfert Galaxies

DAVIDE LENA

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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April, 2015
*Cover image:* flux map for the [NII]λ6583 emission line in the nuclear region of the Seyfert galaxy NGC 1386. The map was derived from integral field observations performed with the Gemini Multi Object Spectrograph on the Gemini-South Observatory.
The Ph.D. Dissertation of DAVIDE LENA has been approved by the undersigned members of the dissertation committee as satisfactory for the degree of Doctor of Philosophy in Astrophysical Sciences and Technology.
An astronomer walks into a bar,
and he is dragged toward the center of the galaxy.

To my lovely girlfriend.
Super-massive black holes (SBHs) have long been identified as the engines of active galactic nuclei (AGNs) and are now considered to play a key role in galaxy evolution. In this dissertation I present results from two observational studies conducted on nearby AGNs with the aim of furthering our understanding of SBH growth and their interplay with the host galaxies.

The first study is an observational search for SBHs spatially offset from the center of their host galaxies. Such offsets can be considered signatures of gravitational recoil following the coalescence of an SBH binary system (formed in the aftermath of a galaxy merger) due to emission of gravitational waves. The study is based on a photometric analysis of fourteen nearby elliptical galaxies observed with the Hubble Space Telescope. I find that parsec-scale offsets are common. However, while these are individually consistent with residual gravitational recoil oscillations, there is a high probability that larger offsets than those actually observed should have been found in the sample as a whole. There are a number of possible explanations for this result: the galaxy merger rate may be lower than current estimates; SBH-binaries may reach the merger stage with a configuration which minimizes recoil velocities; or the SBH oscillations are more quickly damped than predicted.

In the second study I use integral field spectroscopy obtained with the Gemini South telescope to investigate the kinematics of the circum-nuclear ionized gas in two active galaxies: NGC 1386, a Seyfert 2, and NGC 1365, a Seyfert 1. The goal of the study is to investigate outflows in low-luminosity AGNs, and the mechanisms channeling gas (the SBH fuel) from the inner kiloparsec down to a few tens of parsecs from the SBH. I find that the dominant kinematic components can be explained as a combination of rotation
in the large-scale galactic disk and compact outflows along the axis of the AGN “radiation cone”. However, in the case of NGC 1386, there is also compelling evidence for an equatorial outflow, which provides a new clue to the physical processes operating in AGNs.

**Keywords:** (recoiling) supermassive black holes, active galaxies, gas kinematics, integral field spectroscopy, individual galaxies: NGC 1386, 1365.
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I, Davide Lena ("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 April 17, 2015.

Modified portions of this dissertation have previously been published by the Author in peer-reviewed papers appearing in The Astrophysical Journal (ApJ). A few sections have been adapted from a tutorial made publicly available on the online repository arXiv.org. Details on these papers are provided below.


- **Chapter 3** contains sections adapted from the tutorial Lena (2014), entitled *Reduction of Integral Field Spectroscopic Data from the Gemini Multi-Object Spectrograph (a commented example)*. ArXiv e-prints: 1409.8264.

- **Chapter 4** is based on the paper Lena et al. (2015), entitled *The complex gas kinematics in the nucleus of the Seyfert 2 galaxy NGC 1386: rotation, outflows and inflows* (2015, ApJ, 806, 84), co-authored by
I am deeply grateful to my adviser, Andrew Robinson, for his careful and patient guidance over the last five years. I am also greatly indebted to my collaborators and mentors: David Merritt, Thaisa Storchi-Bergman, Rogemar Riffel, Alessandro Marconi, Sandro Capetti, Allan Schnorr-Müller, Daniel Batcheldor, and Neil Nagar. Among them, I would like to remember Dave Axon, whom I have had the luck to know before his untimely passing.

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It is likely that this dissertation would never have been written had I not met Sebastiano Pellicari and Michele Scaffidi, who mentored and fostered my early interest in the Natural Sciences, and Astronomy in particular. However, it is certain that this dissertation would never have been written without the support, patience, and love from my girlfriend and my large family. They gave me a firm reference frame as to where to unfold my life, sharing the burdens which came with my journey.
1. *The complex gas kinematics in the nucleus of the Seyfert 2 galaxy NGC 1386: rotation, outflows and inflows.*


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In this dissertation I present two observational studies of nearby active galactic nuclei (AGNs). The first is a search for recoiling supermassive black holes (SBHs), that is SBHs that received a “kick” due to the anisotropic emission of gravitational waves during the merger of an SBH-binary. The second is a study of the ionized gas kinematics in the nuclear region of the Seyfert galaxies NGC 1386 and NGC 1365. The study of these two galaxies is part of a larger program which aims to investigate the mechanisms that drive gas in, and out of, the vicinity of SBHs in a sample of low-luminosity AGNs.

In this chapter I provide the reader with the background that is necessary to place this work in the broader context of modern Astrophysics. In Section 1.1 I outline the reasoning and the observational evidence that led us to consider SBHs as standard components of galactic nuclei. In Section 1.2 I introduce the concept of activity in galaxies and the “AGN unification model”, a configuration for the nuclear region of active galaxies which explains a wide variety of phenomena on the basis of the SBH accretion rate, spin, and the relative orientation of the nucleus with respect to the observer.

Nuclear activity or, equivalently, the SBH accretion rate, influences the evolution of the host galaxy. This is believed to be due to mechanisms of AGN feeding and feedback, or gas inflows and outflows to and from the SBH. These processes, which I investigated in the work presented in Chapters 3, 4, and 5 are discussed in Section 1.3. Although gas accretion and outflows
provide a channel through which the galaxy and the SBH can communicate and co-evolve, both galaxies and SBHs can also increase their masses through mergers, an important mechanism within the popular “lambda cold dark matter” (ΛCDM) cosmological model. The merger of galaxies hosting SBHs leads to the formation of SBH-binaries, which very likely coalesce in a relatively short time. During the last stages of the coalescence, when the binary reaches separations of the order of 1 milliparsec, the binary orbital energy is radiated away in the form of gravitational waves. This emission is anisotropic because of asymmetries in the system, and as a result, a “kick” is imparted to the coalesced supermassive black hole. This process is introduced in Section 1.4 and it is the main subject of Chapter 2. The chapter synopsis is given in Section 1.5.

### 1.1 Supermassive black holes

Supermassive black holes, exotic compact objects with masses in the range $10^6 \leq M_\bullet \leq 10^9$ solar masses ($M_\odot$), have long been proposed as the engines of active galactic nuclei. The presence of an SBH in the nucleus of a galaxy explains a number of observables, for example: the release of gravitational energy during gas accretion on the SBH provides a straightforward explanation for the astonishing bolometric luminosities observed in AGNs (Lynden-Bell 1969); gas clouds orbiting at sub-parsec radii around the SBH explain the presence of broad emission lines (full-width at half maximum, FWHM, as high as 5000 km s$^{-1}$) and rapid flux variability (e.g. Peterson 1997); energy extraction from spinning SBHs is believed to power the radio jets extending as far as thousands of kiloparsecs from the center of the host galaxy (e.g. Blandford and Znajek 1977, Williams 1995); the kinematics of stars and/or gas in the nuclei of a handful of nearby galaxies imply the presence of SBHs (e.g. Macchetto et al. 1997, Moran et al. 1999, Bacon et al. 2001b).

SBHs are firmly established as the engines of active galaxies, but there is compelling evidence that they are present in the nuclei of non-active galaxies as well. In the late 1960’s Maarten Schmidt showed that the number of quasars per unit volume is not constant with redshift (Schmidt 1968, 1970). Later studies showed a peak in quasar density near redshift $z \approx 2$ (e.g. Shaver et al. 1996 and references therein). If quasars are powered
by gas accretion onto SBHs, then these observations imply that the present Universe is populated by dormant SBHs. In other words, non-active galaxies host SBHs in their nuclei. Observations are indeed consistent with the view that most or all galaxies with stellar masses, $M_\star$, in excess of $10^9 M_\odot$ contain supermassive black holes [Ferrarese and Ford, 2005]. From the full orbit of a star close to the center of the Milky Way (the S2 star), it has been inferred that our own galaxy hosts a supermassive black hole with mass $M_\bullet = 4.3 \times 10^6 M_\odot$ (e.g. Gillessen et al., 2009).

In recent years, intriguing evidence has been presented of the existence of massive black holes even in the nuclei of dwarf galaxies (that is, galaxies with stellar masses in the range $10^8 \lesssim M_\star / M_\odot \lesssim 10^9$). For example, out of approximately 25000 galaxies from the Sloan Digital Sky Survey (SDSS), Reines et al. (2013) identified AGN-like photoionization in 151 galaxies, some of which also show signs of a broad H\textalpha emission line. For their AGN candidates they estimated BH masses in the range $10^5 - 10^6 M_\odot$ (these are often referred to as “intermediate-mass black holes”, or IBHs). While further data are necessary to unambiguously determine whether IBHs really reside in those nuclei, the result adds to the evidence that massive black holes are ubiquitous in the centers of galaxies, perhaps even in the less massive ones.

1.2 The AGN unification model

By the 1970’s, the accumulated evidence for non-stellar processes occurring in galactic nuclei had led to the need to introduce a new class of objects, which became known as “active galactic nuclei”, or “AGNs”. Galaxies hosting an active nucleus are often referred to as “active galaxies”.

AGNs emit over the whole electromagnetic spectrum (from $\gamma$-ray to radio wavelengths) featuring visual luminosities that can reach $10^{46}$ erg s$^{-1}$ (e.g. the quasar 3C 273) or higher, radio luminosities as high as $10^{44}$ erg s$^{-1}$ (e.g. the radio galaxy Cygnus A), and a wide range of other distinctive characteristics: a nuclear point source which can outshine, in the most extreme cases, the host galaxy (e.g. Bahcall et al., 1997); broad emission lines either in direct or polarized light (e.g. Antonucci and Miller, 1985); strong narrow emission lines with characteristic flux ratios (e.g. Baldwin et al., 1981; Kewley et al., 2006); radio emission which can be compact and localized at the nucleus, or extended, in the form of halos, lobes, or jets.
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(e.g. Perley et al., 1984; O’Dea and Owen, 1986); flux enhancement at short optical wavelengths (e.g. Vanden Berk et al., 2001); rapid flux variability and polarization at multiple wavelengths (e.g. Stein et al., 1976; Zamorani et al., 1984); soft and hard X-ray emission (e.g. Elvis et al., 1978; Danese et al., 1986; Shanks et al., 1991).

As the features outlined above appear at different relative strengths, active galaxies have been classified into many different types including Seyfert galaxies, radio galaxies, quasars, QSOs (radio-quiet quasi-stellar objects), LINERs (Low-Ionization Nuclear Emission-line Regions), and blazars. However, it has since been realized that all AGNs can be understood as manifestations of the gravitational potential energy released by matter accreting on an SBH (Rowan-Robinson, 1977; Neugebauer et al., 1980; Lawrence and Elvis, 1982, 1984; see Antonucci, 1993 for an early review). The observed diversity arises largely from (1) different luminosity, which is governed by the SBH mass and accretion rate; (2) the fraction of energy which is either released in the form of radiation, or transported away by a relativistic jet (this in turn depends on the SBH spin); and (3) the orientation of this “engine” to the observer’s line of sight.

While many variants of the model have been proposed, today the general consensus is that it should include the following key elements: an SBH accreting gas from a surrounding accretion disk (the disk is responsible for thermal emission, from EUV to NIR, which is identified with the “big blue bump” in the spectral energy distribution of AGNs); a hot corona, which is located above the accretion disk and responsible for the X-ray continuum; a broad line region (BLR), that is a distribution of clouds located close to the SBH (on milliparsec scales), photoionized by the radiation from the AGN accretion disk (“the AGN continuum”), and responsible for the broad emission lines; an equatorial obscuring structure (“the torus”), probably a distribution of dusty molecular gas clouds, which blocks out the view of the broad line region and the accretion disk from certain viewing angles; the narrow line region, a distribution of low-density clouds (\(n_e \sim 10^{2-3}\) electrons cm\(^{-3}\)) ionized by the AGN continuum, extending as far as a few kiloparsecs from the SBH, and responsible for the narrow emission lines; radio jets approximately perpendicular to the accretion disk. An illustration of these elements is given in Fig.1.1. Recent reviews on the unification model and its components have been presented in Ho (2008) and Netzer (2015).
Table 1.1: APPROXIMATE AGN SPACE DENSITY “HERE AND NOW”

<table>
<thead>
<tr>
<th>Type</th>
<th>Number (Mpc$^{-3}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Field galaxies</td>
<td>$10^{-1}$</td>
</tr>
<tr>
<td>Luminous galaxies</td>
<td>$10^{-2}$</td>
</tr>
<tr>
<td>Seyfert galaxies</td>
<td>$10^{-4}$</td>
</tr>
<tr>
<td>Radio galaxies</td>
<td>$10^{-6}$</td>
</tr>
<tr>
<td>QSOs</td>
<td>$10^{-7}$</td>
</tr>
<tr>
<td>Quasars</td>
<td>$10^{-9}$</td>
</tr>
</tbody>
</table>

Note. — This is a reproduction of Table 13.1 from Osterbrock and Ferland (2006).

According to this model, a Type 2 Seyfert (that is a Seyfert galaxy lacking broad emission lines in the optical spectrum) is observed edge-on, so that the torus prevents a direct view of the BLR. However, the same Seyfert would appear as a Type 1 (that is showing broad emission lines) to a hypothetical observer located closer to the torus axis, from which direction the view of the BLR is not blocked by the torus.

Only a small fraction of galaxies shows signs of activity. Table 1.1, a reproduction of Table 13.1 from Osterbrock and Ferland (2006), shows the approximate space density of AGNs “here and now”. A comparison between the mass function of active and inactive SBHs at redshift $z < 0.352$ has been presented in, e.g., Greene and Ho (2009): for $10^7$ M$_\odot$ black holes, they estimated that the space density of active SBHs is a factor of 170 lower than the space density of inactive SBHs. However, the AGN space density is a function of redshift, environment, and other properties of the host galaxy.

For example, Haggard et al. (2010) found that the fraction of AGNs in field galaxies with absolute $i$-band magnitude in the range $-18 \leq M_i \leq -23$ is consistent with a redshift evolution proportional to either $(1 + z)^3$ or $(1 + z)^4$ for $0.0025 \leq z \leq 0.7$. Although these studies are still affected by large uncertainties, it is clear that the number of AGNs was higher in the past with a peak near $z \sim 2$ (e.g., Shaver et al. 1996, Miyaji et al. 2015).

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1In this context, the mass function gives the number of SBHs in a given mass bin per unit volume.
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Figure 1.1: Schematic representation of the central engine of an active galactic nucleus (not to scale, adapted from Fig.1 in [Urry and Padovani 1995]). A supermassive black hole (SBH) accretes gas from a disk. The broad line region (BLR) – a distribution of clouds orbiting close to the SBH – produces the broad emission lines visible in the optical spectra. An equatorial obscuring structure (“the torus”) blocks the view of the accretion disk and the BLR to observers located far from the torus axis. A corona, consisting of hot plasma, is responsible for the X-ray emission. Low density clouds, distributed on 10 - 1000 pc scales, make up the narrow line region (NLR). These clouds are photoionized by the AGN continuum producing narrow emission lines. Depending on the SBH spin, relativistic radio-emitting jets might be present.
1.2.1 What is the torus?

In Chapter 4 I will discuss the kinematics of the gas in the nucleus of the Seyfert galaxy NGC 1386 where we found evidence for a kinematical feature consistent with rotation and/or outflow about the axis of the AGN radiation cones, in other words, in the plane of the putative torus. We argue that the feature could be related to the torus itself which, it has been suggested by some authors (e.g. Keating et al., 2012), might take the form of a wind of dusty clouds. It is therefore of interest to outline our current understanding of this elusive component of the AGN unification model.

About forty years since the idea of a circumnuclear torus was conceived, the questions of its nature and origin remain lively research topics. One of the most significant pieces of evidence for an obscuring torus came from optical spectropolarimetric observations of the galaxy NGC 1068: while the optical spectrum showed only narrow emission lines, the polarized component was characterized by the presence of broad permitted lines suggesting that an obscuring medium (some dust distribution) was hiding the nucleus from direct view (Antonucci and Miller, 1985). Shortly afterwards, Krolik and Begelman (1986) proposed a model for NGC 1068 where the obscuring medium had a torus-like geometry consisting of a distribution of optically thick molecular clouds, with a inner radius of 1 pc and a hot wind driven from the inner edge of the torus by photoionization and Compton heating.

Since then, an array of models have been proposed to explain obscuration of galactic nuclei. For example: Sanders et al. (1989) proposed that obscuration in AGNs was due to a large-scale geometrically-thin warped disk. Pier and Krolik (1993) proposed a model for NGC 1068 where a compact torus was embedded in a larger, more diffuse structure extending up to few tens of parsecs; in addition, for a sample of Seyfert 1, Seyfert 2 and radio-quiet quasars, they proposed compact (≲ few pc) tori with high optically depth \( \tau_{UV} \gtrsim 1000, \tau_{10\mu} \gtrsim 10 \). However, for a sample of Seyferts 1, Granato and Danese (1994) proposed thick and extended tori, as large as a few hundreds of parsecs, with an optical depth \( \tau_{UV} \gtrsim 30 \). While the models outlined above assumed a continuous dust distribution, clumpy torus models were also further developed (e.g. Nenkova et al., 2002; Hönig et al., 2006; Nenkova et al., 2008a,b; Schartmann et al., 2008) with versions including clumps immersed into a continuous dust distribution or clumps merging to form a sponge-like structure (Stalevski et al., 2012). A substantially different class of mod-
els posit that AGN obscuration is due to dust embedded in hydromagnetic winds (e.g. Konigl and Kartje 1994; Wada 2012; Dorodnitsyn and Kallman 2012).

As radiation from the AGN is reprocessed by dust and emitted in the mid-infrared (MIR), the torus is also believed to play a key role in determining the shape of the spectral energy distribution (SED) of active galaxies. Indeed, the MIR bump visible in some SEDs is attributed to it. It is therefore reasonable to think that SED modeling should help to distinguish between the various torus models. With this goal in mind, Feltre et al. (2012) compared the performance of two widely used models: the smooth-distribution model by Fritz et al. (2006) and the clumpy-distribution model by Nenkova et al. (2008a). However their conclusion is that the resulting SEDs are mostly affected by assumptions relating to dust grain properties (such as the dust chemical composition) rather than the large-scale dust distribution.

Observational investigations of AGN tori have proved challenging, which might be an indication that, when present, they are indeed compact. Perhaps the best direct view of a torus has been obtained with interferometric mid-infrared observations of NGC 1068. Jaffe et al. (2004) showed the presence of a two-component nuclear dust distribution: a warm one, with temperature $T \approx 320$ K, extending 1.7 pc in radius and 2.1 pc thick, and a inner hot component characterized by a temperature $T > 800$ K. Similar results have been found for the Circinus galaxy (e.g. Tristram et al., 2007, 2014).

Estimates of the torus half-opening angle have been made from imaging of the ionization cones in Seyfert galaxies (e.g. Evans et al., 1991; Storchi-Bergmann et al., 1992) producing values in the range $30^\circ - 50^\circ$, consistent with the value inferred from the ratio of obscured versus non-obscured AGNs (e.g. Lawrence, 1991; Osterbrock and Martel, 1993; Schmitt et al., 2003b). Meanwhile, evidence has been amassed at different wavelengths that the properties of the torus (such as inner radius, and covering factor) depend on the AGN luminosity. For example, the inner radius is set by the dust sublimation radius, which is proportional to $L^{1/2}$ (Barvainis, 1987). To test this
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prediction, a number of authors estimated the inner radius of the torus via near-infrared K-band (2.2 \( \mu m \)) reverberation mapping (sublimating dust, at temperatures in the range 1200 - 1800 K, emits at such wavelengths). They found values in the range 0.01 - 1 pc and a proportionality between radius and luminosity which is consistent with the expected \( r \propto L^{1/2} \) relation (e.g. Oknyanskij and Horne, 2001; Minezaki et al., 2004; Koshida et al., 2014). In the “receding torus model” the opening angle increases at higher luminosities as the inner radius recedes (Lawrence and Elvis, 1982; Lawrence, 1991; Grimes et al., 2004; Simpson, 2005; Gandhi et al., 2009; Ueda et al., 2011). Even the very existence of the torus is believed to depend on the AGN luminosity. For example, when modeling the torus as a clumpy wind originating from the accretion disk, Elitzur and Shlosman (2006) proposed that the torus forms when the AGN bolometric luminosity increases above \( \sim 10^{42} \text{ erg s}^{-1} \). 

In summary, there is no doubt that our view of the very heart of some AGNs is blocked by an intervening compact distribution of dust. It is clear that at least approximately it is characterized by cylindrical symmetry and reflection symmetry with respect to the equatorial plane, with an inner radius which might be as close as 0.01 pc from the SBH. However, a number of aspects are still to be clarified: which is the morphology of “the torus”? And how does it change for different AGNs? How is the dust distributed within the torus? Which physical mechanisms generate and maintain its structure? How large is the outer radius? What is its dynamical state? The high resolution integral field spectroscopy presented here provides some interesting insights into the geometry and structure of the torus in NGC 1386.

As anticipated at the end of the previous section, a kinematical feature that might be associated with the torus of NGC 1386 is discussed, along with other kinematical features, in Sections 4.5 and 4.6. A summary of what we learned about the structure of active galactic nuclei from the study of NGC 1386 and NGC 1365 is given in Section 6.2.4.
1.3 AGN feeding and feedback

Several relationships have been observed between the SBH mass and properties of the host galaxy, such as bulge luminosity \cite{Magorrian1998, Gültekin2009}, stellar velocity dispersion \cite{Ferrarese2000}, infrared luminosity \cite{Marconi2003, Sani2011}, and the total mass of globular clusters \cite{Burkert2010}. The origin of such relations could be rooted in a statistical convergence driven by galactic mergers \cite{Jahnke2011}, they could arise partly from selection effects \cite{Batcheldor2010, Schulze2011}, or may be due to the co-evolution of the SBH and the galaxy itself \cite{Heckman2014}. The latter is the most fascinating hypothesis and also the most investigated. But, how does the SBH communicate with the rest of the galaxy? The general answer is: via gas accretion (which requires inflows, or feeding processes), and winds or jets (in other words, outflows, or feedback processes).

I will dedicate the next two subsections to a discussion of the general aspects of inflows and outflows, presenting the features predicted by simulations, the essential physics proposed to explain such phenomena and, last but not least, the picture which is emerging from the observation of nearby AGNs.

1.3.1 Inflows

As discussed in Section \ref{sec:inflows}, gas accretion onto an SBH has a fundamental role in the physics of AGNs: it is their very source of energy. Assuming a mass-to-energy conversion efficiency of 10%, accretion rates as low as $10^{-4} \, M_\odot \, \text{yr}^{-1}$ are sufficient to power AGNs with luminosities of the order of $10^{42} \, \text{erg s}^{-1}$ \cite{Peterson1997}, however, despite the large amounts of gas present in galaxies, only a fraction of them are active. This is because, to transfer gas from a radius of 10 kpc down to 10 pc from the SBH, about 99.9% of its original angular momentum must be removed \cite{Jogee2006}. This requires the presence of a chain of efficient dissipative mechanisms. At the time of writing, the identification of such mechanisms is the goal of a very active research field involving both theorists and observational astronomers. Reviews of the subject have been presented in, e.g., \cite{Shlosman1990};
Traditionally, inflow triggers have been classified into two families: extrinsic and intrinsic (e.g. Shlosman et al., 1990). The extrinsic, or external, include interactions between galaxies, such as flybys and mergers. The intrinsic, or internal, include, for example, the formation of a bar, and they are associated with the secular evolution of a galaxy, i.e. the slow dynamical evolution which is not influenced by interactions with close companions; they are therefore characteristic of isolated galaxies. What all these features have in common is that they are associated with non-axisymmetric potentials.

Already in the 1980’s it was clear that different mechanisms are effective in the removal of angular momentum at different scales: close encounters and galactic mergers (extrinsic mechanisms) have been identified as capable of driving gas from large scales (10 kpc) down to the inner kiloparsec (e.g. Hernquist, 1989; Di Matteo et al., 2005; Springel et al., 2005a,b; Hopkins et al., 2006). Stellar bars (which can be tidally induced by the merger or due to the secular evolution of an isolated galaxy) are also important non-axisymmetric features capable of funnelling gas from a few kiloparsecs down to within a few hundreds of parsecs from the SBH (e.g. Shlosman et al., 1989; Friedli and Martinet, 1993; Englmaier and Shlosman, 2004). When a bar is present, gas flows typically stall at the inner Lindblad resonance, where gas accumulates, resulting in rings of gas (e.g. Jogee et al., 2001) or star formation regions (e.g. Pérez-Ramírez et al., 2000). Simulations presented in Hopkins and Quataert (2010) suggest that, in gas-rich systems, on scales of $\sim 10 - 100$ pc, inflows are achieved through a system of nested gravitational instabilities, similar to the bars-within-bars scenario discussed earlier by Shlosman et al. (1989), but with a range of morphologies, such as nuclear spirals (including one- and three-armed spirals), bars, rings, barred rings, clumpy disks and streams.

Observations support the hypothesis that large-scale bars funnel gas toward the center of galaxies (e.g. Crenshaw et al., 2003a). Imaging has revealed that structures such as small-scale disks or nuclear bars and associated spiral arms are frequently observed in the inner kiloparsec of active galaxies (e.g. Erwin and Sparke, 1999; Pogge and Martini, 2002; Laine et al., 2003). The most common nuclear structures are dusty spirals, estimated to reside in more than half of active galaxies (Martini et al., 2003). A strong
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correlation between the presence of nuclear dust structures (filaments, spirals and disks) and activity in galaxies has also been reported in Simões Lopes et al. (2007). This correlation between dust structures and activity, along with the enhanced frequency of dusty spirals, supports the hypothesis that nuclear spirals are a mechanism for fueling the SBH, transporting gas from kiloparsec scales down to within a few tens of parsecs of the active nucleus.

In recent years 2D spectroscopy of nearby AGNs has provided a direct view of the processes of AGN fueling on scales in the range ∼10 - 100 pc. For instance, Knapen et al. (2000) reported features consistent with gas inflowing along the inner part of a bar and along a two-armed spiral in the core of M100. Evidence for gas inflows along nuclear spirals was also found in NGC 1097 (Fathi et al., 2006). Müller Sánchez et al. (2009) found evidence for gas streaming in the plane of the Seyfert 2 galaxy NGC 1068, connecting the outer gas ring (r ≈ 70 pc) to the inner maser disk (r ≈ 1 pc) with a mass inflow rate of 15 M⊙ yr⁻¹. Evidence for gas inflowing along a nuclear spiral was found with ALMA observations of NGC 1566 (Combes et al., 2014). Davies et al. (2014) studied the H₂ kinematics in a matched sample of five active (Seyfert 1.5 - 2) and five inactive galaxies observing, in the active galaxies, complex kinematics interpreted as a combination of gas inflow, outflow and disk rotation. Where inflow was separable from outflow, the kinematics were consistent with inflows due to bars and nuclear spirals; circumnuclear molecular disks were observed in all of the active galaxies but in only two of the inactive ones.

To summarize, it is now clear that a chain of mechanisms is required to remove angular momentum from the gas, and thus drive it toward the galaxy center where it can be accreted by the SBH. Current spectroscopic facilities achieve a spatial resolution of a few parsecs at the best, for the closest galaxies; more typically, for nearby galaxies, the spatial resolution is in the range 10 - 100 pc. This allowed the identification of a number of kinematical features similar to those produced by simulations, such as inflows along nuclear spirals and bars, however the kinematics in the nuclear region of active galaxies often produce extremely complex spectral features preventing robust and definitive conclusions. It seems fair to say that our understanding of the processes that feed SBHs is just coming out of its infancy.
1.3.2 Outflows

Shortly after the discovery of quasars, astronomers identified peculiar blueshifted absorption lines in their spectra (e.g. Stockton and Lynds 1966; Lynds 1967). They were interpreted as evidence for “expanding envelopes”. In other words, gas outflows. Soon, studies of large samples showed that blueshifted lines were a common feature of quasars (e.g. Weymann et al., 1979) and it became clear that higher ionization species were more blueshifted than the low-ionization ones (e.g. Gaskell 1982). Recent studies suggest that 60% of AGNs, almost independently of their luminosity, host outflows (Ganguly and Brotherton 2008).

Outflows, which are a form of AGN-driven feedback, include winds and radio jets (e.g. Fabian 2012; Heckman and Best 2014). Winds are associated with radiatively efficient systems, such as Seyferts and quasars, where the SBH has a high accretion rate. Such an AGN state is often referred to as “quasar-mode”. Radio jets are instead mostly associated with massive elliptical galaxies where the accretion flow is radiatively inefficient and the SBH accretion rate is low, well below the Eddington limit. This is the so-called “radio-mode”. Because of their relevance to the work presented in this dissertation, I will focus on the winds only.

A number of models have been proposed to explain the launching of winds. Crenshaw et al. (2003b) divide them in four groups, according to the accelerating mechanism: Compton heated winds, radiatively driven flows, hydromagnetic flows, and hybrid models.

**Compton heated winds** originate from the interaction between the hard radiation from the AGN and the accretion disk: X-ray and extreme UV radiation illuminates the disk creating a hot corona via Compton scattering. A wind originates when the temperature of the corona increases above a critical value, the “escape temperature”, above which the corona cannot remain in hydrostatic equilibrium (e.g. Begelman et al. 1983). Radiation pressure from the SBH accretion disk is the main mechanism behind the acceleration of **radiatively driven flows**. In this case, the radial motion under the influence of radiation and the gravity due to a point mass $M$ can be expressed as:
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\[
v \frac{dv}{dr} = \frac{kL}{4\pi r^2 c} - \frac{GM}{r^2},
\]

(1.1)

where the first and the second term in the right-hand side of the equation are the radiation pressure and the gravitational contributions to the acceleration, respectively; \(k\) is the absorption cross section per unit mass, \(L\) is the luminosity of the radiation source, \(c\) is the speed of light, and \(G\) the gravitational constant. **Hydromagnetic outflows** originate from the interaction between coronal ionized gas located above the disk, and lines of the magnetic field frozen into the disk. Gas is ejected along the lines of the magnetic field similarly to beads anchored to a rotating wire (e.g. Blandford and Payne 1982). In *hybrid models* gas acceleration is due to a combination of magnetic and radiative processes, e.g.: Konigl and Kartje (1994) propose that the obscuring equatorial medium of Seyfert galaxies (the torus) consists of a wind which is magnetically driven. However, radiation pressure becomes important beyond the dust sublimation radius, where the presence of dust increases the opacity of the gas (or the absorption cross section in eq.1.1).

As anticipated above, feedback from the SBH in the form of outflows is a primary suspect amongst the mechanisms that may underly relations such as the \(M_\bullet-\sigma\) proportionality. When outflows are incorporated into models of galaxy evolution, their effect on the host galaxy is evident, with a clear impact on the star formation history and galaxy morphology; however AGN feedback is modeled with an extremely simplistic approach, e.g.: to match the observed slope of the \(M_\bullet-\sigma\) relation, Di Matteo et al. (2005) simply assume that 0.5% of the rest-mass energy accreted onto the SBH is transferred to the interstellar medium. Quantifying mass (and kinetic energy) outflow rates from direct observations is thus fundamental to understanding the process and pace of galaxy evolution.

Many of the processes involved in AGN feeding and feedback take place within the inner kiloparsec. Hence the importance of high spatial resolution spectroscopic mapping. In recent years, integral field spectroscopy has allowed detailed investigations of the 2D kinematics in the nuclear regions of AGNs. Studies of nearby Seyferts have revealed the presence of compact outflows (few 100 pc in extent) with velocities of few 100 km s\(^{-1}\) and...
mass outflow rates of few solar masses per year, e.g.: evidence for a bipolar outflow extending about 100 pc north and south of the nucleus, and driven by a radio jet, was found in NGC 6951 (Storchi-Bergmann et al., 2007). Kinematical features consistent with an outflow in the plane of the galaxy, and confined between gas inflowing along spiral arms, were identified in NGC 1097 (Davies et al., 2009). Principal component analysis of a GEMINI datacube revealed features suggestive of a bipolar outflow in M81 (Schnorr Müller et al., 2011). Near-IR observations of seven Seyferts revealed kinematical features consistent with outflows in all of them; typical velocities ranged from 120 km s\(^{-1}\) to 1900 km s\(^{-1}\), and the morphology displayed a broad range of half-opening angles (Müller-Sánchez et al., 2011). Davies et al. (2014) analyzed the molecular gas kinematics in a sample of ten galaxies (five non-active and five Seyferts 1.5-2) finding evidence for outflows in four of the active galaxies; they measured typical speeds of 150 km s\(^{-1}\), and mass outflow rates of 10 M\(_{\odot}\) yr\(^{-1}\). They inferred that the AGN ionization cones intersect the plane of the galaxy, proposing that the galaxy disk acts as the actual reservoir of molecular gas which is experiencing the outflow.

Integral field spectroscopy has enabled a huge leap forward in understanding the processes regulating AGN feeding and feedback, however mass and energy-flow rates are still order of magnitude estimates affected by large uncertainties, and the morphology of inflows and outflows are not so well understood as we might wish. Much work is still required before an accurate and definitive picture can be drawn.

To further our understanding of the relation between SBHs, inflows, and outflows we have been studying two samples of active galaxies: the first is a sample of galaxies characterized by the presence of nuclear dusty spirals, features suspected to trace inflowing gas; the second is a sample of Seyferts and LINERs selected on the basis of the hard X-ray luminosity of the nucleus. In this dissertation I present the results obtained for two galaxies: NGC 1386, from the nuclear spirals sample, and NGC 1365, from the X-ray selected sample. The studies are presented in Chapters 4 and 5.
1.4 Galaxy mergers and recoiling black holes

Gas accretion onto SBHs, and outflows, provide a means for the SBH to co-evolve with the host galaxy. However, within the current standard model of cosmology, another mechanism is expected to play an important role in the co-evolution of galaxies and their nuclear SBHs: growth via galaxy mergers, leading, in turn, to mergers of binary SBHs.

Cold dark matter hierarchical cosmologies ($\Lambda$CDM) predict that galaxies experience multiple mergers during their lifetime (e.g., Coles and Lucchin 2002, Springel et al. 2005c), with minor mergers being more common than major mergers (e.g., Hilz et al. 2013). When two galaxies merge, their central SBHs are expected to form a binary system (Begelman et al. 1980) at the center of the merged system due to dynamical friction. Further tightening of the binary ensues through three-body interactions with stars, or gravitational drag from gas (Merritt and Milosavljević 2005, Mayer et al. 2007), until finally, energy loss due to gravitational wave emission irreversibly drives the two SBHs to coalescence.

In the final stage of SBH-binary coalescence, anisotropic emission of gravitational waves will, in general, impart a recoil velocity to the coalesced object (Bekenstein 1973). Following a recent breakthrough allowing the orbits of spinning black holes to be computed to coalescence (Pretorius 2005, Campanelli et al. 2006, Baker et al. 2006), numerical relativity simulations have produced recoil velocities $v \sim 10^3$ km s$^{-1}$, even reaching $\sim 5 \times 10^3$ km s$^{-1}$ for certain spin configurations (Campanelli et al. 2007b, González et al. 2007, Tichy and Marronetti 2007, Lousto and Zlochower 2011, Lousto et al. 2012). Such velocities would cause large displacements of the coalesced SBH from the center of the galaxy or, in the most extreme cases, eject it entirely from the host (Merritt et al. 2004, Campanelli et al. 2007a, Volonteri et al. 2010).

Recoils exceeding the escape velocity of the host galaxy are expected to be relatively rare (Lousto et al. 2012, e.g.,) and, more frequently, the...
SBH will undergo damped oscillations in the galaxy potential. \( N \)-body simulations (Gualandris and Merritt, 2008) have shown that moderately large kicks (\( \sim \) few \( 10^2 \) km s\(^{-1} \), sufficient to eject the SBH from the core\(^4 \) but not from the galaxy) result in long-lived oscillations which damp on a timescale \( \Delta t \sim 1 \) Gyr. In particular, Gualandris and Merritt identified three dynamical phases for the particular case where the SBH is initially displaced beyond the core radius (\( r_c \sim 10^2 \) pc). In “phase I” the SBH undergoes damped harmonic motion at amplitudes greater than the core radius. These oscillations are damped relatively quickly (\( \sim 10^7 \) yr) by dynamical friction. “Phase II” is characterized by oscillations of amplitude \( \sim 10^{-100} \) pc between the SBH and the stellar core about the center of mass, which persist for up to \( \sim 1 \) Gyr. Finally, in “phase III”, the SBH has reached thermal equilibrium with the surrounding stars and experiences Brownian motion, signifying the end of the event.

Large gravitational recoil kicks would have a variety of observable consequences. In the case of SBHs associated with AGNs, most of the accretion disk and broad emission line gas will remain bound for recoils with velocities \( v_{kick} \lesssim 10^3 \) km s\(^{-1} \) and such systems might be observed as displaced, or velocity-shifted AGNs (e.g., Merritt et al., 2004; Madau and Quataert, 2004; Loeb, 2007; Bonning et al., 2007; Zanotti et al., 2010). Stars moving with orbital velocities \( v < v_{kick} \) would also remain bound to the SBH after the kick, so that a recoiling SBH would be associated with a “hypercompact stellar system” of high internal velocity dispersion (Merritt et al., 2009).

Possible spectroscopic signatures of recoiling SBHs have been identified in a few individual active galaxies (Komossa et al., 2008; Shields et al., 2009; Robinson et al., 2010; Steinhardt et al., 2012), which would indicate large (\( \gtrsim 10^3 \) km s\(^{-1} \)) kick velocities. In addition, systematic searches of large SDSS AGN samples have revealed \( \sim 100 \) objects that exhibit velocity shifts \( \sim 10^3 \) km s\(^{-1} \) between the broad and narrow lines (Bonning et al., 2007; Tsalmantza et al., 2011; Eracleous et al., 2012). Some of these may be recoiling SBHs, or SBH binaries, but alternative explanations for the shifts involving extreme broad line region kinematics cannot be excluded. Perhaps the most interesting case is that of CID-42, a galaxy which hosts

\(^4\)The core (or break) radius, \( r_c \), is defined as the radius where the projected surface brightness distribution of the galaxy becomes shallower than the inward extrapolation of the outer surface brightness profile.
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two compact optical sources separated by \( \approx 2.5 \) kpc and also exhibits a large velocity shift (\( \approx 1300 \, \text{km} \, \text{s}^{-1} \)) between broad and narrow H\( \beta \) emission lines (Civano et al., 2010, 2012; Blecha et al., 2013).

Identifying recoiling SBHs, characterizing their distribution in amplitude, understanding how this distribution varies as a function of redshift, will improve our understanding of the configuration that SBH-binaries reach at the stage of the merger, e.g.: is the configuration such that the recoil velocity can easily reach a given threshold?

Given the central role that galaxy mergers play in the current standard cosmological model, and given that SBH mergers are a corollary of galaxy mergers, it is clear that characterizing the distribution of recoiling SBHs will also set important observational constraints on the galaxy merger rate allowing a better understanding of the evolutionary path that creates present-day galaxies. For example: do massive ellipticals grow through a succession of mergers? Or do they form at high redshift, from the collapse of gas clouds, evolving passively?

The \( N \)-body simulations presented in Gualandris and Merritt (2008) predict that SBHs may continue to undergo fairly large oscillations for a few Gyr, suggesting that SBHs spatially offset from the center of their host galaxies might be present even in the local Universe. With this in mind, we studied a sample of active elliptical galaxies looking for spatial offsets between the nuclear point source (the AGN) and the photometric center defined by the old stellar population of the inner few kiloparsecs. The results of this study are presented in Chapter 2.

1.5 Chapter synopsis

In this dissertation I present the results of two observational studies conducted on nearby AGNs with the aim of furthering our understanding of SBH evolution, growth, and interplay with the host galaxy.

In Chapter 2 I present the results of a search for recoiling SBHs in the nearby Universe (within 100 Mpc of the Milky Way). This is also an observational test of the theoretical scenario proposed for the evolution of SBHs in the aftermath of SBH-binaries coalescence in gas-poor galaxies: long-lived oscillations are expected between the nuclear SBH and the galactic core, the
Introduction

oscillations being the result of anisotropic emission of gravitational waves during the merger of an SBH-binary (e.g. Gualandris and Merritt 2008; Kornreich and Lovelace 2008). The study is based on a photometric analysis of fourteen nearby elliptical galaxies observed with the Hubble Space Telescope.

Chapters 3, 4 and 5 describe a detailed analysis, based on integral field spectroscopy, of the 2D gas distribution, ionization, and kinematics in the inner kiloparsec of the isolated active galaxies NGC 1386 (a Seyfert 2) and NGC 1365 (a barred Seyfert 1). The study aims at furthering our understanding of outflows in low luminosity AGNs, and the mechanisms that channel gas from the inner kiloparsec down to few tens of parsecs from the nuclear SBH. In Chapter 3 I describe the observations, performed with the Gemini Multi-Object Spectrograph on the Gemini South telescope, the data reduction steps, and the techniques employed to analyze the data. In Chapter 4 and 5 I present the results for NGC 1386 and NGC 1365 respectively.

In Chapter 6 I summarize my conclusions in relation to the scientific questions which motivated the work, emphasizing their implications for our understanding of galaxy evolution and active galactic nuclei.
CHAPTER 2

RECOILING SUPERMASSIVE BLACK HOLES: A SEARCH IN THE NEARBY UNIVERSE

2.1 Introduction

The gravitational recoil candidates discovered to date have been identified on the basis of anomalously large velocity shifts ($\gtrsim 10^3$ km s$^{-1}$, e.g. Komossa et al. 2008; Shields et al. 2009; Robinson et al. 2010; Steinhardt et al. 2012) or a large spatial offset ($\gtrsim 1$ kpc, e.g. Civano et al. 2010). If they are indeed recoiling SBHs, we are observing them during the early stages in their dynamical evolution following a large kick; that is, during the large amplitude phase I oscillations predicted by Gualandris and Merritt (2008, hereafter GM08), if the SBH remains bound to the galaxy. However, special configurations of the progenitor binary are required to produce large kicks, which are therefore expected to be relatively rare events (e.g. Lousto et al. 2012, hereafter L12) and furthermore, the subsequent large amplitude phase I oscillations are relatively short-lived.

On the other hand, the $N$-body simulations of GM08 predict that, following a recoil kick sufficiently large to remove the SBH from the galaxy core, the decaying oscillations persist in phase II for $\sim 1$ Gyr, comparable with the time between galaxy mergers (Hopkins et al. 2010, hereafter H10). This suggests that low amplitude SBH displacements resulting from post-merger SBH binary coalescence should be relatively common in the cores of bright elliptical galaxies. Thus, rather than searching for short-lived phase
2.1 Introduction

I oscillations following rare large kicks, an alternative approach to studying the incidence of SBH binary coalescence is to look for phase II oscillations in nearby ellipticals.

Spectroscopic identification of phase II oscillations would be extremely difficult, if not impossible, as the associated velocity shifts would be comparable with gas motions due to rotation, or flows, or turbulence driven by the AGN, or starburst activity. However, it is feasible to directly detect small-amplitude displacements between the AGN and the galaxy photocenter in high spatial resolution images of nearby galaxies. We recently analyzed archival Hubble Space Telescope Advanced Camera for Surveys images of the active giant elliptical M87 and found a projected offset of $6.8 \pm 0.8$ pc ($\approx 0.1$) between the stellar photocenter and the AGN (Batcheldor et al. 2010, hereafter B10; we note, however, that Gebhardt et al. 2011 did not find a significant offset in their near-infrared integral field spectroscopy data).

Here I describe a photometric analysis of archival HST images of 14 nearby ($d < 100$ Mpc), bright ellipticals hosting low-luminosity AGNs, with the aim of directly measuring spatial offsets comparable with the core radius of the galaxy (typically < 500 pc). Our method consists in measuring the relative positions of the AGN point source and the photocenter of the inner 2-3 kpc of the galaxy, assuming that the former marks the SBH position and the latter the minimum of the galactic potential. As long as the AGN is bright enough to be easily detected and faint enough that it does not overwhelm the host galaxy, it is possible to perform standard photometric analysis to locate the photocenter. The “displacement” is then computed as the relative distance between the AGN and photocenter.

In addition to gravitational recoil, there are other mechanisms that seem capable of displacing the SBH from its equilibrium position (B10): orbital motion of SBH-binaries (Komossa 2006), asymmetric radio jets (Shklovsky 1982) and interactions with massive perturbers such as globular clusters, or massive molecular clouds. Our results will therefore be discussed with the goal of identifying the most plausible mechanism at the origin of the observed spatial offset.

The plan of this chapter is as follows: in Section 2.2, I describe the sample; Section 2.3 describes the analysis methods used to determine the photocenter, SBH position and offset, and their uncertainties; in Section 2.4
2.2 The sample

The measured displacements are presented for each galaxy. In Section 2.5, I discuss the results in the context of gravitational recoil and other possible displacement mechanisms. The results for selected galaxies are discussed in more detail within Section 2.6. Conclusions are summarized in Section 2.7.

2.2 The sample

The sample selected for this study consists of 14 nearby, regular, core elliptical galaxies which host AGNs and for which HST images obtained with ACS, NICMOS2, WFPC2 or WFC3 are available in the Hubble Legacy Archive (HLA).

HST observations have revealed that the central light distribution in nearly all nearby early type galaxies can be described by a singular surface brightness profile: \( \Sigma(r) \sim r^{-\gamma} \) as \( r \to 0'1 \), where \( \gamma \geq 0 \). The slope of the innermost surface brightness distribution is bimodal in the sense that there is a paucity of galaxies which have \( 0.3 < \gamma < 0.5 \). Hence, early type galaxies have been classified in two families: “core galaxies”, which have a shallower (\( \gamma \leq 0.3 \)) inner cusp within a “break” (or “core”) radius \( r_c \sim 100 \text{ pc} \), and “power law galaxies”, which have a steep cusp (\( \gamma \geq 0.5 \)) continuing into the HST resolution limit (Lauer et al., 1995). These classifications correlate with several other galaxy properties (e.g., Faber et al., 1997), in particular, core galaxies are on average more luminous than power-law galaxies, with essentially all bright (\( M_V < -22 \)) ellipticals having cores.

Core galaxies are promising systems in which to search for SBH binaries or SBHs displaced by gravitational wave-induced recoils. They are bright ellipticals which are often the dominant components of clusters or groups and are thus likely to have experienced a recent major merger leading to the formation of an SBH binary. The shallow inner surface brightness profile indicates a mass deficit relative to that implied by inward extrapolation of the steeper brightness profile prevailing at larger radii. This is predicted as a natural consequence of depopulation of the inner region of the galaxy by 3-body interactions between an SBH binary and stars crossing the orbit of the binary (“loss-cone stars”, Merritt and Milosavljević 2005). Therefore, “flat” inner surface brightness profiles have been proposed as a clear footprint of the formation of a tightly bound SBH binary (e.g., Faber et al., 1997; Merritt, 2000).
2.2 The sample

In addition, core galaxies tend to have regular photometric structures, and hence well-defined photocenters. In order to accurately locate the position of the SBH, we further require that each galaxy hosts a low luminosity AGN visible as a point source in the HST images.

In order to resolve the low amplitude offsets between photocenter and AGN expected in the phase II oscillations predicted by GM08, we select only galaxies within 100 Mpc.

The sample analyzed in this work was extracted from a sample of 29 core elliptical galaxies previously studied by Capetti and Balmaverde, in a series of three articles (Capetti and Balmaverde 2005; Balmaverde and Capetti 2006; Capetti and Balmaverde 2006) hereafter CB05, BC06 and CB06 respectively. CB05 compiled a radio-flux limited sample of AGNs in early type hosts by selecting radio-detected sources from the VLA surveys of Wrobel and Heeschen (1991) and Sadler et al. (1989). The former is a northern sample of 216 early-type galaxies extracted from the CfA redshift survey (Huchra et al., 1983), with the following criteria: declination $\delta_{1950} \geq 0$; photometric magnitude $B \leq 14$; heliocentric velocity $\leq 3000$ km s$^{-1}$; morphological Hubble type $T \leq -1$. The latter is a similar southern sample of 116 E and S0 galaxies with declination $-45 \leq \delta \leq -32$. Both were observed at 5 GHz with a flux limit of $\sim 1$ mJy.

The 65 objects with available archival HST images were classified as core or power-law galaxies on the basis of the slopes of their nuclear brightness profile as obtained by fitting a broken power law (the so-called “Nuker law”; Lauer et al., 1995; CB05; CB06). For the purpose of this study, we focus on the core galaxies listed in Table 1 of BC06 and impose two additional selection criteria, based on visual inspection of HST images: (i) the presence of an optically bright central point-like source (a low luminosity AGN); (ii) the absence of heavy nuclear obscuration and other photometric irregularities.

The 14 galaxies selected for this study are listed in Table 2.1 together with their distances, core radii and details of the archival data sets that were retrieved for photometric analysis. The sample includes two galaxies (NGC 4696 and NGC 5419) that exhibit double nuclei, separated by $\sim 0.25$. In these cases, it is not known which of the two point sources is the AGN and therefore we assume that the brighter is the AGN (although we have measured displacements relative to both).

The radio source properties, including the total power at 5 GHz and the
2.2 The sample

position angle of any extended structure, are summarized in Table 2.2.
2.2 The sample

Table 2.1: THE SAMPLE

<table>
<thead>
<tr>
<th>Galaxy</th>
<th>Distance</th>
<th>$r_c$</th>
<th>$r_h$</th>
<th>Instrument/Filter</th>
<th>Pixel Scale</th>
<th>ID</th>
</tr>
</thead>
<tbody>
<tr>
<td>NGC 1399</td>
<td>18 ± 1</td>
<td>2.19 (189)</td>
<td>0.99 (86)</td>
<td>WFPC2/PC/F606W</td>
<td>0.05</td>
<td>8214</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>WFPC2/PC/F814W</td>
<td>0.05</td>
<td>5990</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>WFPC3/IR/F110W</td>
<td>0.09</td>
<td>11712</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>WFPC3/IR/F160W</td>
<td>0.09</td>
<td>11712</td>
</tr>
<tr>
<td>NGC 4168</td>
<td>31 ± 6</td>
<td>2.02 (303)</td>
<td>0.09 (14)</td>
<td>WFPC2/PC/F702W</td>
<td>0.05</td>
<td>6357</td>
</tr>
<tr>
<td>NGC 4261</td>
<td>30 ± 2</td>
<td>1.62 (237)</td>
<td>0.428 (62)</td>
<td>NICMOS2/F160W</td>
<td>0.05</td>
<td>7868</td>
</tr>
<tr>
<td>NGC 4278</td>
<td>18 ± 1</td>
<td>0.97 (83)</td>
<td>0.334 (29)</td>
<td>ACS/WFC/F850LP</td>
<td>0.05</td>
<td>10835</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>WFPC2/PC/F814W</td>
<td>0.05</td>
<td>5454</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>NICMOS2/F160W</td>
<td>0.05</td>
<td>7868</td>
</tr>
<tr>
<td>NGC 4373</td>
<td>40 ± 2</td>
<td>1.19 (269)</td>
<td>0.167 (32)</td>
<td>WFPC2/PC/F814W</td>
<td>0.05</td>
<td>5214</td>
</tr>
<tr>
<td>NGC 4486</td>
<td>16 ± 1</td>
<td>9.41 (733)</td>
<td>1 (78)</td>
<td>ACS/HRC/F606W</td>
<td>0.025</td>
<td>B10</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>ACS/HRC/F814W</td>
<td>0.025</td>
<td>B10</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>NICMOS2/F110W</td>
<td>0.05</td>
<td>7171</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>NICMOS2/F160W</td>
<td>0.05</td>
<td>7171</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>NICMOS2/F222M</td>
<td>0.05</td>
<td>7171</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>WFPC2/PC/F814W</td>
<td>0.05</td>
<td>8592</td>
</tr>
<tr>
<td>NGC 4552</td>
<td>15 ± 1</td>
<td>0.49 (36)</td>
<td>0.48 (35)</td>
<td>WFPC2/PC/F814W</td>
<td>0.05</td>
<td>6099</td>
</tr>
<tr>
<td>NGC 4636</td>
<td>13 ± 1</td>
<td>3.44 (219)</td>
<td>0.297 (19)</td>
<td>WFPC2/PC/F814W</td>
<td>0.05</td>
<td>8686</td>
</tr>
<tr>
<td>NGC 4696</td>
<td>37 ± 2</td>
<td>1.4 (251)</td>
<td>0.2 (36)</td>
<td>ACS/WFC/F814W</td>
<td>0.05</td>
<td>9427</td>
</tr>
<tr>
<td>NGC 5419</td>
<td>49 ± 9</td>
<td>$D_n - \sigma$</td>
<td>2.11 (499)</td>
<td>WFPC2/PC/F555W</td>
<td>0.05</td>
<td>6587</td>
</tr>
<tr>
<td>NGC 5846</td>
<td>25 ± 2</td>
<td>1.52 (183)</td>
<td>0.25 (30)</td>
<td>WFPC2/PC/F814W</td>
<td>0.05</td>
<td>5920</td>
</tr>
<tr>
<td>IC 1459</td>
<td>29 ± 4</td>
<td>1.92 (258)</td>
<td>0.43 (60)</td>
<td>WFPC2/PC/F814W</td>
<td>0.05</td>
<td>5454</td>
</tr>
<tr>
<td>IC 4296</td>
<td>50 ± 3</td>
<td>1.44 (347)</td>
<td>0.32 (77)</td>
<td>ACS/HRC/F625W</td>
<td>0.025</td>
<td>9838</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>WFPC2/PC/F814W</td>
<td>0.05</td>
<td>5910</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>NICMOS2/F160W</td>
<td>0.05</td>
<td>7453</td>
</tr>
<tr>
<td>IC 4931</td>
<td>~ 84</td>
<td>0.99 (403)</td>
<td>0.13 (51)</td>
<td>WFPC2/PC/F814W</td>
<td>0.05</td>
<td>8683</td>
</tr>
</tbody>
</table>

Note. — (1) Source name; (2) adopted distance in Mpc (from the HyperLeda extragalactic database); (3) method used to determine the distance: “sbf”, surface brightness fluctuation; “vvir”, from radial velocity, corrected for Local Group infall into Virgo; “$D_n - \sigma$", size-sigma relation (Dressler et al., 1987); (4) core radius as derived by CB05, in arcsec (pc); (5) SBH influence radius ($GM_{BH}/\sigma^2$) in arcsec (pc). Central velocity dispersions are given in Table 2.7. Black hole masses have been derived from the $M_\bullet - \sigma$ relation given in Ferrarese and Ford (2005); (6) HST instrument/camera/filter used; (7) pixel scale in arcseconds/pixels as determined from direct measurement on the frames; (8) proposal identification number. B10*: this is a combined image, see Table 1 in B10 for further details. †A WFC3/IR image is available for NGC 4696, however the complex nuclear features and the pixel size of the camera do not allow one to infer the SBH position with the precision necessary for this work.
### Table 2.2: NOTES ON THE RADIO SOURCES OF INDIVIDUAL GALAXIES

<table>
<thead>
<tr>
<th>Galaxy</th>
<th>Scale</th>
<th>PA</th>
<th>$P_{5\text{GHz}}$</th>
<th>Comments</th>
<th>Nature of the galaxy</th>
</tr>
</thead>
<tbody>
<tr>
<td>NGC 1399</td>
<td>10 kpc</td>
<td>$-10^\circ$</td>
<td>137$^a$</td>
<td>Linear, almost symmetric.</td>
<td>Dominant component of Fornax cluster.</td>
</tr>
<tr>
<td>NGC 4168</td>
<td>...</td>
<td>7 ± 0.3$^b$</td>
<td>12657 ± 610$^e$</td>
<td>Unresolved radio emission.</td>
<td>E2 in Virgo cluster.</td>
</tr>
<tr>
<td>NGC 4261</td>
<td>30 kpc$^f$</td>
<td>87 ± 8°$^b$</td>
<td>12657 ± 610$^e$</td>
<td>Linear, symmetric lobes. W jet brighter than E.</td>
<td>Massive E in the outskirts of Virgo cluster.</td>
</tr>
<tr>
<td>NGC 4278</td>
<td>1.4 pc$^g$</td>
<td>100° − 155°</td>
<td>69 ± 2°</td>
<td>S-shaped, inner jet brightest to the N.</td>
<td>Large E near the center of Coma I cloud.</td>
</tr>
<tr>
<td>NGC 4373</td>
<td>...</td>
<td>...</td>
<td>40$^d$</td>
<td>Compact radio source.</td>
<td></td>
</tr>
<tr>
<td>NGC 4486</td>
<td>1.5 kpc</td>
<td>260°</td>
<td>43552 ± 242$^e$</td>
<td>Linear on kpc scale.</td>
<td></td>
</tr>
<tr>
<td>NGC 4552</td>
<td>0.5 pc$^h$</td>
<td>...</td>
<td>3.345$^d$</td>
<td>T-shaped. No radio lobes.</td>
<td></td>
</tr>
<tr>
<td>NGC 4636</td>
<td>$&lt;1$ kpc$^i$</td>
<td>~50°</td>
<td>12 ± 0.4°</td>
<td>Twin pc-scale extension.</td>
<td>Centaurus Cluster BCG.</td>
</tr>
<tr>
<td>NGC 4696</td>
<td>1.6 kpc$^m$</td>
<td>$-150^\circ$</td>
<td>3345$^d$</td>
<td>Z-shaped. No radio lobes.</td>
<td></td>
</tr>
<tr>
<td>NGC 5419</td>
<td>...</td>
<td>1719$^a$</td>
<td>4 ± 0.2$^b$</td>
<td>Compact morphology.</td>
<td>Dominant component of group S753.</td>
</tr>
<tr>
<td>NGC 5846</td>
<td>...</td>
<td>541$^a$</td>
<td>4 ± 0.2$^b$</td>
<td>Compact source.</td>
<td>Dominant component of group [HG82]50.</td>
</tr>
<tr>
<td>IC 1459</td>
<td>...</td>
<td>541$^a$</td>
<td>4 ± 0.2$^b$</td>
<td>Compact source.</td>
<td>Giant E in group [HG82]15.</td>
</tr>
<tr>
<td>IC 4296</td>
<td>240 kpc$^n$</td>
<td>130°$^n$</td>
<td>5912$^a$</td>
<td>Linear, NW component slightly brighter.</td>
<td>Giant E, BCG of group A3565.</td>
</tr>
<tr>
<td>IC 4931</td>
<td>...</td>
<td>7$^d$</td>
<td>5912$^a$</td>
<td></td>
<td>BCG of A3656.</td>
</tr>
</tbody>
</table>

Note. — Notes on the radio sources of individual galaxies. (1) Optical identification; (2) approximate length of the radio jet/extension; (3) position angle (degrees E of N); (4) total power at 5 GHz [$10^{20}$ W]; (5) comments on the radio source morphology; (6) comments on the nature of the galaxy. $^\dagger$This value is computed for the inner 25 pc. References: $^4$Slee et al. (1994), $^2$Wrobel and Heeschen (1991), $^3$Wrobel (1991), $^4$Sadler et al. (1989), $^6$Shurkin et al. (2008), $^2$Cavagnolo et al. (2010), $^4$Giroletti et al. (2005), $^3$Baade and Minkowski (1954), $^6$Nagar et al. (2002), $^4$Stanger and Warwick (1986), $^6$Taylor et al. (2006), $^2$Killeen et al. (1986b), $^3$Jones et al. (2000), [HG82]: Huchra and Geller (1982).
2.3 Data Analysis

Broad-band images of the sample galaxies acquired with ACS, NIC-MOS2, WFPC2 and WFC3 were retrieved from the Hubble Legacy Archive (HLA), giving preference to images obtained with the highest spatial resolutions and red filters (i.e., F606W and longer wavelengths).

Whenever available, several images taken with different instruments and filters, covering both optical and NIR bands, were obtained for each galaxy. A list of the images analyzed for each galaxy is given in Table 2.1. No additional processing steps were applied beyond the standard HLA reduction pipeline. As the goal of our analysis is simply to determine the relative positions of the isophotal center of the inner few kiloparsecs of the galaxy and the AGN point source within each individual image, this is sufficient for our purposes.

Each image was analyzed according to the following main steps: (1) a mask was constructed to block image defects and distorting features such as dust lanes, jets or bright stars and globular clusters; (2) elliptical isophotes were fitted to the galaxy surface brightness distribution and the photocenter computed as the flux-weighted average of the isophote centers; (3) the position of the point source (assumed to locate the SBH) was determined by fitting a gaussian profile. See Section 2.3.1 and Section 2.3.2 for a more detailed description of these procedures. Sky subtraction was not performed as a uniform background will not affect the photometric analysis, and in many cases it is not possible to measure the sky background as the galaxy covers the frame.

2.3.1 The inner photocenter

Each image was analyzed with the IRAF task ellipse (Jedrzejewski, 1987), which was used to fit elliptical isophotes to the surface brightness distribution. The first step was to construct an image mask in order to minimize distortions due to image defects and intrinsic photometric irregularities.

2IRAF is the Image Reduction and Analysis Facility, a general purpose software system for the reduction and analysis of astronomical data. IRAF is written and supported by the National Optical Astronomy Observatories (NOAO) in Tucson, Arizona. NOAO is operated by the Association of Universities for Research in Astronomy (AURA), Inc. under cooperative agreement with the National Science Foundation.
2.3 Data Analysis

Figure 2.1: HST images of the galaxies in the sample. The number at the bottom represents the length of the whole axes (continues on next page).
Figure 2.1: (continued)
2.3 Data Analysis

Figure 2.1: (continued)

Similarities such as dust features, optical or NIR knots associated with jets, globular clusters, foreground stars, etc. If an exposure time map (the “weight image”) was provided in the retrieved data set, this was used as an initial mask to eliminate cosmic rays, bad pixels, null areas and other image frame blemishes. Applying the initial mask, a first run of *ellipse* was performed to create a zeroth-order photometric model. To account for intrinsic irregularities in the surface brightness distribution, we then created a second mask by subtracting the zeroth-order photometric model from the original image and masking residuals exceeding $\pm n\sigma$, where $\sigma$ is the standard deviation of the residual image, and $n$ is a clipping parameter.

To allow *ellipse* to find the photometric peak, the central region was unmasked and a new run performed. This process was iterated, adjusting $n$ in order to map distorting features in the maximum possible detail. The iteration was terminated when the mask converged and further runs did not add any significant detail.

Once the final mask was constructed, *ellipse* was re-run with the mask applied to determine the photocenter of the galaxy. Elliptical isophotes were fitted between minimum and maximum values of the semi-major axis (SMA) which were usually determined by the core radius ($r_c$) and the image size, respectively. In almost all cases, the minimum SMA was set equal to or greater than the value of $r_c$ as determined by CB05; Table [2.1](#) This was typically $\sim 2''$, or $\sim 300$ pc. In some cases, where a dusty disk is present in the center of the galaxy, the initial SMA was chosen such that the inner ellipse is larger than the disk. The only exception was NGC 4486 (M 87), which has a very large core. In this case, we adopted the SMA range 1–
2.3 Data Analysis

3″ used by B10, who found that isophotes within 1″ are influenced by the AGN point source. The maximum SMA was that of the largest ellipse that completely fits within the image area – that is, only complete isophotes were fitted. This limits our isophotal analysis to the inner few kiloparsecs of each galaxy; the SMA of the outermost ellipse fit varies in the range $1 \lesssim r \lesssim 4$ kpc.

Between these limits, a series of ellipses was fitted to the 2D surface brightness distribution, with the SMA being increased by two pixels at each step. Each fit returned values of the position angle, eccentricity and the pixel $x - y$ coordinates of the center of the ellipse. Finally, the photocenter was obtained as the flux-weighted average of the centers of the elliptical annuli generated by ellipse:

$$(x_{pc}, y_{pc}) = \left( \frac{\sum_i x_i j_i}{\sum_i j_i}, \frac{\sum_i y_i j_i}{\sum_i j_i} \right)$$

where $x_i$ and $y_i$ are the photocenter coordinates of the $i$-th isophote and $j_i$ is a weight, given by the product of the area of the annulus defined by neighbouring isophotes, with the mean intensity within the annulus.

We explored alternative methods for the measurement of the photocenter position, namely a moment based technique and a 2D decomposition of the surface brightness distribution. In the first case, the photocenter position is obtained by weighting the coordinate of each pixel by its own intensity. This method seems to be particularly sensitive to the masking details and to the presence of asymmetries in the light distribution. The second approach, performed with the GALFIT surface brightness fitting program (Peng et al., 2002), requires, at least in some cases, multiple components for a successful fit (e.g. two or more Sérsic profiles) casting doubt on the physical meaning of the recovered photocenter and the errors associated with it.

The IRAF task ellipse was specifically built to fit the light profile of elliptical galaxies with minimal assumptions; the results obtained seem to be weakly dependent on the masking details and errors associated with the fitted parameters have been thoroughly studied (Busko, 1996). Therefore, we prefer to adopt the photocenter position determined with this approach.
2.3 Data Analysis

Figure 2.2: Alternative weighting functions for the mean photocenter, derived from the NICMOS2/F160W image of NGC 4261. Both functions are normalized to their maximum values. **Solid line**: light content of the elliptical annulus with the SMA specified on the horizontal axis. **Dashed dotted**: light content enclosed by the ellipse of the corresponding SMA. We adopted the function represented by the solid line.

2.3.2 The SBH position

We make the key assumption that the point-like source near the center of each galaxy is an AGN, which therefore locates the position of the SBH (see Section 2.5 for a detailed discussion of this assumption).

The AGN point sources are bright enough to be easily detected, but in our sample they are not so bright that the point spread function dominates the host galaxy. In order to determine the position of the SBH, we proceeded as follows. First, a median filtered version of the image was subtracted from the original producing a residual map in which the AGN is a prominent feature\(^3\). In the second step, we used the IRAF task *center* to fit Gaussians

\(^3\)We prefer to subtract a median filtered image instead of the photometric model because in the former method we can control the size of the structures that are removed. That is we can change the dimensions of the box over which the median is computed. This determines the degree of smoothing of the filter and hence the size of the structures removed after the subtraction.
2.3 Data Analysis

to the marginal distributions of the residual point source along the $x$ and $y$ axes.

2.3.3 The photocenter–AGN displacement

For each image of each galaxy, the $x$ and $y$ components of the displacement were measured as the difference in pixels between the $x$ and $y$ co-ordinates of the photocenter and the AGN point source. The significance of the displacement is classified in two steps, considering the $x$ and $y$ components separately. Displacements smaller than $3\sigma$, where $\sigma$ is the error on the displacement (Section 2.3.4.1), are considered non-significant. If the displacement exceeds $3\sigma$ we make a further classification based on the distribution of the isophote center coordinates produced by \textit{ellipse}. For each coordinate, $x$ and $y$, the inter-quartile range (IQR, the difference between the upper and lower quartiles) of the isophote centers was computed. The corresponding displacement is then assigned significance levels of “null”, “low”, “intermediate” or “high” depending on its magnitude relative to the IQR:

- 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, $\Delta x, \Delta y \geq 2.4$ IQR.

The threshold values are based on the fact that, for a normal distribution, $0.8$ IQR is equivalent to $1\sigma$. For an ideal, symmetric galaxy the isophotes would be concentric, giving IQR = 0. Any irregularities in the surface brightness distribution will cause a dispersion in the centers of the fitted elliptical isophotes, resulting in a non-zero IQR. Hence, by normalizing to the IQR, we allow for uncertainties in the recovered offsets due to asymmetric surface brightness distributions arising from, for example, dust lanes or tidal distortions.
2.3 Data Analysis

2.3.4 Errors and biases

2.3.4.1 Position uncertainties

The final error on the measured projected displacement is the combination of the uncertainties in the positions of the photocenter and the AGN point source. As the photocenter is determined by fitting elliptical isophotes, it is important to understand if the errors provided by ellipse are reasonable and robust. To investigate this, we used ellipse to analyze synthetic galaxy images constructed with GALFIT. We also used these simulated galaxies to estimate the uncertainties on both the AGN and photocenter positions.

The model images were constructed by fitting a Sérsic profile and a nuclear point source (a PSF generated with Tiny Tim, [Krist 1993]) to selected galaxies in our sample. We used NGC 4261 and 4278 to build models of NICMOS images, IC 1459 for WFPC2 images and IC 4296 for ACS images. The resulting model surface brightness distributions were populated with gaussian random noise so as to match the signal-to-noise ratio (SN) of the original galaxy image. Four realizations of each synthetic galaxy image were generated and each realization was analyzed using the methods described in Sections 2.3.1 and 2.3.2, superposing the masks obtained from the corresponding real galaxy images.

Ellipse errors: for each isophote fit, the “true error” on the isophote center is computed as the difference between the position returned by ellipse and the known photocenter of the synthetic galaxy (i.e., the center position of the Sérsic component fitted by Galfit). These “true errors” are compared to the errors on the positions of the isophote centers returned by ellipse in Fig. 2.3. The “true” error distribution is slightly broader than that of the ellipse errors, but both distributions are highly peaked, with ~50% of fits producing errors ≤ 0.1 pixels. A detailed study by Busko (1996) of the errors returned by ellipse shows that errors on ellipticity, position angle and center position are unbiased and accurate when the radial gradient relative error is less than 50%. This condition is satisfied for our sample galaxies.

Position errors: the “true errors” on the (x,y) coordinates of the AGN

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4For this purpose, the signal-to-noise ratio is defined as the ratio between the flux of the nuclear point source to the standard deviation of the residual measured in the outer regions of the galaxy after subtracting the photometric model from the image.

5The radial gradient relative error ($\sigma'/I'$) is the relative error on the radial gradient of the intensity. This is a default output of ellipse.
2.3 Data Analysis

Figure 2.3: Error distributions for the \( (x, y) \) co-ordinates of isophote center positions derived from \texttt{ellipse} fits to sixteen simulated galaxy images. For each galaxy, a series of ellipses was fitted to the surface brightness distribution, incrementing the SMA by two pixels at each step, as described in Section 2.3.1. The errors returned by the IRAF \texttt{ellipse} task are compared with the “true errors”, defined as the difference between the known position of the center of the model galaxy and the center position returned by the \texttt{ellipse} fit. The errors on each isophote center returned by \texttt{ellipse} are broadly consistent with the true errors. The error distributions combine results from all sixteen simulated galaxy images. The model images were derived from \texttt{Galfit} fits to the following data: NGC 4261/NICMOS2, IC 1459/WFPC2-PC, NGC 1399/WFC3-IR, IC 4296/ACS-HRC.

and galaxy photocenter positions were also determined for each realization of the synthetic galaxy images, where the true error in each case is defined as the difference between the known positions of the AGN and photocenter (i.e., the positions returned by \texttt{Galfit}) and the values recovered using our analysis methods.

For signal-to-noise ratios characteristic of our data \( (S/N \sim 100) \), the distributions of the “true errors” on the AGN and photocenter positions derived from both the ACS and WFPC2 synthetic galaxy images are narrow and confined within 0.1 pixel. We therefore adopt 0.1 pixel as a conservative estimate of the uncertainty on both the AGN and photocenter positions derived from ACS and WFPC2 data. The “true error” obtained from the
2.3 Data Analysis

Table 2.3: PRECISION OF ISOPHOTAL CENTER AND AGN POSITION

<table>
<thead>
<tr>
<th>Precision</th>
<th>ACS HRC</th>
<th>ACS WFC</th>
<th>WFPC2 PC</th>
<th>WFPC2 WF</th>
<th>NICMOS2</th>
<th>WFC3</th>
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</thead>
<tbody>
<tr>
<td>0.1 pxl</td>
<td>2.5</td>
<td>5</td>
<td>5</td>
<td>10</td>
<td>...</td>
<td>9    mas</td>
</tr>
<tr>
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<td>0.2</td>
<td>0.3</td>
<td>0.3</td>
<td>0.6</td>
<td>...</td>
<td>0.6 pc</td>
</tr>
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<td>1</td>
<td>2</td>
<td>2</td>
<td>4.1</td>
<td>...</td>
<td>3.7 pc</td>
</tr>
<tr>
<td>0.2 pxl</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>10</td>
<td>18 mas</td>
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<td>...</td>
<td>...</td>
<td>...</td>
<td>0.6</td>
<td>1.1 pc</td>
</tr>
<tr>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>4</td>
<td>7.3 pc</td>
</tr>
</tbody>
</table>

Note. — Values are given in milli-arcseconds (first row), in parsecs at the nearest galaxy (13 Mpc, second row) and at the farthest (84 Mpc, third row). Similarly for the other rows. Values for NICMOS2 are computed for a pixel scale of 0.05′′/pixel.

WFC3 and NICMOS2 images exhibit broader distributions, with tails extending to 0.4 pixels. We therefore adopt the median values of the “true errors” as the uncertainties for WFC3 and NICMOS2 data, yielding 0.2 pixels for the photocenter position in both cameras and respectively 0.1 and 0.2 pixels for the AGN.

These uncertainties represent the precision with which we can determine the AGN and photocenter positions for an ideal galaxy, in an image with noise characteristics representative of our data. The adopted uncertainties are summarized in Table 2.3, together with the equivalent angular distances and linear distances corresponding to the closest and furthest of our sample galaxies.

Minimum detectable displacement: the uncertainties on the AGN and photocenter coordinates determine the minimum detectable displacement. We require a 3σ detection for a displacement to be considered significant. Combining the uncertainties on the photocenter and AGN in quadrature, the error on each component of the displacement is σ = 0.14 pxl, for ACS and WFPC2 data, σ = 0.22 pxl for WFC3, and σ = 0.28 pxl for NICMOS2 data. Therefore, the minimum displacements considered significant are ∆x = ∆y ≈ 0.4 pxl, for ACS and WFPC2, ∆x = ∆y ≈ 0.7 pxl for WFC3, and ∆x = ∆y ≈ 0.9 pxl for NICMOS2.
### 2.3 Data Analysis

#### 2.3.4.2 Possible biases

**Asymmetric surface brightness distributions**: the galaxies in our sample were selected to be symmetric and regular, based on visual inspection of the images. However, in some cases, the galaxy extends beyond the edges of the frame and/or is not centered in the image frame. To eliminate the possibility of spurious offsets due to truncation of isophotes by the frame edge, the upper limit on the SMA range used in the surface brightness fits is taken to be that of the largest ellipse that fits completely within the frame (Section 2.3.1).

In addition, subtle intrinsic asymmetries might be present that were not revealed by visual inspection. As discussed by Jedrzejewski (1987), asymmetric surface brightness distributions (such as large-scale lopsidedness in the isophotes) will cause shifts in the isophote centers, which in turn will increase the IQR. Therefore, intrinsic surface brightness asymmetries (or other irregularities) will tend to reduce the level of significance assigned to any measured displacement (Section 2.3.3).

A similar possibility is that the outer isophotes are distorted by tidal interactions with nearby galaxies. As our analysis is confined to the inner few kiloparsecs, such interactions are unlikely to significantly affect our results. Nevertheless, we have verified that the photocenter position does not change significantly when recomputed excluding isophote centers corresponding to ellipse SMAs greater than \( \sim \) 85, 90 and 95% of that of the largest complete ellipse that fits within the image frame.

**Isophote twists and PSF effects**: core galaxies are often characterized by strong isophote twisting at radii interior to the core radius, \( r_c \) (Lauer et al., 2005). In addition, the inner isophotes are distorted by the point spread function; TINY TIM simulations show that for the HST instruments used, the PSF can affect the region within a radius \( r_{\text{PSF}} \sim 15 \) pixels. As typically \( r_{\text{PSF}} \lesssim r_c \), we mitigate both effects by setting \( r_c \) as the minimum SMA for the ellipse fits.

**Lopsided stellar nuclei (LSN)**: observations of the nuclear regions of nearby galaxies have revealed the presence of double nuclei with separations in the range 1–10 pc (Lauer et al., 1993, 1996, 2005; Thatte et al., 2000; Debattista et al., 2006). One explanation for such configurations is that
lopsided stellar orbit distributions tend to persist within the SBH sphere of gravitational influence since orbits do not precess in Keplerian potentials and are not, therefore, axisymmetrized by phase mixing (Peiris and Tremaine, 2003). The best studied example is M31, in which the components of the double nucleus are separated by $\approx 0.5$ ($\approx 2$ pc). Peiris and Tremaine (2003) proposed a model for M31 in which the nucleus consists of an eccentric disk of stars orbiting the SBH, the latter being coincident with the fainter component.

The WFPC2 Planetary Camera (with which most of the images studied here were obtained) resolves spatial separations of $\approx 5$ pc only for galaxies within 20 Mpc. It is possible, therefore, that some of the galaxies in our sample harbor unresolved double nuclei. This will not affect the determination of the galaxy photocenter, since the core is excluded from the isophote fitting. However, if the unresolved nuclei are of unequal brightness as in M31, this could result in a systemic error in the AGN position which may approach the PSF FWHM ($\sim 1 - 2$ pixels). This in turn would result in a spurious displacement.

### 2.4 Results

The results of the photometric analysis are presented in Table 2.4, where we list the $(x, y)$ pixel co-ordinates of the mean photocenter and the point source, the magnitudes of the corresponding components of the displacement, the direction of each displacement component on the sky and the significance level of the displacement, determined as outlined in Section 2.3.3.

Figures 2.4 and 2.5 illustrate examples of the results for galaxies in which, respectively, no significant displacement was found (NGC 4373, Fig. 2.4) and in which the measured displacement is considered significant (NGC 4486, Fig. 2.5). In each figure, the top row of panels shows the original image and the residual images after subtraction of, respectively, the isophotal model generated by *ellipse* fits and a median filtered image. In the middle row are plotted the surface brightness profile and the $x$ and $y$ pixel coordinates of the isophotal centers, all as functions of the ellipse SMA. The positions of the photocenter and the AGN point source are also plotted. The leftmost panel of the bottom row is a scatter plot showing the distribution of the isophote
2.4 Results

centers, colour coded according to SMA. The locus of the cumulative mean photocenter position, computed outwards from the inner SMA limit, is also shown as a solid black line. The last two panels show the distributions of the \((x, y)\) isophote center co-ordinates. The co-ordinates of the mean photocenter and the AGN point source are also plotted in all three panels. Similar figures for the remaining galaxies are presented in Section 2.4.1. Results for individual galaxies are described in detail in Section 2.6.

In the case of NGC 4373, the \(x\) and \(y\) components of the displacement are \(< 1\sigma\) and thus consistent with zero. In the case of the ACS/HRC F814W image of NGC 4486, both the \(x\) and \(y\) components of the displacement are significant at the \(> 3\sigma\) level and their magnitudes are \(\geq 2.4 \times \text{IQR}\) and accordingly classified as having a “high” significance level (Table 2.4).

For four galaxies, two or more images obtained with different instruments and/or filters were analyzed, providing various combinations of wavelength and spatial resolution. The photocenter displacements in milliarcseconds, relative to the AGN point source, are plotted for these cases in Fig. 2.6a. There are two galaxies, NGC 4696 and 5419, in which a second point-like brightness peak is present. In these cases, the following discussion refers to the displacement relative to the primary point source (the brighter, which we take to be the AGN), unless otherwise noted.

AGN–photocenter displacements exceeding the minimum detectable value (i.e., significant at \(3\sigma\) level; Section 2.3.4.1) were measured in at least one direction (\(x\) or \(y\)), in at least one image, for ten out of the 14 galaxies in the sample: NGC 1399, 4168, 4278, 4486 (M87), 4636, 4696, 5419, 5846, IC 4296, and IC 4931. In the remaining galaxies, NGC 4261, 4373, 4552, and IC 1459, the AGN and photocenter are coincident within the position uncertainties (< \(3\sigma\)).

The distribution of the isophote center co-ordinates provides an indication of the systematic uncertainty arising from photometric distortions due to effects such as those outlined in Section 2.3.4.2. As discussed in Section 2.3.3, we assign a significance level for each measured displacement based on its magnitude relative to the IQR, which characterizes the width of the isophote center distribution. Three galaxies exhibit displacements (in at least one direction, in one image) \(\Delta x, \Delta y \geq 1.6 \times \text{IQR}\), that we classify as having intermediate or high significance. These are NGC 4278, 4486 (M87) and 5846. Three more have displacements classified as having low signifi-
2.4 Results

cance: NGC 1399, 5419 and IC 4296 ($\Delta x, \Delta y \geq 0.8 \times \text{IQR}$).

In the two double nucleus galaxies, the photocenter position is much closer to the primary point source than the secondary. The offsets (relative to the primary) are $\approx 0.5$ pxl, but given the large IQR in NGC 4696 the displacement is classified as not significant in this case. In neither galaxy does the photocenter lie between the two “nuclei” (Fig. 2.6b, 2.23 and 2.24).

For the galaxies where multiple images were analyzed, the displacements in mas derived from the different images are consistent to within $2\sigma$ for two of the four galaxies (NGC 1399 and 4278).

In the remaining two galaxies (NGC 4486 and IC 4296), the results from one or more images differ significantly from the others (Fig. 2.6a). In IC 4296, the offset measured from the red (F814W) WFPC2 image is significantly different from those measured from the ACS-F625W and NICMOS2 F160W images, which are consistent to within $2\sigma$. This galaxy has a warped dusty disk oriented approximately E-W, extending $\approx 1''$ either side of the nucleus but it seems unlikely that this structure is the cause of the discrepancy, the origin of which remains unclear.

Several ACS, NICMOS2 and WFPC2 images were analyzed for NGC 4486 (M87). For the ACS red optical image (F814W) we recover the B10 result, which indicates that the photocenter is displaced by $\approx 100$ mas to the north-west of the nucleus. A smaller but less significant offset in approximately the same direction is measured from the WFPC2 F814W image. However, the photocenters derived from the NICMOS2 F110W, F160M and F222W image are consistent with the AGN position. As discussed in detail in Section 2.6, the origin of these differences is unclear. Neither dust, nor the prominent optical jet (also visible in the NIR) appear to provide satisfactory explanations. The central region of the galaxy where the isophote fitting was performed ($1'' \leq r \leq 3''$) appears to be free of large scale dust features. The masking procedure should prevent the jet from distorting the isophote fits but in any case, even when the fits were repeated with different levels of masking and even with no mask at all, no significant differences in the mean photocenter position were found. As there is no compelling reason to favor or discard the results from any given image, we compute a weighted average displacement.

Whether classified as significant, or not, the measured angular photocenter displacements are always small, typically a few $\times 10$ mas and almost
2.4 Results

without exception \(\lesssim 100\) mas. The only cases that exceed 100 mas are the displacements relative to the secondary point sources in the two double nucleus galaxies. Disregarding these, the projected linear displacements are all \(\lesssim 10\) pc. Therefore, for every galaxy analyzed, the measured displacement is a small fraction of the galaxy core radius; as a fraction of \(r_c\), the range in displacement magnitude is approximately 1–10%.

In our previous analysis of NGC 4486 (B10), we found that the galaxy photocenter (in ACS and WFPC images) is displaced in approximately the same direction as the jet, implying that the SBH is displaced in the counter-jet direction. It is therefore of interest to compare the direction of the measured photocenter displacements with the radio source axis for this sample. In Table 2.5, we give the position angle (PA) of the radio source, for those galaxies in which jets or jet-like extended structures have been observed, along with the PA of the measured displacement (as derived from the \(x, y\) components). Five galaxies are associated with relatively powerful, extended (\(\sim 10\) kpc) radio sources: NGC 1399, 4261, 4486, 4696 and IC 4296. Of these, NGC 4486 (M 87; 3C 274), NGC 4261 (3C 270) and IC 4296 (PKS 1333-33) are Fanaroff-Riley Type I (FRI) radio sources, characterized by prominent twin jets ending in kiloparsec-scale lobes (Fanaroff and Riley, 1974). All three also have parsec-scale jets approximately aligned with the kpc-scale structure.

In NGC 4486, the displacement PA derived from our reanalysis of the ACS F814W image agrees with the B10 result. The direction of the weighted mean displacement, derived from displacements obtained from all the images, is also closely aligned with the jet direction. We find a similar result for IC 4296. As already noted, the results from the ACS and NICMOS2 images are consistent and indicate a displacement to the NW. If the discrepant WFPC2 result is disregarded, the weighted mean of the ACS and NICMOS2 displacements yields a PA only \(\sim 4^\circ\) different from that of the large-scale radio axis, with the photocenter displaced on the side of the brighter north-western jet.

The displacement measured in NGC 4261 is not considered to be significant \((<3\sigma)\). Nevertheless, the derived PA is consistent (albeit within the large uncertainty) with that of the radio axis, and again, the offset is in the

\footnote{We omit NGC 5419 from this list, since the origin of its unusual radio source is unclear, see Section 2.6.}
2.4 Results

direction of the brighter western jet.

NGC 1399 also has an FRI-like radio source morphology with a well-defined axis in PA \( \approx -10^\circ \). The measured displacement (classified as low significance) has a consistent PA with a value of \(-17 \pm 16^\circ\). NGC 4696, is one of the galaxies with two optical point sources. Its large scale radio source does not exhibit well-defined jets, but is elongated approximately E–W over \( \sim 10 \) kpc, with the ends of both “arms” bending south. At parsec scales there is a compact core with a one-sided jet emerging to the SW in PA \( \sim -150^\circ \). However, it is not clear which of the two optical nuclei hosts the core radio source (Taylor et al., 2006), complicating the comparison with the photocenter displacement. If the secondary point source is identified as the AGN, then the photocenter, which is close to the primary point source, is displaced approximately in the counter-jet direction. On the other hand, if the primary point source is indeed the AGN, the displacement (which, in any case, is classified as having “null” significance) would be almost perpendicular to the jet.

Three more galaxies have relatively weak, small radio sources that have jet-like features or elongations on sub-kiloparsec scales. The measured photocenter displacements are not aligned with the radio source axis in NGC 4552 or NGC 4636. NGC 4278 has a compact (\( \sim 3 \) pc) source consisting of a core with jet-like features emerging along a SE–NW axis on either side. These features gradually bend to the east and west, respectively, becoming fainter and more diffuse. The weighted mean photocenter position is displaced approximately in the initial direction of the SE jet. According to Giroletti et al. (2005)’s analysis of this source, the jet axis is closely aligned with our line of sight, with the SE component being the oppositely directed counter-jet.
2.4 Results

Figure 2.4: Example of a galaxy where the displacement is not significant. NGC 4373, WFPC2/PC - F814W, scale=0.05′′/pxl. **First row** - left to right: the galaxy (counts s\(^{-1}\)); galaxy after subtraction of the isophotal model; galaxy after subtraction of the median filter. **Second row** - surface brightness profile in counts s\(^{-1}\); second and third panels: \(x\) and \(y\) coordinates of the isophotal centers versus semi-major axis length. Blue diamond: AGN; red bullet: photocenter. The blue diamond and the red bullet are not positioned both at SMA=0 to make the figure clear avoiding superpositions. **Third row** - scatter plot of the isophote centers. The solid line (near the photocenter) is the cumulative photocenter computed including progressively all data from the core radius outward. Different colors for the data points are used to represent the centers of isophotes with SMA length in a given range. Defining \(w = 33\% (SMA_{\text{max}} - r_c)\): green: \(r_c < SMA \leq r_c + w\), orange: \(r_c + w < SMA \leq r_c + 2w\), brown: \(r_c + 2w < SMA < SMA_{\text{max}}\). Second and third panels: histograms of the distributions of the \(x\) and \(y\) coordinates of the isophotal centers.
2.4 Results

Figure 2.5: Example of a galaxy where the displacement is significant. NGC 4486 (M 87), ACS/HRC/F814W, scale=0\textquotesingle 025/pix. **First row** - left to right: the galaxy (counts s$^{-1}$); galaxy after subtraction of the isophotal model; galaxy after subtraction of the median filter. **Second row** - surface brightness profile in counts s$^{-1}$; second and third panels: $x$ and $y$ coordinates of the isophotal centers versus semi-major axis length. Blue diamond: AGN; red bullet: photocenter. The blue diamond and the red bullet are not positioned both at SMA=0 to make the figure clear avoiding superpositions. **Third row** - scatter plot of the isophote centers. The solid line (ending on the photocenter) is the cumulative photocenter computed including progressively all data from the core radius outward. Different colors for the data points are used to represent the centers of isophotes with SMA length in a given range. Defining $w = 33\%(SMA_{\text{max}} - r_c)$: green: $r_c < SMA \leq r_c + w$, orange: $r_c + w < SMA \leq r_c + 2w$, brown: $r_c + 2w < SMA < SMA_{\text{max}}$. Second and third panels: histograms of the distributions of the $x$ and $y$ coordinates of the isophotal centers.
Table 2.4: MEASURED PROJECTED OFFSETS

(1) Optical name; (2) instrument/camera/filter on HST; (3) lower and upper limit, in arcseconds, of the region analyzed; (4) inter-quartile range in pixel, this is the difference between 75th and 25th percentile of the isophotal center dataset; (5) photocenter position in pixel on the frame; (6) nuclear point source position in pixels; (7 - 8) offset of the isophotal center with respect to the nuclear point source in pixels and milliarcseconds; (9) offset in pixel normalized by the corresponding IQR; (10) offset in pc; (11) direction of the offset; (12) type of displacement as defined in Section 2.3.3.

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<thead>
<tr>
<th>Galaxy</th>
<th>Instrument</th>
<th>region</th>
<th>Offset</th>
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<td></td>
<td></td>
<td>(X)</td>
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<td>NGC 4373</td>
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<td>0.58</td>
<td>2328.7 ± 0.1</td>
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<td><strong>0.8 ± 0.14</strong></td>
<td>55 ± 7</td>
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<td>ACS/HRC - F606W</td>
<td>[1:3]</td>
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<td>419.1 ± 0.1</td>
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<td>WFPC2/PC - F814W</td>
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<tr>
<td>NICMOS2 - F160W</td>
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<td></td>
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<td>245.8 ± 0.2</td>
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<td><strong>0.6 ± 0.3</strong></td>
<td>30 ± 15</td>
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<td>NICMOS2 - F110W</td>
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<td></td>
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<td>207.2 ± 0.2</td>
<td>206.8 ± 0.2</td>
<td><strong>0.4 ± 0.3</strong></td>
<td>20 ± 15</td>
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<td>NICMOS2 - F160W</td>
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<td>207.5 ± 0.2</td>
<td>207.4 ± 0.2</td>
<td><strong>0.1 ± 0.14</strong></td>
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<td><strong>0.4 ± 0.3</strong></td>
<td>20 ± 15</td>
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<td>WFPC2/PC - F814W</td>
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<td>0.42</td>
<td>448.3 ± 0.1</td>
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<td><strong>0.7 ± 0.14</strong></td>
<td>35 ± 7</td>
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Notes: — *: for further details see Table 1 in Batcheldor et al. (2010).
Table 2.4: MEASURED PROJECTED OFFSETS (continued)

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<tr>
<th>Galaxy</th>
<th>Instrument</th>
<th>region</th>
<th>X</th>
<th>Y</th>
<th>Offset</th>
<th>Dir Type</th>
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<td>NGC 4552</td>
<td>WFPC2/PC - F814W</td>
<td>[1:15]</td>
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<td>538.9 ± 0.1</td>
<td>538.7 ± 0.1</td>
<td>0.2 ± 0.14</td>
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<td>0.89</td>
<td>500.8 ± 0.1</td>
<td>500.4 ± 0.2</td>
<td>0.4 ± 0.23</td>
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<td>NGC 4636</td>
<td>WFPC2/PC - F814W</td>
<td>[4:14]</td>
<td>0.94</td>
<td>698 ± 0.1</td>
<td>697.4 ± 0.1</td>
<td>0.6 ± 0.14</td>
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<td>0.93</td>
<td>569.9 ± 0.1</td>
<td>570 ± 0.1</td>
<td>0.1 ± 0.14</td>
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<td>NGC 4696</td>
<td>ACS/WFC - F814W</td>
<td>[1.5:16]</td>
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<td>1582.9 ± 0.1</td>
<td>1583.4 ± 0.1</td>
<td>0.5 ± 0.14</td>
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<td>3.78</td>
<td>2977.6 ± 0.1</td>
<td>2977.8 ± 0.1</td>
<td>0.2 ± 0.14</td>
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<td>NGC 5419</td>
<td>WFPC2/PC - F555W</td>
<td>[2:13.5]</td>
<td>0.5</td>
<td>398.4 ± 0.1</td>
<td>397.8 ± 0.1</td>
<td>1.3 ± 0.14</td>
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<td>0.22</td>
<td>447.6 ± 0.1</td>
<td>447.8 ± 0.1</td>
<td>5.1 ± 0.14</td>
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<tr>
<td>NGC 5846</td>
<td>WFPC2/PC - F814W</td>
<td>[1.6:15.8]</td>
<td>0.84</td>
<td>519.5 ± 0.1</td>
<td>518.2 ± 0.4</td>
<td>1.3 ± 0.4</td>
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<td>1.05</td>
<td>466 ± 0.1</td>
<td>466.4 ± 0.1</td>
<td>0.4 ± 0.14</td>
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<td>IC 1459</td>
<td>WFPC2/PC - F814W</td>
<td>[2.5:15]</td>
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<td>536.4 ± 0.1</td>
<td>536.7 ± 0.1</td>
<td>0.3 ± 0.14</td>
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<td>0.50</td>
<td>510.5 ± 0.1</td>
<td>510.7 ± 0.1</td>
<td>0.2 ± 0.14</td>
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## Table 2.4: MEASURED PROJECTED OFFSETS (continued)

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<tr>
<th>Galaxy</th>
<th>Instrument</th>
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<th>Offset</th>
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<td>PC</td>
<td>NPS1</td>
<td>NPS2</td>
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<td></td>
<td>[pxl]</td>
<td>[mas]</td>
<td>[IQR]</td>
<td>[pc]</td>
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<tr>
<td>IC 4296</td>
<td>ACS/HRC - F625W</td>
<td>0.49</td>
<td>833.3 ± 0.1</td>
<td>832.6 ± 0.2</td>
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<td>0.38</td>
<td>785.3 ± 0.1</td>
<td>784.8 ± 0.1</td>
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<td>WFPC2/PC - F814W</td>
<td>0.39</td>
<td>551.5 ± 0.1</td>
<td>552 ± 0.18</td>
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<td>0.5 ± 0.2</td>
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<td>0.13</td>
<td>515 ± 0.1</td>
<td>514.9 ± 0.18</td>
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<td>NICMOS2 - F160W</td>
<td>0.13</td>
<td>420.8 ± 0.2</td>
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<td>1.07</td>
<td>253.4 ± 0.2</td>
<td>252.7 ± 0.1</td>
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<td>IC 4931</td>
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<td>1.29</td>
<td>403.6 ± 0.1</td>
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<td>0.66</td>
<td>505.9 ± 0.1</td>
<td>505.8 ± 0.1</td>
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Figure 2.6a: Offset of the isophotal center with respect to the SBH as measured with different instruments, at different frequencies. Each photocenter is centered on an ellipse whose axes represent the IQR of the isophote centers dataset used to derive the photocenter. Error bars represent the error on the offset. The diamond marks the origin of the reference frame (SBH position).
2.4 Results

Table 2.5: RADIO JET AND PHOTOCENTER POSITION ANGLES

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<th>PA (deg)</th>
<th>jet displacement</th>
<th>NPS1</th>
<th>NPS2</th>
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<tr>
<td>kpc-scale jets:</td>
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<tr>
<td>NGC 1399</td>
<td>−10</td>
<td>−17 ± 16°</td>
<td>...</td>
<td>low</td>
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<tr>
<td>NGC 4261</td>
<td>87 ± 8</td>
<td>297 ± 38 (117 ± 38)</td>
<td>...</td>
<td>non significant</td>
</tr>
<tr>
<td>NGC 4486</td>
<td>290 ± 3</td>
<td>307 ± 1 (127 ± 1)</td>
<td>...</td>
<td>†</td>
</tr>
<tr>
<td>NGC 4696</td>
<td>210 (+30)</td>
<td>112 ± 15</td>
<td>36 ± 1</td>
<td>†</td>
</tr>
<tr>
<td>IC 4296</td>
<td>130</td>
<td>338 ± 7 (158 ± 8)</td>
<td>...</td>
<td>low</td>
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<tr>
<td>pc-scale jets:</td>
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<tr>
<td>NGC 4278</td>
<td>100 − 155</td>
<td>152 ± 3</td>
<td>...</td>
<td>†</td>
</tr>
<tr>
<td>NGC 4552</td>
<td>50</td>
<td>333 ± 21</td>
<td>...</td>
<td>low</td>
</tr>
<tr>
<td>NGC 4636</td>
<td>35</td>
<td>261 ± 9 (81 ± 9)</td>
<td>...</td>
<td>null</td>
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Notes: — Photocenter position angles are computed with respect to the nuclear point source. Angles increase east of north. When multiple values have been derived from different images an error weighted mean is computed. Values in parenthesis indicate the supplementary angles (i.e. $\theta + 180^\circ$). † The significance changes for different instruments (see Table 2.4). a This value changes to $−8 ± 16^\circ$ when only WFPC2 results are considered. b This value changes to $312 ± 8^\circ$ ($132 ± 8^\circ$) when only ACS and NICMOS2 results are considered. See Table 2.2 for references on the radio jet PA.

![Figure 2.6b](image1.png)

Figure 2.6b: As in Fig. 2.6a for the galaxies showing a double nuclear point source. The offset of the fainter nuclear point source with respect to the SBH is marked with a diamond and the label NPS2.
2.4 Results

2.4.1 Images, surface brightness and isophotal center distributions

Figure 2.7: As in Fig 2.4 for NGC 1399, WFPC2/PC - F606W, scale=0'05/pix.
2.4 Results

Figure 2.8: As in Fig 2.4 for NGC 1399, WFPC2/PC - F814W, scale=0′05/pixel.
Figure 2.9: As in Fig. 2.4 for NGC 1399, WFC3/IR - F110W, scale=0\textquoteleft 09/pixel.
Figure 2.10: As in Fig 2.4 for NGC 1399, WFC3/IR - F160W, scale=0''09/pix.
Figure 2.11: As in Fig.2.4 for NGC 4168, WFPC2/PC - F702W, scale=0′′05/pixel.
Figure 2.12: As in Fig 2.4 for NGC 4261, NICMOS2 - F160W, scale=0.05/pxl.
Figure 2.13: As in Fig 2.4 for NGC 4278, ACS/WFC - F850LP, scale=0\textquotesingle 05/pixel.
2.4 Results

Figure 2.14: As in Fig. 2.4 for NGC 4278, WFPC2/PC - F814W, scale=0’05/pxl.
Figure 2.15: As in Fig. 2.4 for NGC 4278, NICMOS2 - F160W, scale=\textquotesingle 0.05/pxl.
Figure 2.16: As in Fig 2.4 for NGC 4486 (M 87), ACS/HRC - F606W, scale=0'025/pxl.
Figure 2.17: As in Fig. 2.4 for NGC 4486 (M 87), NICMOS2 - F110W, scale=0′05/pix.
2.4 Results

Figure 2.18: As in Fig 2.4 for NGC 4486 (M 87), NICMOS2 - F160W, scale=0f05/pxl.
Figure 2.19: As in Fig. 2.4 for NGC 4486 (M 87), NICMOS2 - F222M, scale=0‘05/pxl.
Figure 2.20: As in Fig. 2.4 for NGC 4486 (M 87), WFPC2/PC - F814W, scale=0′/05/pixel.
Figure 2.21: As in Fig. 2.4 for NGC 4552, WFPC2/PC - F814W, scale=0'05/pixel.
Figure 2.22: As in Fig. 2.4 for NGC 4636, WFPC2/PC - F814W, scale=0''05/pix.
Figure 2.23: As in Fig. 2.4 for NGC 4696, ACS/WFC - F814W, scale=0.05′/pxl.
Figure 2.24: As in Fig.2.4 for NGC 5419, WFPC2/PC - F555W, scale=0.05/pxl.
Figure 2.25: As in Fig 2.4 for NGC 5846, WFPC2/PC - F814W, scale=0′05/pixel.
Figure 2.26: As in Fig. 2.4 for IC 1459, WFPC2/PC - F814W, scale=0′′05/pxl.
Figure 2.27: As in Fig. 2.4 for IC 4296, ACS/HRC - F625W, scale=0′025/pixel.
Figure 2.28: As in Fig.2.4 for IC 4296, WFPC2/PC - F814W, scale=0\textquoteright05/pxl.
Figure 2.29: As in Fig. 2.4 for IC 4296, NICMOS2 - F160W, scale=0''05/pix.
Figure 2.30: As in Fig. 2.4 for IC 4931, WFPC2/PC - F814W, scale=0'05/pix.
2.5 Discussion

In this section we will examine our key assumption that the SBH position is marked by the nuclear point source. We will then discuss the possible origins of the observed offsets. Most of the displacement mechanisms considered below have been previously discussed in B10. Nevertheless, I summarize them here in order to provide context for our new results.

2.5.1 The AGN nature of the nuclear point sources

Our sample of 14 core elliptical galaxies was selected from the 26 (out of 29) studied by BC06 that were identified as containing AGN based on the presence of i) an unresolved optical or X-ray source; ii) an “AGN-like” optical spectrum, or iii) radio jets. Most of our sample of 14 exhibit two or more AGN signatures in addition to the presence of a radio source and optical point source nucleus. Optical or UV variability has been detected in HST observations of NGC 4486 (Perlman et al., 2003), NGC1399 (O’Connell et al., 2005), NGC4552 (Cappellari et al., 1999; Maoz et al., 2005) and NGC 4278 (Cardullo et al., 2009). Hard X-ray point sources have been detected in NGC 4261, 4278, 4486, 4552, 5419 and IC 1459 (González-Martín et al., 2009). Weak broad Hα lines (NGC 4278, 4636 and NGC 4168), or emission line ratios indicative of AGN photoionization (NGC 4261, 4486, 4552, 5846) have also been detected in several galaxies (Ho et al., 1997). In addition, the radio sources in most objects feature compact (≲ 1 pc) cores (NGC 1399, 4168, 4373, 4552, 5419, IC 1459) and/or parsec or kpc-scale jets (NGC 4261, 4278, 4486, 4696, IC 4296; see Section 2.6 for references). Only IC 4931, which by comparison has been relatively little studied, lacks supporting evidence indicating the presence of an AGN in the form of X-ray, radio or line emission.

There is, therefore, plenty of evidence that these galaxies (with the possible exception of IC 4931) host AGNs. However, it does not necessarily follow (except in cases where optical/UV variability has been observed) that the optical or NIR point sources are themselves manifestations of the AGN, rather than, for example, nuclear star clusters. Low luminosity radio loud AGNs are thought to be powered by radiatively inefficient accretion flows (see, for example, Ho 2008, Balmaverde et al., 2008 and references therein), with most of the accretion power channeled into the kinetic energy of the
2.5 Discussion

Radio jets. Detailed studies of NGC4486 (Di Matteo et al., 2003), IC 1459 (Fabbiano et al., 2003) and IC 4296 (Pellegrini et al., 2003) show that this is the case for at least three galaxies of our sample.

In low luminosity radio galaxies, the optical, near infrared and X-ray luminosities of the nuclei correlate tightly with the core radio luminosity, implying a common origin in non-thermal emission from the jet (Chiaberge et al., 1999; Capetti and Balmaverde, 2005; Baldi et al., 2010). This is supported by polarization measurements: Capetti et al. (2007) found that the optical nuclei of the nine nearest FR I radio galaxies in the 3C catalogue, including two galaxies from our sample, NGC 4486 (M87, 3C 274) and NGC 4261 (3C 270), have high polarizations (2−11%), which they attribute to synchrotron emission. The optical or UV variability of the point sources in NGC 4486 and three other galaxies, noted above, is also consistent with jet synchrotron emission. More generally, BC06 found that their sample of core elliptical galaxies, from which this sample is drawn, also exhibit optical-radio and X-ray-radio correlations and indeed form a continuous distribution with the radio galaxies, extending these correlations to lower luminosities. Therefore, there is direct evidence, in the form of optical polarization and/or optical/UV variability that the nuclear sources in five of our sample galaxies are produced by synchrotron emission associated with the radio core source, presumably the base of the jet. It is reasonable to assume, given the correlations found by BC06, that the same is true for the rest of the sample.

The base of the jet is, in turn, very close to the SBH. Arguably the best studied jet is that of M87. Using multifrequency observations made with the Very Long Baseline Array, Hada et al. (2011) were able to show that the radio core at 43 GHz is located within 14-23 Schwarzschild radii of the SBH and accretion flow. In the optical, the lower optical depth should move the peak of the emission even closer to the SBH.

In summary, we contend that there are good reasons to believe that the optical or near-infrared point sources in our galaxies reveal the position of the SBH.

2.5.2 Recoiling SBHs

Here we consider if the measured SBH displacements are consistent with residual oscillations due to gravitational recoils generated by coalescence of
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an SBH binary.

GM08 used \textit{N}-body simulations to study the post recoil dynamical evolution of an SBH in representative core elliptical galaxy potentials. They found that when the recoil velocity is sufficient to eject the SBH from the core ($v_{\text{kick}}$ in the range $\sim 40 - 90\%$ of the escape velocity, $v_{\text{esc}}$), the subsequent motion is characterized by three phases. The initial large-amplitude ($>r_c$) oscillations are damped relatively quickly ($\sim 10^7$ yr) by dynamical friction (phase I). When the amplitude becomes comparable with the core radius, $r_c$, the SBH and the stellar core undergo long-lived oscillations about their center of mass, which persist for $\sim 1$ Gyr (phase II). Finally, the SBH reaches thermal equilibrium with the stars, experiencing low-amplitude Brownian motion (phase III).

As our measured displacements are $\lesssim 0.1 r_c$, it is highly unlikely that they represent phase I oscillations. This would require either fortuitous timing (the SBH would have to be caught whilst passing through or close to the equilibrium position) and/or orientation (the oscillation direction would have to be closely aligned with the line of sight) for each galaxy. We also rule out phase III Brownian motion due to interactions with individual stars, which will produce negligibly small amplitudes in real galaxies (GM08). The possibility of Brownian oscillation due to interactions with massive perturbers is discussed in Section 2.5.4. Here, we focus on phase II which, as already noted, is characterized by long-lived damped oscillations at amplitudes $< r_c$.

In this phase, the characteristic damping time is given by GM08 as:

$$\tau \approx 15 \frac{\sigma^3}{G^2 \rho M_*} \approx 2 \times 10^9 \sigma_{300}^{-3.86} r_{500}^2 \text{ yr} \quad (2.2)$$

where the approximation on the right-hand side makes use of the $M_* - \sigma$ relation [Ferrarese and Ford 2005], $\sigma$ being the 1D stellar velocity dispersion, with $r_{500} \equiv r_c/(500 \text{ pc})$ and $\sigma_{300} \equiv \sigma/300$ km s$^{-1}$. For our galaxies, eq. (2.2) yields values of $\tau$ in the range $0.02 - 4.85$ Gyr, with an average of 1.2 Gyr (Table 2.7). The rms amplitude of the SBH motion with respect to the galaxy center is expected to evolve as:
where \( t_c \) is the time at which the oscillation amplitude has decayed to a scale comparable to the core radius \( r_c \) (B10).

Simulations indicate that the galaxy merger rate is a strong function of redshift and galaxy mass (e.g., Fakhouri et al. [2010] H10). The merger rate for brightest cluster galaxies has recently been determined observationally by Lidman et al. [2013], who find \( \approx 0.4 \) mergers per Gyr at \( z \sim 1 \), implying a mean time between mergers of \( \approx 2.5 \) Gyr. If we take this as representative of our sample, equations 2.2 and 2.3 together suggest that a “typical” rms displacement (ignoring projection effects) is \( \sim 0.2 \) \( r_c \). This suggests that larger displacements than were actually observed might be expected if due to post gravitational recoil oscillations.

However, equation 2.3 describes the oscillation amplitude rather than the instantaneous displacement and moreover the above estimate does not account for projection effects, or the range in damping timescales characterizing our sample galaxies, or for variations in the merger rate. In order to investigate in more detail the likelihood of obtaining the observed displacements in our sample, if they result from post-recoil oscillations, we have constructed a simple Monte-Carlo simulation based on the GM08 \( N \)-body simulations. Details of the method are given in Section 2.5.3. However, we start from the assumption that, after any kick large enough to move the SBH beyond the core radius, the distance, \( R \), of the SBH from the center of the galaxy is given by:

\[
R(t) = R_0 e^{-\Delta t/\tau} \sin(\omega_c \Delta t) \tag{2.4}
\]

where \( \Delta t \) is the elapsed time since the kick, i.e., the time since the last merger, \( \tau \) is the damping time given by eq. 2.2 and \( \omega_c \) is the SBH oscillation frequency calculated from eq. 2.7. We set \( R_0 = r_c \), since phase II begins when the oscillation amplitude is roughly equal to the core radius. We then suppose that each galaxy is observed at a random time, \( \Delta t \), since its last merger, where the probability that the merger occurred at time \( \Delta t \) follows an exponential distribution characterized by a mean time-between-mergers,
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This distribution is sampled to generate corresponding values of $R_i \equiv R(t_i)$, which are then projected onto the sky plane assuming that the recoil kicks have random directions. The distribution of projected displacement for each galaxy is then used to compute the probability, $p_i$, of observing a displacement larger than that actually measured, given a kick of sufficient magnitude.

These probabilities were computed for two values of the mean time between mergers: $t_m = 5.0$ Gyr and $t_m = 0.4$ Gyr, which were derived from the galaxy merger rate models of H10 for redshifts $z < 1$, mass ratios $q > 0.1$ and galaxy masses $\log(M_{\text{gal}}/M_\odot) > 11$ and $\log(M_{\text{gal}}/M_\odot) > 12$, respectively (see Section 2.5.3 for details). The two values of $t_m$ are representative of the mass range covered by our sample, and illustrate the effect on the displacement probabilities of the strong galaxy mass dependence of the merger rate.

The probabilities, $p_i$, are listed for each galaxy in Table 2.6 for both values of $t_m$. The probabilities $P(d > x)$ of observing a projected displacement $d$ exceeding distance $x$ are plotted as functions of $x$ in Figures 2.31a and 2.31b for each galaxy, along with the observed displacement.

As would be expected, the smaller value of $t_m$ results in larger values of $p_i$; clearly if $t_m \lesssim \tau$, there is a greater chance of observing a large displacement than when $t_m >> \tau$. For $t_m = 0.4$ Gyr, $p_i > 0.5$ for all but two galaxies (NGC 4278 and NGC 4552) and $p_i \geq 0.95$ for all 6 galaxies that have masses $\geq 10^{12} M_\odot$ (for which this value of $t_m$ is presumably most relevant). On the other hand, for $t_m = 5.0$ Gyr, all but four galaxies have $p_i < 0.5$, including five of the six having displacements considered significant at the level of $> 0.8$ IQR (the exception is M87, for which $p_i = 0.75$).

Considering the sample as a whole, the probability of not observing a displacement larger than those actually measured in any of the galaxies in the sample is simply $P = \prod_i (1 - p_i)$. For $t_m = 0.4$ Gyr, this is negligibly small, $P \sim 10^{-17}$. Even for $t_m = 5.0$ Gyr, $P \approx 3 \times 10^{-4}$, indicating that it is statistically unlikely that larger displacements were not observed, given the occurrence of a recoil kick sufficient to trigger phase II oscillations.

However, it is unlikely that all the galaxies in the sample experienced a recoil kick big enough to move the SBH beyond the core radius. Assuming that the potential experienced by the SBH can be approximated as a harmonic potential ($\phi = \frac{1}{2} \omega^2 x^2$), we estimated the kick velocity required to
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displace the SBH out to the core radius for each galaxy, obtaining values in the range $159 \lesssim v_{\text{kick}} \lesssim 325$ km s$^{-1}$, with an average of $v_{\text{kick}} \approx 240$ km s$^{-1}$ (the values for each galaxy are listed in Table 2.7).

L12 have studied kick velocity distributions for “hang-up” kicks, which arise in binary configurations where the SBH spins are partially aligned with the orbital angular momentum by pre-merger accretion. For spin magnitude and orientation distributions derived from accretion simulations and a mass ratio distribution based on galaxy merger studies (including both minor and major mergers), they generate probability distributions for the magnitude of the recoil velocity for two extreme cases of “hot” and “cold” gas disks (i.e., corresponding to adiabatic indices $\gamma = 5/3$ and $7/5$, respectively). The former regime is likely to be most applicable to the ellipticals in our sample and in this case, probabilities range from $p_k \approx 66\%$ for kicks $> 100$ km s$^{-1}$ to $\approx 33\%$ for kicks $> 300$ km s$^{-1}$. Our Monte-Carlo simulation assumes that the coalescence event produces a recoil large enough to produce phase II oscillations (i.e., the values given in Table 2.7). As the probabilities $p_i$ are conditional on the occurrence of a kick of sufficient magnitude, the probability that both events will occur is $p_k \times p_i$. There is thus a smaller probability of observing a displacement larger than actually measured for each galaxy. Using the kick probabilities given by L12, we find that the probability of not observing a displacement larger than those actually measured in the entire sample is $P' \approx 8 \times 10^{-4}$ for $t_m = 0.4$ Gyr and $P' \approx 5 \times 10^{-2}$ for $t_m = 5.0$ Gyr.

As the merger rate increases with redshift, we may have underestimated the time-between-mergers by integrating over the redshift range $z = 1 \rightarrow 0$. However, the higher value of $t_m$ used in the simulation implies a merger rate ($\sim 0.2$ mergers Gyr$^{-1}$) consistent with that given by the models of H10 for log($M_{\text{gal}}/M_\odot) > 11$ galaxies at $z = 0$ (see their Fig. 3). The rate for major mergers is a factor 2–3 lower than the rate for major and minor mergers combined, which we used to estimate $t_m$. However, although the magnitude of the recoil velocity is a function of SBH mass ratio (with the largest recoils occurring for mass ratios characteristic of major mergers), even small ($q > 0.1$) mass ratios are capable of producing kicks $\sim 200$ km s$^{-1}$, large enough to trigger phase II oscillations in our galaxies [Lousto et al., 2010]. Minor mergers were, in any case, included in computing the kick velocity distribution presented by L12.

Thus, even allowing for the distribution of kick velocities, the Monte-
2.5 Discussion

Carlo simulation suggests that it is highly likely that displacements larger than those actually measured would have been observed in this sample if each galaxy has experienced at least one merger leading to an SBH-binary coalescence and gravitational recoil within the last few Gyr. In fact, our simulations suggest that \( t_m \geq 30 - 40 \, \text{Gyr} \), corresponding to a merger rate \( \sim 0.03 \, \text{mergers Gyr}^{-1} \), is required for a \( > 50\% \) chance of not observing larger displacements in the sample.

If, indeed, the formation of a binary SBH is an inevitable outcome of galaxy mergers, explanations must be sought in the evolution of the binary or that of the recoiling SBH. Possibilities include (1) the binary stalls before reaching the radius at which gravitational wave emission drives rapid coalescence; (2) if coalescence occurs, the mass ratio or spin-orbit properties of the binary are such as to typically preclude recoil velocities large enough to displace the SBH to the core radius \( \gtrsim 240 \, \text{km s}^{-1} \); or (3) the damping time for the recoil oscillations may be shorter than predicted by the pure \( N \)-body simulations.

Alternatively, it is possible that galaxy mergers are much more infrequent than inferred from studies based on the current \( \Lambda \text{CDM} \) framework (see Kroupa, 2014, and references therein for a detailed discussion).

Although our results imply that SBH displacements due to gravitational recoil are much less common than might be inferred from theoretical considerations, this does not preclude the possibility that observed displacements in individual galaxies are due to recoil oscillations. Indeed, the \( p_i \) values listed in Table 2.6 indicate that for \( t_m = 5.0 \, \text{Gyr} \), the chance of not observing a larger displacement, given a sufficiently large kick, is \( \gtrsim 30\% \) for all objects having a displacement considered significant. Even for \( t_m = 0.4 \, \text{Gyr} \), there are still three of these galaxies for which \( 1 - p_i \geq 0.25 \). The likelihood that the recovered offset is due to SBH coalescence is discussed for individual galaxies in Section 2.6.

Assuming that the measured displacements are indeed due to phase II recoil oscillations, we have used eq. 2.3 to estimate the merger epoch for those galaxies with displacements rated at least as “low significance” in terms of the isophote centroid IQR. Allowing for the time taken for the SBH binary to form and subsequently coalesce in the center of the merged galaxy, and for phase I oscillations, the elapsed times since the merger are typically \( \sim \) several Gyr, comparable with the mean time between galaxy mergers.
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estimated here for galaxy masses \( \log(M_{\text{gal}}/M_\odot) > 11 \), and consistent with the observationally determined merger rate for brightest cluster galaxies [Lidman et al., 2013].

Eq. 2.2 used to estimate the SBH damping time, relies on the \( M_\bullet - \sigma \) relation (Ferrarese and Ford, 2005). To test the dependence of our result on the value adopted for \( M_\bullet \) we use eq. 6 in Lauer et al. (2007) to estimate SBH masses using the \( M_\bullet - M_V \) relation (see Table 2.8 and Section 2.5.3 for more details). Using these alternative masses, and taking into account the kick velocity distribution computed by L12, we derive new values for \( P' \) obtaining \( 1 \times 10^{-3} \), instead of \( 8 \times 10^{-4} \), for \( t_m = 0.4 \) Gyr and \( P' \approx 0.14 \) instead of 0.05 for \( t_m = 5 \) Gyr. The likelihood of our result is somewhat increased for \( t_m = 5 \) Gyr, however there is still a large probability of finding displacements larger than those measured, leaving our basic conclusion unchanged.

No useful constraints can be obtained on the merger epoch from consideration of the time necessary to replenish the stellar population of the core. This is roughly the relaxation time, \( T_{\text{rel}} \), at the influence radius of the central SBH, which can be estimated as:

\[
T_{\text{r}}(r_i) \approx 1.2 \times 10^{11} \sigma_{100}^{7.47} \text{ yr}
\]

Merritt (2013, eq. 3.5). Given that the measured velocity dispersion is always > 100 km s\(^{-1}\) in the centers of our galaxies (see Table 2.7), it is clear that the replenishment time is much longer than the timescales involved in the SBH merger-recoil event (\( \sim 10^9 \) yr).

In general, coalescence of an SBH-binary results in a re-orientation of the SBH spin axis, leading to a sudden flip in the direction of the associated radio jet (Merritt and Ekers, 2002). Therefore, the radio source morphology may act as a “signpost” of SBH coalescence. However, powerful extended radio sources have lifetimes \( \sim 10^6 - 10^8 \) yr (e.g., Parma et al., 1999; O’Dea et al., 2009; Antognini et al., 2012), much shorter than the time-between-mergers, even for massive galaxies. Thus even if a spin flip took place, morphological traces of this event, such as a change in jet direction, would not necessarily be evident in the current (post-coalescence) radio source. The radio source properties of individual galaxies are discussed in Section 2.6.

It is notable that in four of the six galaxies in which significant displace-
2.5 Discussion

ments have been found, the displacements are also approximately aligned with the radio jet axis (Section 2.4 and Table 2.5). This number includes three of the four that have powerful kpc-scale jets (Section 2.4 and Table 2.5), suggesting jet power asymmetries as a possible displacement mechanism (as discussed below). However, such alignments do not necessarily argue against gravitational recoil. In their statistical study of the coalescence of spinning black hole binaries Lousto et al. (2010) find that the recoil velocity is preferentially aligned (or counter-aligned) with the orbital angular momentum of the progenitor binary and moreover, that the spin direction distribution of the recoiling SBH peaks at an angle of \( \approx 25^\circ \) to the orbital angular momentum (for an equal mass progenitor binary; the probability distribution is broader and peaks at larger angles for smaller mass ratios). This suggests, assuming that the jet traces the spin axis of the recoiling SBH, a tendency for the displacement to be somewhat, but not greatly, misaligned with the jet axis, consistent with what is observed in these objects.

2.5.3 Distribution of recoil displacements

Here I outline the method used to estimate the probability distributions for displacements resulting from post-recoil oscillations of a kicked SBH. For our purposes, of the three phases predicted by GM08, only phase II (when the oscillation amplitude becomes comparable with the galaxy core radius) is of interest. The initial, large amplitude phase I oscillations are short-lived, while in phase III the residual oscillations are indistinguishable from Brownian motion (which is considered separately in Section 2.5.4).

In the GM08 \( N \)-body simulations, phase II oscillations occur for kick velocities in the range \( v_{\text{kick}} \sim 0.4 - 0.9 \ v_{\text{esc}} \). The simulations also indicate that the subsequent evolution does not depend strongly on the magnitude of the initial kick. Therefore, we assume that, given any initial kick large enough to displace the SBH beyond the core radius, the distance, \( R \), of the SBH from the center of the galaxy evolves during phase II as a damped harmonic oscillator:

\[
R(t) = R_0 e^{-\Delta t/\tau} \sin(\omega_c \Delta t). \tag{2.6}
\]

The initial amplitude, \( R_0 \), is set by the condition that phase II begins
Table 2.6: PROBABILITIES TO OBSERVE LARGER DISPLACEMENTS

<table>
<thead>
<tr>
<th>Galaxy</th>
<th>$d_i[r_c]$</th>
<th>$p_i(t_m = 0.4 \text{ Gyr})$</th>
<th>$p_i(t_m = 5 \text{ Gyr})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>NGC 1399</td>
<td>0.01</td>
<td>0.75</td>
<td>0.11</td>
</tr>
<tr>
<td>NGC 4168</td>
<td>*0.02</td>
<td>0.98</td>
<td>0.89</td>
</tr>
<tr>
<td>NGC 4261</td>
<td>&lt;0.01</td>
<td>0.94</td>
<td>0.23</td>
</tr>
<tr>
<td>NGC 4278</td>
<td>0.1</td>
<td>0.36</td>
<td>0.04</td>
</tr>
<tr>
<td>NGC 4373</td>
<td>&lt;0.01</td>
<td>0.99</td>
<td>0.58</td>
</tr>
<tr>
<td>NGC 4486</td>
<td>0.01</td>
<td>0.99</td>
<td>0.71</td>
</tr>
<tr>
<td>NGC 4552</td>
<td>&lt;0.05</td>
<td>0.10</td>
<td>0.01</td>
</tr>
<tr>
<td>NGC 4636</td>
<td>*0.01</td>
<td>0.99</td>
<td>0.69</td>
</tr>
<tr>
<td>NGC 4696</td>
<td>*0.02</td>
<td>0.97</td>
<td>0.42</td>
</tr>
<tr>
<td>NGC 5419</td>
<td>0.02</td>
<td>0.97</td>
<td>0.46</td>
</tr>
<tr>
<td>NGC 5846</td>
<td>0.04</td>
<td>0.90</td>
<td>0.25</td>
</tr>
<tr>
<td>IC 1459</td>
<td>&lt;0.01</td>
<td>0.92</td>
<td>0.21</td>
</tr>
<tr>
<td>IC 4296</td>
<td>0.01</td>
<td>0.97</td>
<td>0.37</td>
</tr>
<tr>
<td>IC 4931</td>
<td>*0.03</td>
<td>0.95</td>
<td>0.46</td>
</tr>
</tbody>
</table>

Notes: — Probability to observe a projected displacement larger than the value actually observed in this work (in units of core radii) at a random time after the last kick. Probabilities are computed for a mean time between galactic mergers $t_m = 0.4 \text{ Gyr}$ and $5 \text{ Gyr}$. The symbol “*” indicates $3\sigma$ offsets that were classified as “null” after the normalization for the coordinates IQR. The symbol “<” indicates offsets that do not reach the $3\sigma$ level.

when the oscillation amplitude is comparable to the core radius; $\Delta t$ is the time since the kick, i.e., the time since the last merger, and $\omega_c$ is the SBH oscillation frequency:

$$\omega_c = \sqrt{\frac{3 \sigma_{c2}}{4 r_{c2}}}$$

(2.7)

Equation 2.7 is obtained by combining the radial oscillation frequency in a spherical core of uniform density, $\omega_c = [(4\pi/3)G\rho_c]^{1/2}$, with equation 13 in GM08:

$$\sigma_{c2} = F^2 \frac{4\pi}{9} G\rho_c r_{c2}^2$$

(2.8)
2.5 Discussion

with $F \approx 2$. The damping time, $\tau$, is given by equation 2.2. The adopted parameter values are listed in Table 2.7.

Suppose that we observe a galaxy at a random time since its last merger. For simplicity, we assume that galaxy mergers occur stochastically and can be represented as a Poisson process. The probability that the last merger occurred at time $\Delta t$ ago is then:

$$P(\Delta t) = t_m^{-1} e^{-\Delta t/t_m}, \Delta t > 0$$  \hfill (2.9)

which is associated with the cumulative distribution:

$$P(< \Delta t) = 1 - e^{-\Delta t/t_m}$$  \hfill (2.10)

where $t_m$ is the mean time between galaxy mergers.

The galaxy merger rate is uncertain but simulations indicate that it is a function of redshift, galaxy mass and mass ratio (e.g., Bell et al., 2006; Conselice et al., 2009; Hopkins et al., 2010; Burke and Collins, 2013). Here, since the phase II damping times are typically $\sim 1$ Gyr (Table 2.7), we consider redshifts $z \leq 1$ and estimate the mean time between galaxy mergers as the ratio between the lookback time corresponding to $z = 1$ and the number of mergers, $N$, during that time. The latter was determined using the analytical fits to semi-analytical models for galaxy merger rates given by H10. Integrating the merger rate as given by equation 5 in H10 over redshift, we find for the number of mergers,

$$N = t_H A(M_{\text{min}}) \int_0^1 (1 + z)^{\beta(M_{\text{min}})-5/2} dz$$ \hfill (2.11)

where $t_H = 13.7$ Gyr is the Hubble time, the normalization constant $A(M_{\text{min}})$ and the slope $\beta(M_{\text{min}})$ are given as functions of the galaxy mass threshold $M_{\text{min}}$, for mergers with mass ratio $q > 0.1$, by equations 9 & 10 in H10. For $\log M_{\text{gal}} \geq \log M_{\text{min}} = 11$, we find $N \approx 1.5$ for the number of mergers per galaxy between $z = 0$ and $z = 1$. However, we note that $N$ could vary between 0.75 and 3, allowing for systematic uncertainties of a factor two in $A(M_{\text{min}})$ and 0.2 in $\beta(M_{\text{min}})$. The look back time at $z = 1$ is $t_L = 7.731$ Gyr.
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for $H_0=71$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_M = 0.27$ and $\Omega_{\text{vac}} = 0.73$, yielding a mean time between galactic mergers $t_m \approx 5$ Gyr.

The simple analytical functions provided by H10 do not accurately reproduce the numerical results for the most massive galaxies. Therefore, we use an average merger rate for $z \leq 1$ estimated from their Figure 3, for $\log M_{\text{gal}} > 12$. The rate for $q > 0.1$ mergers is roughly constant for $z \leq 1$ and it seems reasonable to adopt an average value of 2.5 mergers/galaxy/Gyr. This corresponds to $t_m \approx 0.4$ Gyr.

The stellar mass, $M_{\text{gal}}$, is derived for each galaxy from the relation:

$$\Upsilon = 10^{0.4(M_K - M_{\odot K})} \frac{M_*}{M_{\odot}}$$

(2.12)

where $\Upsilon$ is the mass-to-light ratio and $M_K$ is the K-band magnitude given by BC06. For the mass-to-light ratio, we use a representative value, $\Upsilon = 3.1$, computed as the average value of the ratio between the virial mass and the K-band luminosity for the sample of nearby core ellipticals studied by Sani et al. (2011).

As the derived values of $M_{\text{gal}}$ span the range $11 \lesssim \log M_{\text{gal}} \lesssim 12$ we compute displacement probability distributions for the limiting cases $t_m = 0.4$ Gyr and $t_m = 5.0$ Gyr. For comparison, Lidman et al. (2013) find an observationally-derived major merger rate of $\approx 0.38$ mergers Gyr$^{-1}$ for brightest cluster galaxies at $z \sim 1$, implying $t_m \approx 2.6$ Gyr.

From the cumulative distributions given by eq. 2.10 we extract random times in order to generate a set of $R_i \equiv R(t_i)$ from equation 2.6 for each galaxy, for both values of $t_m$. Projected displacements are then calculated:

$$R_{i,p} = R_i \sin(\theta_i)$$

(2.13)

where $\theta_i$ is the angle between the displacement direction, assumed to be randomly oriented, and the line of sight. Finally, the distribution of the projected offsets is computed. In Figs. 2.31a and 2.31b we plot the probability, $P(d > x)$, of observing a displacement, $d$, larger than a given value, $x$, as a function of $x$. Values of the measured displacements are also plotted. The probability of generating a projected displacement larger than the value actually measured is listed for each galaxy in Table 2.6 for both values of
2.5 Discussion

The damping time computed from eq. \ref{eq:2.2} depends on the mass of the SBH. Measurement uncertainties for SBH masses in galaxies beyond the Local Group are typically large and are probably dominated by poorly-understood systematics, given that none of these galaxies exhibits a clear central rise in the stellar velocities (Merritt, 2013, Section 2.2). In Table \ref{tab:2.8} we list SBH masses estimated from the $M_\bullet - \sigma$ relation (Ferrarese and Ford, 2005), from the $M_\bullet - M_V$ relation for bright galaxies ($M_V < -19$, Lauer et al., 2007) and from direct measurements (stellar or gas dynamics modeling). For most of our galaxies the discrepancy in the masses recovered with different methods is small. We compute damping times using SBH masses from the $M_\bullet - M_V$ relation finding a smaller average damping time $\bar{\tau} = 0.66$ Gyr, although the new damping times for individual galaxies are not systematically smaller than those computed using the $M_\bullet - \sigma$ SBH masses. We then compute new values for the probabilities presented in Table \ref{tab:2.6} and the corresponding cumulative probabilities of not observing displacements larger than those actually measured in this work ($P$). We obtain $P = 10^{-16}$ ($10^{-3}$), instead of $10^{-17}$ ($10^{-4}$), for an average time between galactic mergers $t_m = 5$ (0.4) Gyr. After taking into account the kick probabilities given by L12, as specified in Section 2.5.2, the probability of not observing a displacement larger than those actually measured in the entire sample is $P' \approx 1 \times 10^{-3}$, instead of $8 \times 10^{-4}$, for $t_m = 0.4$ Gyr and $P' \approx 0.14$ instead of 0.05 for $t_m = 5.0$ Gyr. The different masses adopted for the SBH caused, therefore, a difference in $P$ of one order of magnitude. Nevertheless, even for $t_m = 5$ Gyr, there remains a large probability of finding displacements larger than those actually observed, if these galaxies experienced gravitational recoil events within the last few Gyr.

2.5.4 Other displacement mechanisms

We now consider several other mechanisms that may plausibly produce SBH displacements.

1. **Asymmetric jets**: if the AGN jets are intrinsically asymmetric in power output, the resulting net thrust can push the SBH away from the original equilibrium position (Shklovsky, 1982; Saslaw and Whittle, 1988). Kornreich and Lovelace (2008) determine the SBH acceleration for this sce-
2.5 Discussion

Figure 2.31a: Section a displacement larger than the value specified on the x-axis in units of the core radius for $t_m = 0.4$ Gyr. The observed displacement is marked as a filled circle. The filled square (in NGC 4694 and 5419) marks the offset of the secondary point source.
Figure 2.31b: Section a displacement larger than the value specified on the x-axis in units of the core radius for $t_m = 5$ Gyr. The observed displacement is marked as a filled circle. The filled square (in NGC 4694 and 5419) marks the offset of the secondary point source.
2.5 Discussion

Table 2.7: PARAMETERS OF RECOIL OSCILLATION MODEL

<table>
<thead>
<tr>
<th>Galaxy</th>
<th>$r_c$ [pc]</th>
<th>$\sigma$ [km s$^{-1}$]</th>
<th>log($M_{\text{gal}}$)</th>
<th>$\tau$ [Gyr]</th>
<th>$2\pi/\omega_c$ [Gyr]</th>
<th>$v_{\text{kick}}$ [km s$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>NGC 1399</td>
<td>189</td>
<td>346</td>
<td>11.70</td>
<td>0.16</td>
<td>0.004</td>
<td>300</td>
</tr>
<tr>
<td>NGC 4168</td>
<td>303</td>
<td>184</td>
<td>11.44</td>
<td>4.85</td>
<td>0.012</td>
<td>159</td>
</tr>
<tr>
<td>NGC 4261</td>
<td>237</td>
<td>309</td>
<td>11.85</td>
<td>0.40</td>
<td>0.005</td>
<td>273</td>
</tr>
<tr>
<td>NGC 4278</td>
<td>83</td>
<td>237</td>
<td>10.99</td>
<td>0.14</td>
<td>0.002</td>
<td>205</td>
</tr>
<tr>
<td>NGC 4373</td>
<td>269</td>
<td>246</td>
<td>12.01</td>
<td>1.25</td>
<td>0.008</td>
<td>213</td>
</tr>
<tr>
<td>NGC 4486</td>
<td>733</td>
<td>334</td>
<td>12.00</td>
<td>2.84</td>
<td>0.014</td>
<td>325</td>
</tr>
<tr>
<td>NGC 4552</td>
<td>36</td>
<td>252</td>
<td>10.55</td>
<td>0.02</td>
<td>0.001</td>
<td>218</td>
</tr>
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<td>NGC 4636</td>
<td>219</td>
<td>203</td>
<td>11.58</td>
<td>1.73</td>
<td>0.008</td>
<td>176</td>
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<tr>
<td>NGC 4696</td>
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<td>12.08</td>
<td>0.96</td>
<td>0.007</td>
<td>220</td>
</tr>
<tr>
<td>NGC 5419</td>
<td>499</td>
<td>351</td>
<td>12.26</td>
<td>1.09</td>
<td>0.01</td>
<td>304</td>
</tr>
<tr>
<td>NGC 5846</td>
<td>183</td>
<td>239</td>
<td>11.83</td>
<td>0.64</td>
<td>0.005</td>
<td>207</td>
</tr>
<tr>
<td>IC 1459</td>
<td>258</td>
<td>306</td>
<td>11.68</td>
<td>0.49</td>
<td>0.005</td>
<td>294</td>
</tr>
<tr>
<td>IC 4296</td>
<td>347</td>
<td>333</td>
<td>12.17</td>
<td>0.64</td>
<td>0.011</td>
<td>196</td>
</tr>
<tr>
<td>IC 4931</td>
<td>397</td>
<td>288</td>
<td>12.12</td>
<td>1.52</td>
<td>0.01</td>
<td>249</td>
</tr>
</tbody>
</table>

average 286 277 11.73 1.20 0.007 239

Note. — (1) Galaxy name; (2) core radius from CB05; (3) stellar velocity dispersion from Hyperleda; (4) stellar mass of the galaxy; (5) dynamical time; (6) damping time; (7) kick velocity required to displace the SBH up to the core radius. The dominant source of errors in the quantities presented above is the stellar velocity dispersion.

\[ a_{\bullet} \approx 2.1 \times 10^{-6} f_{\text{jet}} \dot{m} \text{ cm s}^{-2} \]  

(2.14)

where $\dot{m} \equiv \dot{M}_a/\dot{M}_{\text{edd}}$ and $f_{\text{jet}} = L_{\text{jet}}/L_a^{\frac{3}{2}}$. $\dot{M}_a$ is the mass accretion rate, $\dot{M}_{\text{edd}} \approx 2.2 \left( M_{\bullet}/10^8 M_\odot \right) M_\odot \text{yr}^{-1}$ the Eddington accretion rate, $L_a$ the accretion luminosity and $L_{\text{jet}}$ is the jet luminosity. For asymmetrical, op-
positely directed jets $L_{\text{jet}}$ is the difference in the luminosities of the two jets.

Under the assumption that the restoring force from the galaxy is negligible (a reasonable approximation for the low-density cores of “core galaxies”), Eq. 2.14 can be integrated to obtain an expression for the displacement:

$$\Delta r \approx 340 \ f_{\text{jet}} \dot{m} \ t_6^2 \ \text{pc}$$

where $t_6$ is the time over which the SBH is accelerated to produce an offset $\Delta r$.

The best candidates for jet thrust displacements are the four galaxies (NGC 1399, 4261, 4486 and IC 4296) that have relatively powerful kpc-scale jets (Section 2.4 and Table 2.2). Of these, we did not detect a significant displacement in NGC 4261, which has an FR I radio source. NGC 4486 and IC 4296 also host FR I radio sources and NGC 1399 has an FR I-like morphology, despite its relatively low power. Interestingly, all three of these galaxies exhibit photocenter displacements that are at least approximately (within $20^\circ$) in the jet direction (Table 2.5). This implies that the SBH is displaced relative to its equilibrium position in the counter-jet direction, as might be expected if the displacements are related to intrinsic asymmetries in jet power. NGC 4486 (M87) has already been discussed in detail by B10, who concluded that a jet power asymmetry amounting to $\sim 3\%$ of the accretion luminosity can explain the observed displacement, for a radio source lifetime $\sim 10^8$ yr. We find similar results in the cases of NGC 1399 and IC 4296, where the observed displacement can be produced for a jet asymmetry $< 1\%$ of the Bondi accretion luminosity, again for a radio source lifetime $\sim 10^8$ yr (see Section 2.6 for details).

A close alignment between the displacement and the (initial) jet direction is also found for the low power pc-scale radio source in NGC 4278. In this case, Giroletti et al. (2005)’s interpretation of the radio data implies that the photocenter is displaced in the counter-jet direction, with the jet axis being closely aligned with the line of sight. Assuming that the SBH is displaced along the jet axis, the de-projected magnitude of the displacement would be $\sim 100 – 200$ pc. Nevertheless, it seems possible that this could result from jet thrust, if sustained for $\sim 10^8$ yr (Section 2.6).
2.5 Discussion

The double nucleus galaxy NGC 4696 does not show well-defined jets on kpc scales, but has a one-sided pc-scale jet in PA ≈ −150°. The displacement relative to the brighter nucleus is considered non-significant because of the large IQR. However, as already noted, it is not known which of the two optical nuclei hosts the AGN producing the radio jet. If it is the fainter nucleus, the photocenter displacement is approximately in the counter-jet direction, which is not consistent with jet acceleration of the SBH (which would cause the SBH to be displaced in the counter-jet direction).

The remaining two objects which exhibit displacements considered to be significant (NGC 5419 and 5846) do not have well-defined jets on either parsec or kiloparsec scales.

2. Stalled SBH binaries: in the aftermath of a galaxy-galaxy merger, the SBH binary orbit shrinks at first due to dynamical friction and subsequently through slingshot ejection of stars intersecting the orbit. Investigations of quasi-steady spherical models suggested that the evolution of the binary stalls at separations ∼ 1 pc, due to a paucity of interacting stars, rather than hardening to the point at which gravitational wave emission drives the final inspiral to coalescence (the so-called “final parsec problem”; e.g., Merritt and Milosavljević, 2005). Based on N-body simulations, Merritt (2006) estimated “typical” semi-major axes for stalled binaries, finding \( a_{\text{stall}} \lesssim 10 \) pc for an SBH mass ratio \( q = 0.5 \) and \( a_{\text{stall}} \lesssim 3 \) pc for \( q = 0.1 \), respectively. If the binary center of mass is located at the photocenter, the displacements of the primary and secondary components would be \( \Delta r_1 \sim a_{\text{stall}} q/(1 + q) \) and \( \Delta r_2 \sim a_{\text{stall}} / (1 + q) \), respectively, giving \( \Delta r_1 \sim 3 \) (0.3) pc and \( \Delta r_2 \sim 7 \) (3) pc for \( q = 0.5 \) (0.1). Thus stalled binaries could produce displacements comparable with our results, particularly if the secondary SBH is accreting and the mass ratio is near unity.

It has been argued that stalling can be avoided in galaxies containing significant amounts of nuclear gas (e.g., Escala et al., 2005; Cuadra et al., 2009; Mayer et al., 2007). Even in purely stellar nuclei, N-body simulations sometimes find that evolution of the binary can continue efficiently due to the presence of centrophilic orbits (Khan et al., 2011; Preto et al., 2011; Gandadris and Merritt, 2012). However the existing gas-dynamical simulations probably do not yet have enough spatial resolution to follow the binary’s evolution to sub-parsec scales, and the N-body simulations appear to not yet have large enough \( N \) that their results can be robustly extrapolated to
the much larger-$N$ regime of real galaxies (Vasiliev et al., 2014).

Another possibility, discussed by Antonini and Merritt (2012), is accretion of a less massive galaxy by a giant elliptical, such as NGC 4486, which has a pre-existing depleted core (presumably the result of the evolution of SBH binaries formed in previous mergers). In such situations, dynamical friction is very inefficient in the core due to the lack of stars moving slower than the sinking object. The orbital eccentricity can increase rapidly while the apoapsis hardly changes, resulting in a slowly evolving SBH binary in a highly eccentric orbit. The simulations presented by Antonini and Merritt (2012) indicate that in an M87-like core, a low mass ratio binary ($q \approx 10^{-3}$) can persist over a Hubble time in an increasingly eccentric orbit with a semi major axis $\sim 10$ pc. If the secondary SBH is accreting, it will be visible as an off-center AGN; if both components of the SBH binary are accreting, a double nucleus might be observed (perhaps as in NGC 4696 and NGC 5419).

Helical distortion or “wiggling” of parsec-scale radio jets has been linked to putative SBH binaries in several AGNs, with the jet wiggles being variously attributed to orbital motion, precession of the accretion disk around the jet-emitting black hole or to geodetic precession (e.g., Begelman et al., 1980; Roos et al., 1993; Katz, 1997; Romero et al., 2000; Lobanov and Roland, 2005). However, the periods ($\sim 3$ years) and separations ($\sim 10^{-2}$ pc) typically inferred from analyses of jet wiggles are much smaller than would be the case for a stalling binary. If the $\sim$ pc-scale displacements measured in this work are interpreted as SBH binary orbits, periods $\sim 10^{4-5}$ years are implied for total masses $\sim 10^{8-9}$ $M_\odot$. Geodetic precession is insignificant at these separations. The wavelength of jet wiggles caused by orbital motion is given by $\lambda_{\text{jet}} \sim v_{\text{app}}t_{\text{orbit}}$, where $v_{\text{app}} = \beta c \sin \theta/(1 - \beta \cos \theta)$ is the apparent jet velocity (for a jet speed $v_{\text{jet}} = \beta c$ and inclination to the line of sight, $\theta$) and $t_{\text{orbit}}$ is the orbital period. Therefore, assuming $\beta \sim 1$, a pc-scale binary will produce very long wavelength wiggles in the jet ($\sim 10$ kpc). In general, due to the combination of orbital and jet velocities, the jet will precess on the surface of a cone which, for a pc-scale binary of mass $\sim 10^9$ $M_\odot$ will have a half-opening angle $\lesssim 1^\circ$ (see Equation 7 in Roos et al., 1993). Thus, orbital motion would cause only small curvatures in the jet over $\sim$ kpc scales, which would be difficult to discern as the jet loses collimation, or to distinguish from jet bending due to environmental effects, such as ram pressure. This will also be the case for disk precession, since the precession
2.5 Discussion

period exceeds the orbital period. Therefore, although the jet morphology has been mapped in detail from pc to kpc scales for a number of our sample galaxies (see Table 2.2 for references), these observations are unlikely to provide unambiguous clues as to the presence, or not, of a stalled pc-scale binary.

3. Massive perturbers: galaxy centers host a variety of potential perturbers with masses ranging from \( \sim 1 M_\odot \) (e.g., stellar mass black holes and neutron stars) to \( \sim 10^4 \sim 10^7 M_\odot \), such as giant molecular clouds and stellar clusters.

Gravitational interactions with these objects will cause the SBH to undergo a type of Brownian motion, with the amplitude of the root-mean-square displacement given by:

\[
\Delta r_{\text{rms}} \approx \left( \frac{\tilde{m}}{M_*} \right)^{0.5} r_c
\]  
(2.16)

where \( \tilde{m} \) is proportional to the second moment of the mass distribution of the massive perturbers:

\[
\tilde{m} \equiv \frac{\int n(m)m^2 dm}{\int n(m)mdm}
\]

with \( n(m) \) \( dm \) being the number of perturbers with masses in the range \( m, m + dm \) \( \text{(Merritt, 2013 eq. 7.63)} \).

The offsets measured in this work range from 0.01 to 0.1 \( r_c \), but are typically \( \sim 0.01 r_c \) (Table 2.6). For a typical SBH mass of order \( 10^9 M_\odot \) (Table 2.8), rms displacements \( \sim 0.01r_c \) can be generated by Brownian motion for \( \tilde{m} \sim 10^5 M_\odot \).

The mass functions of globular clusters, gas clumps and giant molecular clouds in the inner 100 pc of the Galaxy have been estimated by Perets et al. (2007). For comparison, using the mass functions presented in their paper, we find that \( \tilde{m} \) can be as high as \( 10^5 M_\odot \) for a population of giant molecular clouds. The Milky Way, of course, is very different from the galaxies studied here. However, as recently discussed by Antonini and Merritt (2012), the low efficiency of dynamical friction in low density cores favors the formation of a population of stalling massive objects in the cores of giant ellipticals.
2.5 Discussion

Therefore, it seems plausible that displacements of order those observed could result from Brownian motion due to a population of massive perturbers. In several galaxies, the observed displacements are approximately aligned with the kpc-scale radio jets. This suggests that the displacement is not random, at least in these cases, favoring other mechanisms (i.e., gravitational recoil or jet thrust) that are expected to offset the SBH in the jet direction. Nevertheless, we conclude that Brownian motion cannot be excluded as the cause of the displacement in any individual galaxy, particularly those where the offsets are not aligned with kpc-scale jets, i.e. NGC 4278, 5846 and 5419.
2.5 Discussion

Table 2.8: SBH MASSES

<table>
<thead>
<tr>
<th>Galaxy</th>
<th>M_•-σ</th>
<th>M_•-M_V</th>
<th>log(M_•/M_⊙)</th>
<th>stars</th>
<th>gas</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1)</td>
<td>(2)</td>
<td>(3)</td>
<td>(4)</td>
<td>(5)</td>
<td></td>
</tr>
<tr>
<td>NGC 1399</td>
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<td>8.71</td>
<td>8.64\textsuperscript{a}, 9.01\textsuperscript{b}</td>
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<td></td>
</tr>
<tr>
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<td>8.56</td>
<td>...</td>
<td>...</td>
<td></td>
</tr>
<tr>
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<td>8.81</td>
<td>...</td>
<td>8.69\textsuperscript{c}</td>
<td></td>
</tr>
<tr>
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<td>8.17</td>
<td>...</td>
<td>...</td>
<td></td>
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<tr>
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<td>8.66</td>
<td>8.72</td>
<td>...</td>
<td>...</td>
<td></td>
</tr>
<tr>
<td>NGC 4486</td>
<td>9.30</td>
<td>9.04</td>
<td>9.74\textsuperscript{d}</td>
<td>...</td>
<td></td>
</tr>
<tr>
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<td>8.71</td>
<td>8.49</td>
<td>...</td>
<td>...</td>
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<td>NGC 4636</td>
<td>8.25</td>
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<td>NGC 4696</td>
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<td>...</td>
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<td>8.64</td>
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</tr>
<tr>
<td>IC 1459</td>
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<td>8.94</td>
<td>9.40\textsuperscript{e}</td>
<td>8.53 - 8.98\textsuperscript{e-h}, 8.15 - 8.75\textsuperscript{f}</td>
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</tr>
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<td>average</td>
<td>8.87</td>
<td>8.88</td>
<td></td>
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</tbody>
</table>

Note. — (1) Galaxy name, (2) masses from the \( M_\bullet - \sigma \) \cite{Ferrarese and Ford, 2005} using the velocity dispersion specified in Table 2.7, (3) masses from the \( M_\bullet-M_V \) relation from eq.6 in \cite{Lauer et al., 2007}; values for \( M_V \) have been taken from \cite{Lauer et al., 2007}, when not available (NGC 4373, 5846 and IC 4296) they have been taken from NED (\( V_T \) values from the RC3 catalog, \cite{de Vaucouleurs et al., 1991}), (4) masses from stellar orbit modeling, (5) masses derived from gas kinematics. Masses have been scaled to the distances assumed in this work. \textsuperscript{†}The authors warn that these values might be affected by non-gravitational motions in the gas (i.e. inflows or outflows). References: \textsuperscript{a}Gebhardt et al. \cite{2007}, \textsuperscript{b}Houghton et al. \cite{2006}, \textsuperscript{c}Ferrarese et al. \cite{1996}, \textsuperscript{d}Gebhardt et al. \cite{2011}, \textsuperscript{e}Cappellari et al. \cite{2002}, \textsuperscript{f}Verdoes Kleijn et al. \cite{2000}.
### Table 2.9: SUMMARY

<table>
<thead>
<tr>
<th>Galaxy</th>
<th>Offset (pc)</th>
<th>PA (deg)</th>
<th>Suspected Origin</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>NPS1</td>
<td>NPS2</td>
<td>Gravitational</td>
</tr>
<tr>
<td>NGC 1399</td>
<td>1.7 ± 0.4</td>
<td>...</td>
<td>✓</td>
</tr>
<tr>
<td>NGC 4278</td>
<td>7.6 ± 0.4</td>
<td>...</td>
<td>✓</td>
</tr>
<tr>
<td>NGC 4486</td>
<td>4.3 ± 0.2</td>
<td>...</td>
<td>✓</td>
</tr>
<tr>
<td>NGC 5846</td>
<td>8.2 ± 2.5</td>
<td>...</td>
<td>✓</td>
</tr>
<tr>
<td>IC 4296</td>
<td>3.8 ± 0.7</td>
<td>...</td>
<td>✓</td>
</tr>
<tr>
<td>NGC 5419</td>
<td>7.5 ± 1.7</td>
<td>62 ± 2</td>
<td>252 ± 13</td>
</tr>
</tbody>
</table>

Galaxies with two nuclear sources

Notes: — Projected offsets of the photocenter with respect to the AGN and their possible origin. When multiple images have been analyzed, values presented here are the error weighted average. Position angles (PA) are given in degrees East from North. NPS = nuclear point source.
2.6 Notes on individual sources

In this section the galaxies are ordered according to the significance assigned to the displacement.

2.6.1 NGC 4278 (high/intermediate)

NGC 4278 is a large elliptical near the center of the dense Coma I cloud which is characterized by the presence of an extended dust distribution extending over an arc ranging from N to NW relative to the photocenter (Carollo et al., 1997). Radio interferometry (VLBA) observations reveal a low-power, parsec-scale source (∼ 45 mas) with twin mildly-relativistic S-shaped jets emerging from a compact, flat spectrum core (Giroletti et al., 2005). Within the inner 7 mas the jets are oriented SE–NW but then bend to the east and west, respectively, forming an “S” shape. Giroletti et al. argue that the jets are closely aligned with the line of sight (with a viewing angle ∼ 2–4°) with the NW jet approaching and the bends being explained by amplification of intrinsically small deviations due to projection effects. These characteristics and the presence of atomic hydrogen suggest that the galaxy may have experienced a minor merger with another member of the cloud (Gerin and Casoli, 1994).

Photometric analysis. Three images, obtained with ACS/WFC-F850LP, WFPC2/PC-F814W and NICMOS2/F160W, respectively, were analyzed for this galaxy (Figs 2.13, 2.14 and 2.15). Photocenter–AGN displacements of intermediate or high significance are detected in all three. The uncertainty-weighted average displacement has an amplitude $\Delta r \geq 7.6 \pm 0.4$ pc and direction SE (PA = 152 ± 3°). The photocenter positions derived from each image are plotted relative to the AGN position in Fig 2.6a. The photometric analysis of the optical ACS and WFPC2 images shows that the $y$ co-ordinate of the isophote centers migrates southward at intermediate SMA, then northward at larger SMA. These irregularities are not present in the NICMOS2 image and are likely due to the dust N-NW of the center.

Offset origin. The extended dust distribution produces a large-scale asymmetry in surface brightness, which is particularly evident in optical and UV wavelengths. This may bias the photocenter, shifting it in the opposite direction (S-SE) to the dust. As the AGN is a point source, its position should not be significantly affected by the dust distribution and thus it
would appear to be shifted N-NW relative to the photocenter. Therefore, the offsets recovered from ACS and WFPC2 data may be partly due to asymmetric extinction. However, the effects of dust are not apparent in the NIR (NICMOS2) image, from which an offset of similar magnitude and direction was recovered. Therefore, we believe that the measured displacement is not simply an artifact of extinction, although this may contribute.

Relative to the core radius, NGC 4278 has the largest displacement \( \approx 0.1 r_c \) (Table 2.6) in our sample. If it is due to phase II oscillations of the SBH following gravitational recoil (see Section 2.5.2), we estimate that the probability of observing a projected displacement larger than that actually measured is 4 (36)% for a mean time-between-mergers of \( t_m = 5 \) (0.4) Gyr (Table 2.6) and given a kick large enough to displace the SBH at least as far as the core radius. The “hot” disk recoil velocity distribution of L12 indicates a 45% probability of a sufficiently large kick \( \gtrsim 200 \text{ km s}^{-1} \), Table 2.7 occurring in an SBH coalescence event. Therefore, we consider residual oscillations following gravitational recoil to be a plausible explanation for the displacement.

In this case, we can estimate the merger epoch. Supposing the SBH to be undergoing phase II oscillations, we combine eq.2.2 and 2.3. Using the measured (projected) offset as a lower limit for \( r_{\text{rms}} \), \( r_{\text{rms}} \gtrsim 7.6 \) pc, and taking the values of \( r_c \) (core radius) and \( \sigma \) (stellar velocity dispersion) from Table 2.7, we find that \( (t - t_c) \lesssim 5\sigma \approx 0.7 \) Gyr has elapsed since the amplitude of the oscillation damped down to \( r \sim r_c \). This implies that the onset of phase II occurred no later than \( \sim 0.7 \) Gyr ago. As phase I is shorter than phase II, this scenario is consistent with an SBH-SBH coalescence event that occurred within \( 2(t - t_c) \sim 1.4 \) Gyr. The total evolution time from the beginning of the galactic merger to SBH binary coalescence is suggested to be of order \( 10^8 \) yr (Gualandris and Merritt, 2012). Adding this time to the estimated kick epoch, we infer that a galaxy merger that took place up to \( \sim 1.5 \) Gyr in the past could be responsible for a recoil kick consistent with the observed displacement.

Although the displacement is approximately in the direction of elongation of the mas-scale radio core (155° over the inner \( \sim 7 \) mas), the low power \( (P_{5\text{GHz}} \approx 70 \times 10^{20} \text{ W}, \text{ Wrobel} 1991) \) and compact nature (\( \sim 3 \) pc) of the radio source argue against jet thrust as the cause of the offset.

We find no compelling reasons to exclude either a stalled binary on an
2.6 Notes on individual sources

eccentric orbit, or massive perturbers (Section 2.5.4) as possible causes of the displacement.

2.6.2 NGC 5846 (intermediate)

NGC 5846 is the dominant component of a small, compact group of \( \approx 50 \) galaxies (Huchra and Geller, 1982). A companion galaxy, NGC5846A, is located 0.7 arcmin to the S, but there is no evidence of an interaction. The presence of dust lanes in an apparent spiral pattern approximately centered on the compact radio core suggests a past merger, or accretion of a gas rich galaxy (Moellenhoff et al., 1992; Forbes et al., 1996). The optical nucleus has a LINER spectrum (Ho et al., 1997) and HST imaging (Masegosa et al., 2011) reveals extended H\( \alpha \) emission in a wide structure extending up to 2\( \arcsec \) W of the nucleus. The presence of two radio emitting bubbles located roughly symmetrically at \( \sim 0.6 \) kpc from the center and a “ghost” X-ray cavity suggest that the galaxy recently experienced stronger AGN activity, for which Machacek et al. (2011) derive a duty cycle of \( \sim 10 \) Myr. The radio morphology is complex: Filho et al. (2004) report VLBA observations at 2.3, 5 and 15 GHz which resolve the core into multiple blobs roughly aligned along the N–S axis. The nature of this structure is unclear, possibilities include an AGN jet, or compact supernovae remnants (e.g. Tarchi et al., 2000).

Photometric Analysis. One image, obtained with WFPC2/PC - F814W was analyzed for this galaxy (Figure 2.22). We find a photocenter–AGN displacement \( \Delta r \gtrsim 8.2 \pm 2.5 \) pc in the direction W–SW (PA = 253 \( \pm 8^\circ \)) which is considered to be of intermediate significance. The isophote centers show systematic migrations of \( \approx 2 \) pixels in both \( x \) and \( y \) coordinates, from W to E and S to N, respectively, as the SMA decreases from 300 to 200 pixels. These migrations are possibly the result of the dust lanes to the S and NE of the nucleus. The \( y \)-component of the displacement is not significant. The \( x \)-component is considered to be of intermediate significance (1.6 IQR) and is unlikely to be an artifact of extinction, which in this case, would bias the photocenter such as to increase the \( x \)-displacement. Of more concern is the determination of the AGN position. The central source is relatively weak and embedded in an asymmetric structure that affects the gaussian fits used to determine the AGN position. We therefore assign a larger uncertainty to the \( x \)-component of the AGN position.
2.6 Notes on individual sources

**Offset origin.** For \( t_m = 5 \) (0.4) Gyr, we estimate a 25 (90)% probability of finding a displacement larger than that observed, if due to phase II recoil oscillations. The probability of a recoil kick large enough (\( \gtrsim 240 \) km s\(^{-1}\); Table 2.7) to initiate these oscillations is \( \sim 45\% \) (L12).

As for NGC 4278, we use equations 2.2 and 2.3 and values from Table 2.7 to estimate the time since the onset of phase II, finding \( (t-t_c) \lesssim 6.2 \tau \) or 4 Gyr. This implies an upper limit to the time elapsed since the putative SBH-binary coalescence event of \( 2(t-t_c) \) or 8 Gyr.

Although, as noted, there is “fossil” evidence for previous jet activity, the AGN does not currently produce a powerful radio jet, so it seems unlikely that the displacement is due to jet acceleration. However, interactions with massive perturbers or an SBH binary on a highly eccentric orbit remain possibilities.

2.6.3 NGC 4486 (M87, intermediate)

NGC 4486 (M87) is the dominant galaxy of the Virgo Cluster. It hosts the best studied extragalactic jet, which exhibits prominent knots at optical and IR wavelengths yet, apart from this, the brightness profile is regular and featureless. The peculiarly large population of globular clusters, its size and location, and the presence of stellar streams support the hypothesis that the galaxy has experienced a number of minor mergers during its lifetime (Janowiecki et al., 2010). A remarkable feature is the unusually large core, which has a radius \( r_c \sim 9.41 \) (CB05). This characteristic makes M87 a special case in our sample in that for all the other galaxies we restricted the isophotal analysis to radii larger than the core radius, whereas for M87 we analyzed isophotes within the core radius in order to be consistent with B10.

**Photometric analysis.** A total of six images obtained with ACS/HRC, WFPC2/PC and NICMOS2 were analyzed (see Table 2.1), including the combined ACS images (ACS/HRC/F606W and ACS/HRC/F814W) previously analyzed by B10. The results of the photometric analysis are shown in Figs. 2.5 and 2.16–2.20 and the measured displacements relative to the AGN are plotted in Fig. 2.6a. In all images, we analyzed isophotes within the range \( 1'' \leq r \leq 3'' \), for consistency with B10. The displacements measured in different images vary in amplitude and significance. Notably, none of the three NICMOS2 images (F110W, F160W and F222W) exhibit significant
displacements at the $\geq 3\sigma$ level. Furthermore, the $1\sigma$ uncertainties, when converted to linear distances, do not encompass the significant displacements recovered from the optical images. The displacements measured from the ACS and WFPC2 images also differ in amplitude but there is a tendency for the photocenter to be displaced NW of the AGN, roughly in the direction of the radio jet. The isophote centers are reasonably stable – although there are deviations $\sim 1 - 2$ pixels ($\leq 0^\prime 1$), systematic trends with SMA are not generally evident (Figs. 2.5 and 2.16–2.20). The most significant displacement is obtained from the ACS/HRC F814 image, for which the isophote centers cluster tightly around the mean photocenter (Fig. 2.5). The measured displacement of the photocenter relative to the AGN is $\Delta r = 7.7 \pm 0.3$ pc NW, implying that the SBH is displaced by $\Delta r$ in the counter-jet direction. This result is in agreement with the displacement obtained by B10 from a similar analysis. The main differences between the method used by B10 and that employed in this paper are the iterative technique used here to generate the mask and the weight function used to derive the isophotal center: while B10 used a conventional uncertainty weight, here we weight for the light content of each isophotal annulus (see Section 2.3.1).

The weighted average displacement has a magnitude $4.3 \pm 0.2$ pc and direction NW (PA = $307 \pm 1^\circ$).

**Offset origin.** The presence of a large number of bright globular clusters visible in all the images analyzed allows us to define a common reference frame which we can use to compare results from images obtained with different instrument/filter combinations. After selecting several globular clusters as reference points and matching their positions, we plotted the AGN and photocenter positions determined from the different images in the reference frame defined by the ACS image (Fig. 2.32). The AGN position as measured from the different images is fairly stable whereas the photocenters exhibit differences in position much larger than the scatter ($\sim 0.5$ pixels) in the AGN position. This indicates that the differences in the displacements are due largely to differences in the positions of the photocenters. The origin of these discrepancies is unclear. Unlike other galaxies, there is no evidence of dust extinction or other asymmetries that may account for different results at different wavelengths.

We conducted several trials in order to determine the influence of (i) the degree of masking applied to the jet, (ii) the bright knot visible NW of
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Figure 2.32: M87 - Using a set of bright globular clusters visible in all the frames, we matched the AGN and isophotal center position with the coordinate system defined by the ACS frame. The result shows that while the AGN (diamonds) remains fairly stable, the isophotal center (crosses) has the larger scatter accounting for the discrepancies in the recovered offsets. The smaller error is associated with results from ACS, the larger with results from NICMOS. Results from only three images out of six are shown to make the image clear.

the nucleus in the ACS image. The results were found to be independent of the degree of masking; no significant differences in the photocenter positions were found when the analysis was performed with no masking at all or with heavy jet/knot-masking.

As a fraction of the rather large core radius, the weighted mean displacement is only \( \approx 0.01 \) \( r_c \) (Table 2.6). We estimate a 85 (99)% probability of finding a displacement larger than that observed for \( t_m = 5 \) (0.4) Gyr, assuming phase II recoil oscillations were triggered. The probability of obtaining the relatively large recoil kick (\( \gtrsim 325 \) km s\(^{-1}\); Table 2.7) required for phase II oscillations is \( \approx 33\% \) (L12).

The apparent close alignment of the offset with the jet direction favors jet acceleration but is also generally consistent with gravitational recoil. However, as there is no reason to expect such an alignment if the displacement is due to gravitational interactions with massive perturbers, or orbital motion in a SBH-binary, these mechanisms are disfavored. A detailed discussion of the possible displacement mechanisms is given in Section 4 of B10.
NGC 1399 (low)

NGC 1399 is a regular giant E1 and is the central and dominant galaxy of the Fornax cluster (Ferguson 1989). It is associated with a low power radio source characterized by two nearly bi-symmetric jets extending \( \sim 10 \) kpc, approximately N and S of the core (PA \( \approx 9^\circ \) W of N, Killeen et al. 1988). Shurkin et al. (2008) report the presence of X-ray cavities associated with the radio lobes. NGC 1399 has been the subject of a number of dynamical studies (e.g. Houghton et al. (2006) and references therein). In particular, Houghton et al. performed near-infrared adaptive optics assisted spectroscopic observations of the central 1\textquoteleft 5 of the galaxy and found evidence of a kinematically decoupled core and offset asymmetric isophotes that they considered to be consistent with the presence of a M31-like double nucleus. The asymmetric isophotes, elongated in the direction E-SE, are localized in a region much smaller than that used for our isophotal analysis (\( r > 2'5 \)).

Photometric analysis. Four images, obtained with WFPC2/PC - F606W, F814W and WFC3/IR - F110W, F160W, were analyzed for this galaxy. From the F606W image we find a low significance displacement of amplitude 1.7 \( \pm \) 0.4 pc, in almost the same N-NW direction as the radio jet axis, PA = \(-8^\circ \pm 16^\circ\). A 2\( \sigma \) offset in the same direction was recovered from the WFPC2/PC - F814W image, which is consistent within the errors with the F606W result. Offsets recovered from the WFC3 images are classified as non-significant, but, given their large error bars, they are consistent with the WFPC2 results (Fig. 2.6a). The error weighted offset, computed including results from both WFPC2 and WFC3, is 1.5 \( \pm \) 0.4 pc with PA = \(-17^\circ \pm 16^\circ\). The isophote fitting analysis (Figs. 2.7 to 2.10) reveals a remarkably regular photometric structure well modeled by concentric elliptical isophotes. For both images, the isophote center co-ordinates vary little with SMA and are very tightly clustered, with narrow (\( \lesssim 0.5 \) pixel) distributions in \( x \) and \( y \).

Offset origin. The weighted mean displacement is small compared to the core radius, \( \approx 0.01 \) \( r_c \) (Table 2.6). A minimum kick velocity \( \gtrsim 300 \) km s\(^{-1}\) (Table 2.7) is required to trigger phase II recoil oscillations; the probability of generating a kick of at least this magnitude is \( \sim 33\% \) (L12). Assuming that phase II recoil oscillations were triggered, we estimate the probability of finding a displacement larger than that observed to be 11 (75)\%, for \( t_m = 5 (0.4) \) Gyr.

If the observed displacement is due to a recoiling SBH, we estimate that
(t - t_c) \lesssim 1.6 \text{ Gyr} has elapsed since the oscillation damped below the core radius, using \( \tau = 0.17 \text{ Gyr} \) and \( \sigma = 346 \text{ km s}^{-1} \) (Table 2.7).

The close alignment of the displacement with the radio axis is consistent with both recoil and jet acceleration as the cause of the displacement. If the latter, eq. 2.15 implies that, for a Bondi accretion rate \( \dot{M}_b \sim 0.04 \text{ M}_\odot \text{ yr}^{-1} \) \cite{loewenstein2001} and a \( 10^9 \text{ M}_\odot \) black hole, an asymmetry in the radio jet power in the range

\[
3 \times 10^{-4} \lesssim f_{\text{jet}} \lesssim 3 \times 10^{-3}
\]

that persists for \( t \sim 10^8 \text{ yr} \) would be needed to produce an offset \( 1.8 \lesssim \Delta r \lesssim 18 \text{ pc} \).

Other mechanisms (interactions with massive perturbers and a stalled SBH binary), are disfavored by the alignment between the displacement and jet direction. The presence of an unresolved M31-like double nucleus as suggested by \cite{houghton2006} might also explain the measured offset, although as in the case of a binary SBH, the alignment with the radio source axis would have to be regarded as fortuitous.

### 2.6.5 IC 4296 (low)

The properties of this galaxy have been extensively studied in a series of papers by \cite{killeen1986a} and \cite{killeen1988}. It is a fairly circular elliptical which is the brightest component in the small group A3565. It is associated with the extended low-to-intermediate luminosity radio source PKS 1333-33 \cite{mills1960}, which has two quasi-symmetric slightly curved jets with an average position angle \( \sim 130^\circ \) and terminating in lobes \( \sim 200 \text{ kpc} \) from the core \cite{killeen1986b}. The curvature along the jets is consistent with the motion of the galaxy through the group intergalactic medium \cite{killeen1988}. On the parsec scale, a jet and counter-jet emerge from the unresolved core in PA \( \sim 140^\circ \), consistent with the large-scale radio source, with the brighter jet on the NW side. The brightness asymmetry is attributed to Doppler boosting \cite{pellegrini2003}. Isophotal studies suggest tidal interactions with the smaller companion IC 4299 \cite{younis1985}. Nevertheless, \cite{efstathiou1980} show that the isophotal ellipticity and position angle are constant at all radii.
from 2.4 to 48.8 arcsec (a region much larger than that studied in this work, $1.5 < \Delta r < 6.5$), which suggests that any distortions due to interactions with companion galaxies are negligible over this scale.

**Photometric analysis.** Three images, obtained with ACS/HRC-F625W, WFPC2/PC-F814W and NICMOS2-F160W, were analyzed for this galaxy. In the ACS image a displacement of $\Delta r \geq 5.2 \pm 1$ pc was found. On the basis of the IQR, that is considered to be of low significance. The displacement obtained from the NICMOS2 image is not considered significant, but is consistent with the ACS result, albeit within large errors. For the WFPC2 image, the $y$-component of the displacement is consistent with the ACS result but the $x$ component exhibits a marginally significant difference and in fact indicates a displacement in the opposite direction (E). However, neither component of the WFPC2 displacement is classified as significant. These results are summarized in Fig. 2.6a.

The discrepancy in the photocenter positions appears to be linked to systematic migrations in the isophote center co-ordinates determined from the fits in the NICMOS2 and WFPC2 images: there are systematic migrations northwards in the NICMOS2 image (Fig. 2.29) and eastwards in the WFPC2 image (Fig. 2.28) resulting in distributions with large IQRs in the $y$ and $x$ co-ordinates, respectively. In contrast, the co-ordinates extracted from the ACS image (Fig. 2.27) show little variation with SMA and cluster quite symmetrically around the photocenter.

This galaxy exhibits a warped dusty disk, which crosses the nucleus in a roughly E-W direction and is clearly visible in all three images (Figs. 2.27, 2.28 and 2.29). This feature is too small ($r \lesssim 0.9$) to affect the photocenter position, which is calculated from isophote fits over radii $1.5 < r < 6.5$. However, it does create large gradients in the background brightness around the nucleus which affect the gaussian fits to the central peak, especially when large fitting-boxes are used. The effects are particularly noticeable for the WFPC2 image, where the AGN position systematically shifts South-East as the size of the fitting-box is increased. This was mitigated by reducing the size of the fitting-box until stable values were found for the AGN co-ordinates.

The average error-weighted offset obtained for this galaxy from the ACS, NICMOS2 and WFPC2 images is $\Delta r \geq 3.8 \pm 0.7$ pc in $\text{PA} = -22 \pm 7^\circ$ E of N.
Offset origin. The status of IC 4296 as the brightest member of its group and the fact that it has a kinematically peculiar core (Killeen et al., 1986b) suggest that this galaxy has experienced minor mergers during the past few Gyr.

The weighted mean displacement is a small fraction of the core radius, \( \approx 0.01 \, r_c \) (Table 2.6). The probability of generating a recoil kick large enough to trigger phase II recoil oscillations (\( \gtrsim 200 \, \text{km s}^{-1} \); Table 2.7), is \( \sim 45\% \) (L12) and given that phase II oscillations were triggered, we estimate a 37 (97)\% probability of finding a displacement larger than that observed, for \( t_m = 5 \) (0.4) Gyr.

Using eqs. 2.2 and 2.3 with \( \sigma = 333 \, \text{km s}^{-1} \), \( r_{\text{rms}} \geq 3.8 \, \text{pc} \) and \( r_c = 347 \, \text{pc} \), we find \( (t - t_c) \lesssim 9 \, \tau \approx 5.8 \, \text{Gyr} \). In this case, the low density of the large core is responsible for the long damping time.

It has been pointed out by Killeen et al. (1986b) that on kpc scales the radio jets exhibit transverse oscillations with wavelengths \( \sim 10 \, \text{kpc} \) and an amplitude comparable with the jet width. Similar oscillation wavelengths are expected from precession due to orbital motion in a \( \sim \, \text{pc} \) scale SBH binary (see Section 2.5.4). However, Killeen and Bicknell (1988) found that, in detail, the oscillation pattern is not consistent with precession and favor instead helical Kelvin-Helmholtz instabilities.

If we disregard the discrepant WFPC2 result, the direction of the weighted mean displacement derived from the NICMOS2 and ACS images is \( \text{PA} = 132 \pm 8^\circ \). In projection, therefore, the displacement is remarkably well-aligned with the radio source axis, suggesting jet acceleration as a plausible candidate for the displacement mechanism. Pellegrini et al. (2003) infer a viewing angle \( \theta = 63.5 \pm 3.5^\circ \) for the parsec-scale jets. Assuming that the displacement is in the same direction in space as the jet, the de-projected amplitude is \( \Delta r_{\text{jet}} = 4.3 \pm 3 \, \text{pc} \).

Given that the galaxy is characterized by a low density core, taking the age of the radio source to be \( t \sim 10^8 \, \text{yr} \) (Killeen and Bicknell, 1988), \( \dot{M}_a = \dot{m}_{\text{Bondi}} \sim 0.02 \, \text{M}_\odot \, \text{yr}^{-1} \) (Pellegrini et al., 2003), \( M_\bullet \sim 10^9 \, \text{M}_\odot \) from the \( M - \sigma \) relation and \( 3 \lesssim \Delta r \lesssim 30 \, \text{pc} \), we find from eq. 2.15 that

\[
10^{-3} \lesssim f_{\text{jet}} \lesssim 9.7 \times 10^{-3}.
\]

Therefore, an asymmetry in jet power amounting to \( \lesssim 1\% \) of the accre-
tion luminosity could account for the observed offset if it persists for $\sim 10^8$ yr.

The close alignment with the radio jet axis argues against the displacement being caused by gravitational interactions with massive perturbers.

### 2.6.6 NGC 5419 (low, double nucleus)

This galaxy is the dominant member of the cluster Abell S753 (Abell et al. 1989). A low surface brightness X-ray halo is centered on the galaxy and extends over a radius $r \approx 16\arcmin$ (190 $h^{-1}$ kpc). An unusual diffuse radio source, PKS B1400-33, is associated with the cluster, but is offset relative to the X-ray emission and NGC 5419 (Subrahmanyan et al. 2003). The galaxy is located just beyond the NW edge of the extended radio emission and itself is associated with a bright, compact radio source. The low surface brightness and steep spectral index of the diffuse source suggest that it is a relic, with a spectral age of $5 \times 10^8$ yr. However, it is unclear if the relic was created by an earlier episode of powerful activity in NGC 5419, or whether it is a relic lobe injected into the cluster by a previously active double radio source located outside the cluster (the scenario favored by Subrahmanyan et al. although an optical counterpart has not been firmly identified). If the relic originated from NGC 5419, the spatial offset may be due to proper motion of the galaxy or to buoyancy of the synchrotron plasma (e.g., McNamara et al. 2001).

**Photometric analysis.** The galaxy has a double nucleus (Lauer et al. 2005; Capetti and Balmaverde 2006), which is well-resolved in the WFPC2 planetary camera image (WFPC2/PC-F555W). The two nuclei are separated by 0\arcsec{27}, with the fainter (secondary) nucleus located almost at the south of the brighter (primary) nucleus. The photocenter is offset by $\Delta r_1 \gtrsim 7.5 \pm 1.7$ pc W-SW (PA = 252 $\pm 12^\circ$) from the primary and $\Delta r_2 \gtrsim 62 \pm 2$ pc N-NW (PA = 346 $\pm 2^\circ$) from the secondary nucleus.

A periodic pattern is visible in the residual image obtained after subtraction of the photometric model (middle panel in Fig. 2.24). This is likely to be due to the pronounced “boxiness” of the isophotes, which could not be perfectly reproduced even though higher harmonics were included in the model. The isophote center co-ordinates cluster fairly tightly around the photocenter, which is closest to the primary nucleus, and generally show little variation with SMA (Fig. 2.24), with the exception of a small migration...
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(≈ 0′′05) eastward of the photocenter in the inner 170 pixels (8′′5).

**Offset origin.** The projected separation between the two nuclei \( (\Delta r \approx 75 \text{ pc}) \) is slightly smaller than the estimated SBH influence radius \( (r_h \approx 90 \text{ pc}) \) and much smaller than the core radius \( (r_c \approx 500 \text{ pc}; \text{Table } 2.1) \). Hence, it is possible that the secondary nucleus is a second SBH, or even the nucleus of a satellite galaxy, on a slowly-evolving orbit in the low-density core (Antonini and Merritt, 2012).

The displacement of the photocenter relative to the primary nucleus is a small fraction of the core radius, \( \approx 0.02 r_c \) (Table 2.6). The probability of generating a recoil kick velocity large enough to trigger phase II recoil oscillations \( (v \gtrsim 300 \text{ km s}^{-1}; \text{Table } 2.7) \), is \( \approx 33\% \) (L12) and given that phase II oscillations occur, we estimate a 46 (97)% probability of finding a displacement larger than that observed, for \( t_m = 5 \) (0.4) Gyr. Using eqs. 2.2 and 2.3 with \( \sigma = 351 \text{ km s}^{-1} \), \( r_{\text{rms}} \geq 7 \text{ pc} \) and \( r_c = 500 \text{ pc} \), we find \( (t - t_c) \lesssim 9 \tau \approx 10 \text{ Gyr} \), a factor ten larger than the estimated spectral age of the diffuse radio source. Therefore, if an SBH binary coalescence event is responsible for the displacement, it seems likely that it pre-dates the AGN phase that created the radio relic (if indeed NGC 5419 is the origin of the relic).

2.6.7 Notes on other galaxies

In the following galaxies, photocenter – SBH displacements were not considered significant.

2.6.7.1 NGC 4168

NGC 4168 is an E2 in the Virgo cluster. Broad H\( \alpha \) has been detected in its nuclear optical spectrum, resulting in classification as a Seyfert 1.9 (Ho et al., 1997). VLBA observations at 8.4 GHz show an unresolved radio source with no evidence of jets (Anderson et al., 2004). Although the galaxy appears very regular in the WFPC2-WF/F606W image, the photometric analysis reveals systematic variations in the isophote centers with SMA that are much larger in amplitude than the displacement between the mean photocenter and the AGN position (Fig. 2.11). In particular, there is an abrupt shift to the E in the \( x \) co-ordinate and a systematic migration to the S in \( y \), for SMA \( \gtrsim 260 \text{ pixels (13″)} \). The measured displacements in \( x \)
and $y$ are $< 0.8$ IQR and therefore considered “null” results.

### 2.6.7.2 NGC 4261

NGC 4261 is a massive elliptical (E2-3) in the outskirts of the Virgo cluster. Nolthenius [1993] identifies this galaxy as the dominant member of a group of 33 galaxies, the Virgo W cloud. It is associated with a bright FR1 radio source, 3C 270, which has twin jets close to the plane of the sky, $\theta = 63 \pm 3^\circ$, and aligned on the axis W-E, PA = 87 $\pm$ 8$^\circ$, with the western radio component slightly brighter than the eastern [Jones et al. 2000; Worrall et al., 2010]. Deep imaging reveals the presence of tidal tails to the NW and a tidal fan SE [Tal et al., 2009] while [Giordano et al., 2005] find anisotropies in the globular cluster distribution.

[Cappellari et al. (2007)] report the presence of a kpc-scale kinematically decoupled core hosting a 100 pc scale disk of dust, cool molecular and atomic gas ([Jaffe et al., 1993; Jaffe and McNamara, 1994]). [Jaffe et al. (1996) & Ferrarese et al. (1996)] studied the central region of this galaxy in detail using HST/WFPC2/PC1 V (filter F547M), R (F675W) and I (F791W) images. After correcting the R images for line emission, they determined that the central dusty disk is characterized by a rotation axis which closely matches the axis of the jets but it is not coaxial with the semi-major axis of the galaxy. The disk is not centered on the AGN, nor on the photocenter, which they find is itself displaced relative to the AGN by $\Delta r = 3.3 \pm 1.3$ pc NE.

In this study, we chose to analyze a NICMOS2 F160W image (with a pixel size of $0''.05$), since the nuclear source is bright and dust extinction and contamination due to emission from ionized gas are minimized. The galaxy exhibits boxy isophotes which are difficult to model accurately. Even though the third and forth harmonics were included in the isophote fits, the residual image still shows a spiral pattern suggesting that a more complex model perhaps involving multiple components would be necessary to successfully model the surface brightness distribution (Fig. 2.12). Nevertheless, the isophote centers are relatively stable, except for a slow migration to the N for SMA $\gtrsim 120$ pixels ($6''$). The mean photocenter displacement relative to the AGN is $\Delta r = 3.3 \pm 2.2$ pc W-NW (PA = 297 $\pm$ 38$^\circ$). The $x$ component of the displacement is large compared to the IQR. However, because of the large uncertainty in positions derived from NICMOS2 images (0.23 pixels), we do not consider this offset significant.
2.6 Notes on individual sources

2.6.7.3 NGC 4373

This galaxy is located in the outskirts of the Hydra-Centaurus supercluster and is associated with a compact radio source (Sadler et al., 1989). It forms an isolated pair with IC 3290 (Sadler and Sharp, 1984), which is located 2′ W-SW of NGC 4373. Gritzbauch et al. (2007) suggest that there is an ongoing strong interaction with the companion. Our photometric analysis of the WFPC2/PC-F814W image reveals boxy isophotes which produce cross-shaped residuals, even though higher harmonics were included in the isophote fits (Fig. 2.4). The y coordinate of the isophote center position has a narrow distribution centered on the mean photocenter and shows only a slight drift northward, for SMA > 170 pixel (8′′5). The x coordinate exhibits a systematic migration eastwards from the photocenter, resulting in a broader, skewed distribution. The mean photocenter is consistent with the AGN position within the uncertainties.

2.6.7.4 NGC 4552

NGC 4552 is a typical giant elliptical in the Virgo cluster which hosts a very low-luminosity AGN. HST imaging and spectroscopy reveal a variable UV point source that has optical emission lines characteristic of AGN (Cappellari et al., 1999; Maoz et al., 2000). Interestingly, a second, transient UV source of comparable luminosity, but offset from the first by 0′′14, was present in 1991, but was not detected in 1993 (Renzini et al., 1995; Cappellari et al., 1999; Maoz et al., 2005). Radio observations at 8.4 (Filho et al., 2000) and 5 GHz (Nagar et al., 2002) show the presence of a flat spectrum radio core. Nagar et al. (2002) also report variability at the ∼ 20% level on a ∼ 1 year timescale and find evidence of pc-scale jets, or extensions, along the East-West axis. NGC 4552 exhibits several morphological features indicative of past mergers, including three concentric shells at 5′, 7′ and 10′ from the nucleus (Malin, 1979). Traces of a recent minor merger with a gas rich satellite galaxy have been identified in the presence of dust patches in the inner region (van Dokkum and Franx, 1995), and Hα emission extending up to ∼ 2.5 kpc from the center (Trinchieri and di Serego Alighieri, 1991; Macchetto et al., 1996).

The photometric analysis of the WFPC2/PC-F814W image shows that the y-coordinate of the isophote center migrates systematically southward...
Notes on individual sources

relative to the photocenter for $\text{SMA} > 200$ pixels ($10''$) with a maximum shift $\lesssim 0''2$ (Fig. 2.21). There is a smaller westward shift in the $x$ coordinate. The inner $0''3$ of the residual image shows evidence of an arc-like dust lane partly encircling the central source with an opening toward the S. This feature was previously noted by Carollo et al. (1997) and Cappellari et al. (1999) (see Fig. 12 in the latter) and is the cause of the increased uncertainty on the $y$ co-ordinate of the AGN position. We did not find a significant ($> 3\sigma$) displacement in this object.

2.6.7.5 NGC 4636

NGC 4636 is a giant elliptical in the outskirts of the Virgo cluster. Its nucleus has a LINER emission line spectrum, in which a weak broad H$\alpha$ line has been detected (Ho et al., 1997). It has a jet-like radio source extending $\approx 1.5$ kpc either side of the nucleus in position angle $\theta \approx 33^\circ$ (Birkinshaw and Davies, 1985). NGC 4636 is also associated with a luminous, extended X-ray source with a peculiar morphology featuring two symmetric, arm-like extensions emerging from the bright central region and extending up to $\approx 8$ kpc along the NE-SW axis. Other fainter arm-like features emerge from the nucleus and Jones et al. (2002) suggest that these features trace cyclic nuclear outburst events occurring on a timescale $\sim 10^7$ yr. According to Temi et al. (2003), the observed FIR fluxes (at 60, 90 and 180 $\mu$m) suggest the accretion of dust in a recent (within $\sim 10^8$ yr) merger with a gas-rich galaxy.

Our isophotal modeling of the WFPC2/PC-F814W image indicates the presence of faint dust lanes inspiraling toward the nucleus (Fig. 2.22). There is a systematic shift in the isophote centers to the north and west relative to the photocenter for $\text{SMA} > 170$ pixels ($8''5$), which results in broad distributions in the $x$ and $y$ co-ordinates (Fig. 2.22). The photocenter position is consistent with the AGN position in the $y$ direction, but exhibits a $> 3\sigma$ offset in $x$. Nevertheless, as the IQR of the isophote center coordinate distribution exceeds the displacement we consider this a null result.

2.6.7.6 NGC 4696 (double nucleus)

NGC 4696 is the dominant galaxy of the Centaurus cluster. There is an extensive literature on the multi-wavewelength properties of this galaxy,
2.6 Notes on individual sources

which has a secondary nucleus \cite{Laine2003} offset by $\approx 0.3$ to the SW of the primary \cite{Laine2003} and Fig. 2.23. The double nucleus is partially surrounded by a complex of dust lanes and associated emission line filaments, the most prominent of which is in the form of a spiral leading towards the center. These features have been interpreted as evidence of a recent minor merger with a gas-rich galaxy \cite{Sparks1989, Farage2010} alternatively the emission-line gas may have been “drawn out” by rising radio bubbles \cite{Canning2011}. The galaxy is associated with the moderately powerful radio source PKS 1246-410, which extends $\approx 10$ kpc along an approximately E-W axis, with the ends of both arms bending southwards. The radio source wraps around the region of brightest X-ray emission, suggesting interactions between the radio plasma and the hot thermal gas \cite{Taylor2006}. VLBA observations also obtained by \cite{Taylor2006} reveal a relatively weak core and a one-sided jet extending over $\approx 25$ pc in PA $= -150^\circ$.

Subtraction of our photometric model from the ACS/WFC-F814W image (Fig. 2.23) clearly shows the dust features around the nucleus. The positive residuals probably trace the emission-line filaments. The isophote centers exhibit large excursions, resulting in broad distributions in both $x$ and (especially) $y$ coordinates. Although we measure a 3$\sigma$ offset in $x$ between the brightest nucleus and the mean photocenter, we consider this a null result because of the large IQR.

2.6.7.7 IC 1459

IC 1459 is a giant elliptical galaxy (E3–4) and a member of a loose group (identified as “group 15” in \cite{Huchra1982} of ten galaxies, which are mainly spirals. Despite its relatively unremarkable appearance to casual inspection, this galaxy turns out to be notably peculiar (see \cite{Forbes1995} for a detailed analysis): it has one of the faster counter rotating kinematically distinct cores \cite{Franx1988}, faint stellar spiral arms \cite{Malin1985}, outer shells \cite{Forbes1995} and irregular dust lanes or patches near the nucleus \cite{Forbes1994}. It has a hard X-ray point source \cite{Gonzalez2009} and a strong, compact radio core at 5 GHz \cite{Slee1994}.

We analyzed a WFPC2/PC-F814W image (Fig. 2.26). After subtraction of the photometric model, the residual image shows a periodic pattern,
indicating that the isophotes deviate from perfect ellipses. Systematic variations in the isophote center co-ordinates are seen in both $x$ and $y$, with increasing scatter also present for SMA $> 230$ pixels ($11''5$). We did not find a significant ($> 3\sigma$) displacement in this galaxy.

2.6.7.8 IC 4931

This relatively little studied galaxy is the brightest member of the group A3656 (Postman and Lauer, 1995). Its radio source is relatively weak, with a total radio flux at 5 GHz of 0.9 mJy (see Table 2.2 to compare with other galaxies). It is also detected at 1.4 GHz with a flux density of 22 mJy (Brown et al., 2011). Apart from the optical nucleus and the radio emission, there is no supporting evidence indicating the presence of an AGN such as an X-ray point source, or line emission.

Our analysis of the WFPC2/PC-F814 image (Fig. 2.30) shows large systematic variations in the isophote center co-ordinates, with the $x$ coordinate in particular migrating up to $0''.4$ W relative the photocenter for SMA $\gtrsim 100$ pixels ($5''$). The co-ordinate distributions are among the broadest of the whole sample, spanning a range of $0''.5$ in $x$. We measured a $\sim 3\sigma$ offset between the photocenter and the AGN in the $x$ co-ordinate (E), but this is considered a null result because of the large IQR.

2.7 Summary and Conclusions

We have analyzed HST archival images of 14 nearby core elliptical galaxies, each of which hosts a central point-like source associated with a low-luminosity AGN, in order to search for offsets between the AGN and the galaxy photocenter. Such AGN–photocenter displacements are possible signposts of gravitational recoils resulting from the coalescence of an SBH binary.

We find significant ($> 3\sigma$) differences between the positions of the nuclear optical (or NIR) point source and the mean photocenter of the galaxy, as determined from isophote fits, in ten of the 14 galaxies in the sample. Assuming that the mean photocenter locates the minimum of the galactic potential well and that the point source locates the position of the AGN and hence the SBH, these results imply that the SBH is displaced from its equilibrium position by angular distances ranging between 20 and 90 mas,
2.7 Summary and Conclusions

or projected linear distances in the range $1 - 10$ pc. As spurious offsets may occur as a result of large-scale isophotal asymmetries, only displacements of magnitude $> 0.8 \times$ the inter-quartile range of the distribution of isophote center coordinates (equivalent to $1\sigma$ for a gaussian distribution) are considered “real”. There are six galaxies that exhibit displacements $> 0.8$ IQR with three of these (NGC 4278, NGC 4486 and NGC 5846) having displacements $> 1.6$ IQR (equivalent to $2\sigma$). In every case, the measured displacement of the SBH relative to the galaxy photocenter is a small fraction ($1$–$10\%$) of the galaxy core radius, which is typically $r_c \sim 300$ pc, for these galaxies.

Approximate alignments between the SBH–photocenter displacements and the radio source axis were found in four of the six galaxies considered to have significant displacements, including three of the four that have FR I, or FR I-like radio sources with relatively powerful and well-defined kpc-scale jets. Indeed, in every case in which there is both a significant displacement and an unambiguous jet, the two are approximately aligned.

Lacking detailed knowledge of the merger history of the galaxies, or of the SBH binary parameters (such as mass ratio and spin configuration) that determine the recoil velocity, it is not possible to directly test the hypothesis that the displacements are caused by residual gravitational recoil oscillations. Instead, we used a simple Monte-Carlo model to investigate if the measured displacements are consistent with gravitational recoil. We find that the displacements in individual objects can plausibly be attributed to residual gravitational recoil oscillations following a major or minor merger within the last few Gyr. However, for plausible merger rates there is a high probability of larger displacements than actually observed, if SBH coalescence events took place in these galaxies.

That larger displacements were not observed suggests that the frequency of gravitational recoil kicks large enough to trigger long-lived oscillations is lower than predicted, perhaps because the evolution of the SBH binary typically results in a configuration that suppresses recoil kicks with velocities $\gtrsim 200$ km s$^{-1}$. Alternatively, the post-recoil oscillations may be damped more quickly than predicted by pure $N$-body simulations. In either case, gas may play an important role (e.g., Dotti et al. [2010], Sijacki et al. [2011]). Otherwise, it is possible that galaxy mergers are much more infrequent than implied by the current $\Lambda$CDM paradigm (Kroupa [2014]).
Several other mechanisms are capable of producing the observed displacements, with the observed alignments between the SBH–photocenter displacements and the radio source axis favoring jet acceleration in some objects. An approximate displacement–radio axis alignment is also expected for gravitational recoil, but not for orbital motion in pre-coalescence SBH binaries or interactions with massive perturbers. However, both of the latter mechanisms are capable of producing displacement amplitudes comparable to those observed and cannot be ruled out in individual objects.

In general, it is not possible to unambiguously distinguish between different mechanisms (including recoil) on the basis of the displacement measurements alone for individual galaxies. However, with a larger sample it may be possible to distinguish mechanisms using statistical arguments. Thus, for jet acceleration the displacement direction should be strongly correlated with the radio jet, with the amplitude correlating with jet power. In the case of gravitational recoil, a weaker correlation with jet direction might be expected. However, no such correlations are expected for binary SBH, or massive perturbers.
3.1 Introduction

In Section 1.3, I discussed the importance of gas inflows and outflows in the life-cycle of AGNs and their host galaxies: inflows transport gas from the outer region of the galaxy down to the accretion disk of the SBH; via the accretion of such gas the galaxy nucleus becomes active. Outflows contribute to the removal of angular momentum from the gas and transfer matter and kinetic energy to the interstellar medium, perhaps setting the observed proportionality between SBH, bulge, star formation rate, and other properties of the host galaxy. Because of the strong interplay that seems to exist between nuclear activity and galaxy evolution, it is important to reach a full understanding of outflows and the chain of mechanisms that funnel gas toward the SBH.

In order to investigate these interactions, we have assembled two samples of nearby AGNs, mostly Seyferts. The first one consists of galaxies characterized by nuclear dusty spirals (features believed to trace inflows). The second one is a sample of Seyferts and LINERs selected on the basis of their nuclear hard X-ray luminosity (a proxy for the SBH accretion rate). With these samples we aim to (1) determine if there is a transition in the behavior of the circumnuclear gas kinematics from low-luminosity to high-luminosity AGNs, and investigate the effect of other factors such as host galaxy proper-
3.2 Integral field spectroscopy

Integral field spectroscopy (IFS) is a technique which combines imaging and spatially resolved spectroscopy in a single exposure. The final product of an IFS observation is a “cube”, that is a traditional 2D image with an additional dimension containing the spectra corresponding to each and every spatial pixel.

An integral field spectrograph is made by coupling a spectrograph to an integral field unit (IFU). Four main IFU designs have been used so far. Depending on the technique used to map the 2D object field onto the spectrograph slit, they are classified as “lenslet, fiber, fiber-lenslet or image-slicer” IFUs.

The “fiber” IFU design was initially proposed by Vanderriest (1980): using optical fibers it mapped the 2D field into a pseudo slit at the entrance of a spectrograph. Examples of instruments making use of this principle include DensePak and SparsePak at the WYIN telescope (Barden and Wade, 1988), and INTEGRAL on the William Herschel Telescope. The major advantage which comes with the use of fibers is the large freedom in the mapping and “relocation” of the original 2D image: the flexibility of the fibers allows one to map the image plane (typically circular, or rectangular) into one or mul-
3.2 Integral field spectroscopy

tiple slits at the entrance of a spectrograph. In addition, it is possible to use
the fibers to transport the incoming signal to relatively large distances from
the telescope, where it can be analyzed and recorded by a separate instru-
ment. This solution has recently been adopted within the project GRACES
(Gemini Remote Access to CFHT ESPaDOnS Spectrograph). To combine
the large collecting area of GEMINI and the high resolving power of the
ESPaDOnS spectrograph on the Canada-France-Hawaii-Telescope (CFHT),
light is collected by the GEMINI-North telescope, then it is transported, via
fibers, for 270 meters to the ESPaDOnS spectrograph on the nearby CFHT.
The main disadvantages of fiber IFUs are (1) the low filling factor (the poor
spatial sampling of the 2D image) due to the presence of inactive parts of the
fibers and their support, and (2) the focal ratio degradation (decollimation
of the incoming beam of light) which affects the fibers receiving light at the
high focal ratio typical of large telescopes.

IFUs such as TIGER (Courtes, 1982; Bacon et al., 1995), SAURON
(Bacon et al., 2001a) and OASIS are “lenslet” IFUs: they use an array of
microlenses, or lenslets, to sample the 2D FOV. Each microlens produces an
image of the exit pupil which is then dispersed into a spectrum by a grism.
Contrary to the “fiber” design, where dead space between the fibers does
not allow for a full coverage of the image plane, this technique fully samples
the image. However, to avoid overlapping on the CCD, the spectra must
occupy a relatively small portion of the chip, resulting in a short spectral
extension. The CCD, in turn, is not used very efficiently as many pixels do
not record any signal.

A hybrid design produced the successful lineage of “fiber-lenslet” IFUs.
In these instruments, light passes through an array of lenslets coupled to a
fiber bundle. Light is then transferred into one or more pseudo slits and fed
to a spectrograph. Examples of such instruments are the IFU on the Gemini
Multi Object Spectrograph (Allington-Smith et al., 2002), VIMOS on the
Very Large Telescope (VLT, Le Fèvre et al., 2003), PMAS and PPAK at
Calar Alto (Roth et al., 2005). This design solves the two main limitations
of the “fiber” IFUs: hexagonal or square lenslets, which are oversized with
respect to the fiber core, allow for a unity filling factor, and they decrease the
focal ratio of the incoming beam (low focal ratios are ideal for propagation
within the fibers).

The last class of IFU makes use of the “image-slicer” design (Weitzel
In this case, the 2D plane of the object is imaged by a series of stacked tilted mirrors (the slicing mirror), each image-slice is reflected into a second set of mirrors (the imaging mirrors) which re-image the field into a long stripe at the spectrograph slit. Instruments making use of this technique are, for example, MUSE (Henault et al., 2003) and SINFONI (Eisenhauer et al., 2003) on VLT, and NIFS (McGregor et al., 2003) on GEMINI. The main advantages of these instruments are a continuous spatial sampling of the image, avoiding the filling factor problem associated with fiber IFUs; they can be also cooled to cryogenic temperatures, making them particularly well suited for infrared IFS; and they are not affected by focal ratio degradation, a problem arising from the many reflections within the fibers. However, the optical system may be large.

The Gemini Multi Object Spectrographs (GMOS, Hook et al., 2004 and references therein) are two twin instruments placed on each of the GEMINI telescopes, two 8.1m optical and infra-red telescopes located at Cerro-Pachon (Chile, GEMINI-South) and Mauna Kea (Hawaii, GEMINI-North).

GMOS is an optical instrument primarily designed to perform multi-slit spectroscopy but capable of operating in four modes: imaging, long-slit spectroscopy, multi-object spectroscopy and integral field spectroscopy. The latter is the mode used to perform the observations discussed in this dissertation. An extensive description of the GMOS IFU has been presented in Allington-Smith et al. (2002).

The GMOS-IFU is an optical fiber-lenslet IFU operating at wavelengths in the range 0.4 - 1 \( \mu m \). Light is collected by two pick-off mirrors which allow the simultaneous observation of two fields separated by 60'. One of the fields is dedicated to the observation of the background sky, while the other observes the object of interest. After being intercepted by the pick-off mirrors, light is channeled through a system of lenses which enlarges the field by a factor of 3.3 and directs the photons into a 2D array of lenslets. The lenslets are bonded to 1500 fibers: 1000 to sample the object and 500 for the sky background. While the fiber cores are only 67 \( \mu m \) in diameter, the lenslets are 407 \( \mu m \) in size to minimize light losses and achieve a filling factor close to unity (in other words, virtually all incoming photons are fed
3.4 Observations

to the fibers because the lenslets fully sample the spatial dimension of the image. Each lenslet covers 0\arcsec2 on the sky. Through the fibers, light is transferred to the spectrograph slit, which is placed at the telescope focus, where fibers are again bonded to an array of lenslets. Finally the photons are channeled into the spectrograph and, from there, to the CCD.

The GMOS-IFU can be operated in either single-slit or two-slit mode. Only half of the fibers are used in the single-slit mode (500 for the object and 250 for the sky). Because of the field-to-slit mapping, this maximizes the spectral range covered by the observation, however only half of the full FOV is sampled, that is 3\arcsec5 \times 5\arcsec for the object and 2\arcsec5 \times 3\arcsec5 for the background. All of the fibers are used in the two-slit mode achieving the coverage of the full FOV of the instrument, that is 5\arcsec \times 7\arcsec for the object and 5 \times 3\arcsec5 for the background. However, only half of the spectral range covered with the single-slit mode is now achieved. Observations presented in this dissertation were performed in two-slit mode, sacrificing spectral range for spatial coverage.

3.4 Observations

The galaxies discussed in the next two chapters, NGC 1386 and NGC 1365, were observed in queue mode with the GMOS-IFU mounted on the GEMINI-South telescope. The instrument was used in two-slit mode, with the R400 grating in combination with the r filter. This configuration yielded a spectral resolution R = 1918, covering the spectral range 5600 - 7000 Å. To account for dead fibers and to facilitate the removal of cosmic rays, we performed spatial and spectral dithering (small offsets in the spatial and the spectral dimensions, respectively).

Detailed descriptions of the observations are given in Sections 4.2 and 5.2 for NGC 1386 and NGC 1365 respectively.

3.5 Data reduction

Data reduction was performed using the IRAF packages provided by the GEMINI Observatory and specifically developed for the GMOS instrument.

1 http://www.gemini.edu/sciops/data-and-results/processing-software?q=node/11822

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3.5 Data reduction

The data reduction process includes bias and sky subtraction, flat-fielding, trimming, wavelength and flux calibration, building of the data cubes at a sampling of $0.1 \times 0.1$ arcsec/pixel, final alignment and combination of the cubes resulting from each exposure. The final cubes contain 7030 spectra for NGC 1386 and 76110 spectra for NGC 1365.

A detailed description of the procedure has been presented in Lena (2014). A summary is given below.

3.5.1 Calibration data

Fiber identification and flat-field reduction. Flat fields are obtained by uniformly illuminating the CCD, and they are used to correct for pixel-to-pixel sensitivity variations. In the case of a fiber-lenslet integral field unit, such as the one mounted on the GMOS, flats are also used to correct for the different lenslet/fiber throughputs. To this end, the data are divided by the response curve derived from the flat.

Two types of flats are associated with the GMOS IFU data: lamp and twilight flats. Lamp flats are obtained with the Gemini Facility Calibration Unit (GCAL, Ramsay-Howat et al. [2000]), an instrument mounted to one side of the Gemini Instrument Support Structure (ISS). To obtain a GCAL flat, the science fold mirror is rotated so that it is illuminated by the GCAL beam. Twilight flats are obtained by observing the bright sky at twilight (the sky itself acts as a uniformly illuminated area), and they are used to further correct for illumination patterns in the GCAL lamp.

I started the data reduction by reducing a GCAL flat. During this process, performed with the IRAF task *gfreduce*, good and bad fibers are interactively identified: IRAF automatically identifies the fibers, assigning an identification number (ID) to each fibre. However, this process is not perfect and two IDs may be assigned to the same fiber, or a missing fiber might be assigned an ID. Such errors prevent correct reconstruction of the final data cubes. Fibers were, therefore, identified and “traced” interactively. A database with the fiber IDs was then produced by IRAF and used to trace the fibers in all of the frames associated with the given flat-field frame.

After the interactive reduction of the first GCAL flat, the twilight flat was reduced.

The response curve. From the reduced GCAL flat-field the CCD re-
response curve is derived. This function represents the relative fiber throughput and will be subsequently used to normalize the spectra. The response curve is computed by IRAF as an average of the input spectra along the direction perpendicular to the dispersion axis. The average was fitted by a cubic spline of order 95. To account for illumination patterns in the lamp used to obtain the flat-field, a twilight sky response map was also created: during this process, spectra of the sky are divided by the response map of the flat-field. These spectra are then averaged in the dispersion direction producing a sky-to-lamp ratio for each fiber. Finally, the lamp response map is multiplied by this ratio.

**Arc reduction and wavelength calibration.** To calibrate the wavelength of the spectra, the CuAr (Copper-Argon) GCAL lamp was used to generate spectra with known emission lines, the “arcs”. Arc frames were reduced with the IRAF task `gfreduce`. Wavelength calibration was performed interactively with the task `gswavelength`: lamp emission lines were interactively identified and a Chebishev polynomial of order three was used to calibrate the wavelength axis from pixel to angstroms. Visual inspection of the calibrated arc frames showed that higher order polynomials produced a lower quality calibration.

**Reduction of the standard star.** To perform absolute flux calibration of the “science” data, a standard star was observed for each galaxy. Details of their spectral type and IDs are given in Section 4.2 and 5.2 for NGC 1386 and NGC 1365 respectively.

To reduce the data, the IRAF task `gfreduce` was applied multiple times. In the first run, the bias was subtracted from the data and the fibers were traced. The bias is a pedestal signal added to keep the signal positive, and it must be removed from both the science and the calibration data. One or more bias frames are provided by the GEMINI staff for each dataset. `Gfreduce` was applied again to perform flat fielding, extract the spectra and remove cosmic rays. Using the wavelength transformation previously established, the data were wavelength calibrated. One more application of `gfreduce` was used to subtract the sky background from the data. To perform this operation, `gfreduce` calls the task `gfskysub`: spectra from the sky IFU field are averaged into one and subtracted from the data. Once these operations were completed, the IRAF task `gfcube` was used to assemble the

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spectra from each fiber into a datacube.

The standard star was observed to flux calibrate the data. To perform flux calibration, a detector sensitivity curve was created with the aid of the tasks `gfapsum` and `gsstandard`. The first task sums all of the spectra from the science IFU field into one. The second task performs the calibration by comparing the observed fluxes in a series of bandpasses with photometric flux measurements of the observed star.

Finally, the IRAF task `gscalibrate` was used to flux calibrate the standard star. This operation consists in dividing the spectra by the sensitivity function previously computed.

### 3.5.2 Science data

The science data, i.e. the data obtained from the observation of NGC 1386 and NGC 1365, were reduced following the same steps described for the reduction of the standard star: data were bias subtracted, flat fielded, cleaned of cosmic rays, wavelength calibrated, sky subtracted, and flux calibrated.

The creation of the final datacube is somewhat more subtle for the science data. This is for two reasons. The first is that the region of interest within the galaxy is larger than the FOV of the IFU. Observations were therefore made at two different pointings to observe the desired region of the galaxy. The second reason is that spatial and spectral dithers (i.e. small offsets) were applied to facilitate the removal of cosmic rays, and to account for dead fibers and the CCD gaps. When the final datacube is created, all such offsets must be properly specified in a text file that IRAF will take as an input.

### 3.6 Fitting of the spectral features

Three main quantities can be derived from the modeling of a spectrum with emission or absorption lines: velocity, velocity dispersion, and flux under the line (if the line is in emission) or equivalent width (if the line is in absorption). Toward this end, I used customized IDL\(^2\) routines.

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\(^2\)IDL, or Interactive Data Language, is a programming language used for data analysis and visualization.
3.6 Fitting of the spectral features

3.6.1 Emission lines

To model the continuum and the profiles of the most prominent emission lines \( \text{[H} \alpha \text{]} \), \([\text{NII}] \lambda \lambda 6548,6583\), \([\text{SII}] \lambda \lambda 6716,6731\), \([\text{OI}] \lambda 6302\) and \([\text{FeVII}] \lambda 6087\) I used a code adapted from PROFIT (Riffel, 2010). The continuum under the lines and in the adjacent spectral region was typically modeled with a polynomial of the form:

\[
C(\lambda) = a + b\lambda
\] (3.1)

where \( a \) and \( b \) are free coefficients and \( \lambda \) is a given array of wavelengths.

Emission lines were modeled with one or more Gaussians of the form:

\[
G(\lambda) = \frac{A}{\sqrt{2\pi}\sigma_g} \exp \left( -\frac{(\lambda - \lambda_{\text{peak}})^2}{2\sigma_g^2} \right)
\] (3.2)

were \( A \), \( \sigma_g \) and \( \lambda_{\text{peak}} \) were free parameters. Line peak velocities were derived from the peak wavelength as:

\[
v = \frac{\lambda_{\text{peak}} - \lambda_{\text{lab}}}{\lambda_{\text{lab}}} c
\] (3.3)

where \( \lambda_{\text{lab}} \) was the rest wavelength measured in air and \( c \) was the speed of light in vacuum. Velocity dispersions were derived as:

\[
\sigma = \frac{\sigma_g}{\lambda_{\text{lab}}} c
\] (3.4)

and fluxes were derived by integration of the fitted function.

The routine used to perform the fit makes use of the fitting engine \textit{mp-fit} (Markwardt, 2009), a Levenberg-Marquardt nonlinear least-square fitting procedure based on a translation of the popular FORTRAN package MINPACK-1 (Moré, 1978; Moré and Wright, 1993).

Given the complexity and diversity of the spectra analyzed, I give more detailed descriptions for the strategy used for each galaxy in Section 4.3 for NGC 1386 and Section 5.3 for NGC 1365.
3.6 Fitting of the spectral features

3.6.2 Absorption lines

To fit absorption lines and recover the line of sight velocity distribution (LOSVD) for the stellar kinematics, I used a public, and commonly used, IDL code provided on Michele Cappellari’s website\footnote{http://www-astro.physics.ox.ac.uk/~mxc/software/}. The code implements the Penalized Pixel Fitting method (pPFX) described in Cappellari and Emsellem (2004). A summary of the fitting procedure is given below.

The LOSVD parameters are determined by minimizing the $\chi^2$ over a set of $N$ pixels:

$$\chi^2 = \sum_{n=1}^{N} r_n^2$$

(3.5)

with $r_n$ the residual defined as:

$$r_n = \frac{G_{\text{mod}}(x_n) - G(x_n)}{\Delta G(x_n)}$$

(3.6)

where $G_{\text{mod}}(x)$ is a model galaxy spectrum, $G(x)$ is the observed galaxy spectrum, and $\Delta G(x)$ is the measurement error on $G(x)$. The model spectrum is given by:

$$G_{\text{mod}}(x) = \sum_{k=1}^{K} w_k [B * T_k](x) + \sum_{l=0}^{L} b_l P_l(x), \ w_k \geq 0$$

(3.7)

where $B(x) = \mathcal{L}(cx)$ is the broadening function, with $c$ the speed of light and $\mathcal{L}(v)$ the desired LOSVD, $T$ is a library of stellar templates, the symbol * indicates a deconvolution, $P_l(x)$ are Legendre polynomials of order $l$ which model low-frequency differences in shape between the observed and the model spectrum, $(w_1...w_k, b_0...b_L)$ are weights.

Following the approach of van der Marel and Franx (1993) and Gerhard (1993), Cappellari and Emsellem expand the LOSVD in a Gauss-Hermite (GH) series:

$$\mathcal{L}(v) = e^{-\frac{(1/2)y^2}{\sigma\sqrt{2\pi}}} \left[ 1 + \sum_{m=3}^{M} h_m H_m(y) \right]$$

(3.8)

where $H_m$ are the Hermite polynomials and $y = (v - V)/\sigma$. Now the LOSVD
3.6 Fitting of the spectral features

is defined by the parameters $V$ (the representative velocity), $\sigma$ (the velocity dispersion), and $h_3...h_M$ (the GH coefficients).

Because of low S/N, the GH coefficients might be underconstrained. In that case, the spectral line is better described by a Gaussian profile (e.g. Bender et al., 1994). To account for this scenario, Cappellari and Emsellem use a penalized $\chi^2$ which biases the solution toward a Gaussian when the GH coefficients $h_m$ are underconstrained. They adopt the following expression for the penalized $\chi^2$:

$$\chi^2_p = \chi^2(1 + \lambda^2 \mathcal{D}^2),$$

where $\lambda^2 \mathcal{D}^2$ is the penalty term. $\mathcal{D}$ is the deviation of the line profile from the best-fit Gaussian; for the chosen expression of $\mathcal{L}(v)$, eq.3.8 van der Marel and Franx (1993) showed that $\mathcal{D}^2 \approx \sum_{m=3}^{M} h_m^2$. The parameter $\lambda$ is the “bias”, a numerical value which biases the GH coefficients, $h_m$, toward zero, unless the fit is significantly improved by their inclusion. To fit the stellar kinematics in NGC 1386, I adopted the default value: $\lambda = 0.7 \times \sqrt{500/N}$, with $N$ equal to the number of good pixels.

It is computationally more efficient to minimize the residuals, instead of computing $\chi^2$. Therefore, Cappellari and Emsellem feed the nonlinear least-square optimizer with the perturbed residuals defined as:

$$r_{n,p} = r_n + \lambda \sigma(r) \mathcal{D}$$

$$\sigma^2(r) = \frac{1}{N} \sum_{n=1}^{N} r_n^2.$$ (3.11)

In summary, to perform the fit, the algorithm goes through the following steps:

1. Starts from an initial guess for the parameters $V$ and $\sigma$ while the GH coefficients are fixed at zero.

2. Eq.3.7 is solved for the weights $(w_k, b_l)$.

3. Residuals are computed from eq.3.6

4. Perturbed residuals are derived from eq.3.10

5. Perturbed residuals are given in input to a nonlinear least-square routine and the procedure is iterated from step (2) to fit the parameters...
3.6 Fitting of the spectral features

\[(V, \sigma, h_3, ..., h_M)\].

Details of the stellar templates used to derive the stellar kinematics in NGC 1386 are given in Section 4.4.2.1.
CHAPTER 4

GAS KINEMATICS IN THE SEYFERT 2 GALAXY NGC 1386

4.1 Introduction

NGC 1386 is an Sb/c spiral galaxy (Malkan et al., 1998), located in the Fornax cluster (Sandage, 1978), which hosts a Seyfert 2 nucleus. At a distance of 15.6 Mpc (determined from surface brightness fluctuations, Jensen et al., 2003) the linear scale is 76 pc arcsec$^{-1}$. The inclination with respect to the line of sight is $\theta \approx 65^\circ$, as derived from the ratio of the apparent axes using values from the 2MASS catalog (Jarrett et al., 2003) available in NED.\footnote{NED is the NASA/IPAC Extragalactic Database (NED) which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.}

Being one of the nearest Seyferts, NGC 1386 has been extensively studied. Sandage (1978) classified NGC 1386 as a high excitation galaxy on the basis of its high $\text{[OIII]}\lambda5007/\text{H}\beta$ line intensity ratio. High resolution observations at 8.4 GHz show the presence of a non-variable compact source confined within the central arcsecond and elongated southward in position angle $PA \approx 170 - 175^\circ$ (Nagar et al., 1999; Mundell et al., 2009). HST imaging of the [OIII] and H$\alpha + [\text{NII}]$ emission reveals a jet-like distribution of ionized gas organized in knots along the north-south axis and extending over a distance of about 2$''$ from the nucleus (Ferruit et al., 2000). Despite the close alignment between ionized gas and radio emission, direct
4.1 Introduction

comparison suggests that there is no detailed association amongst the two
(Mundell et al., 2009). Early 2D spectroscopic observations (Weaver et al.,
1991; Rossa et al., 2000), supported by more recent studies (e.g. Schulz and
Henkel, 2003; Bennert et al., 2006), have already revealed the presence of
a complex nuclear spectrum showing the presence of a strong narrow com-
ponent, following rotational motion, superposed on a broader component
suggestive of high-velocity outflows or inflows.

The chapter is organized as follows: I describe the data analysis in Section 4.3. Results are presented in Section 4.4 and discussed in Section 4.5. In Section 4.6 I present our interpretation of the results, summarizing the
main findings and the proposed model in Section 4.7.
4.1 Introduction

Figure 4.1: **Left:** HST image of NGC 1386 (WFPC2/F606W-PC, proposal ID: 5446). The vertical dashed line marks the semi-major axis (PA = 25° east of north). **Center:** zoom-in on the box in the left panel showing the structure map corresponding to the observed field-of-view. The map was derived from the image in the left panel. The dashed line indicates the approximate position angle (PA = 76° east of north) and extension of a faint bar-like [OIII] emission observed by Ferruit et al. (2000). **Right:** continuum map as obtained from our data; labels mark spaxels from which the representative spectra plotted in Fig. 4.2 have been extracted.
4.1 Introduction

Figure 4.2: Representative spectra from individual spaxels A, C and N, as marked in the top right panel of Fig. 4.1.
4.1 Introduction

Figure 4.3: Gaussian fits to the representative spectra shown in Fig. 4.1. Top: three component fit. Middle: two component fit. Bottom: single component fit. Crosses show the data points and the grey solid lines show the summed fit, with dashed and dashed-dotted lines showing the individual components as labelled. The lower sub-panel in each figure shows the residuals of the fit.
4.2 Observations

NGC 1386 was observed on September 23, 2011 with the Integral Field Unit (IFU) of the Gemini Multi-Object Spectrograph (GMOS; Allington-Smith et al., 2002; Hook et al., 2004) mounted on the Gemini South Telescope (program ID: GS-2011B-Q23). Two adjacent fields were observed, each covering $7 \times 5 \text{ arcsec}^2$, resulting in a total angular coverage of $7.5 \times 9.5 \text{ arcsec}^2$ with $0''2$ sampling, centered on the nucleus and extended along the galaxy semi-major axis (position angle PA = 25$^\circ$). In the top panels of Fig.4.1 we show the observed field-of-view (FOV) on an HST image, the corresponding “structure map” created via the contrast-enhancement technique defined by Pogge and Martini (2002), and a continuum image obtained from our observation.

In order to account for dead fibers in the IFU, $\pm 0''.3$ spatial dithering was applied along both axes while a 5 nm spectral dithering was applied to account for CCD gaps. This resulted in 12 exposures of 375 seconds each. From measurements on the standard star, observed immediately after the galaxy, we determined that the seeing limited the spatial resolution to $0''.9 \pm 0''.1$, corresponding to $46 \pm 5 \text{ pc}$ at the galaxy distance.

In order to cover the wavelength range 5600-7000 Å, which includes the emission lines $\text{[FeVII]} \lambda 6086$, $\text{[OI]} \lambda 6300$, $\text{H}\alpha + \text{[NII]} \lambda \lambda 6548, 6583$, $\text{[SII]} \lambda \lambda 6716, 6731$ and several stellar absorption features, we used the IFU in two-slits mode with the grating GMOS R400 in combination with the r(630 nm) filter, this yields a spectral resolution $R = 1918$ corresponding to a velocity dispersion $\sigma \approx 66 \text{ km s}^{-1}$. A portion of the spectrum including the most prominent emission lines is shown in the bottom panel of Fig.4.1 for some representative regions of the field of view (FOV).

The typical accuracy in the wavelength calibration is 0.14 Å (or 6 km s$^{-1}$ at $\lambda = 6583$ Å). Flux calibration was performed against the standard star LTT 1788, of spectral type F (a main sequence star), and it is expected to be accurate to $\approx 10\%$. 
4.3 Emission line fitting

We used customized IDL\(^2\) routines to model the continuum and the profiles of the most prominent emission lines (H\(_\alpha\), [NII]\(\lambda\lambda 6548,6583\), [SII]\(\lambda\lambda 6716,6731\), [OI]\(\lambda 6300\) and [FeVII]\(\lambda 6086\)). Gaussian profiles were fitted to the lines in order to derive centroid velocities, velocity dispersions and fluxes. Four separate runs were performed to fit the H\(_\alpha\)+[NII] lines, the [SII] doublet, the [OI] line and [FeVII]. Given the limited range in wavelength of the fitted spectral regions, the local continuum adjacent to the lines was modeled with a first order polynomial.

Visual inspection of the spectra suggests that, besides [FeVII], emission line profiles within \(\approx 1''\) of the nucleus mostly result from the superposition of one relatively narrow component (\(\sigma \approx 90\) km s\(^{-1}\)) and two broader components (\(\sigma \approx 200\) km s\(^{-1}\)), see for example the [NII] and [SII] profile for spectrum N in Fig.4.4. Hereafter we will refer to the components as “narrow” and “broad” (note, however, that the broad components are not from the “classical” broad line region of AGN where line widths exceed 1000 km s\(^{-1}\)). Beyond the central 2'' the lines are clearly unblended and single-peaked requiring only one Gaussian to be satisfactorily modeled. Between 1'' and 2'' the line profiles mostly present a narrow core and a broad base. We interpret the latter as due to the blending of the two broad components and we fit these lines with two Gaussians: one for the narrow core and one for the broad base. Note, however, that for a fraction of the spaxels in this region the spectra can still be successfully modeled with three Gaussians.

In order to fit the H\(_\alpha\)+[NII] lines we assumed, for each component of the fit (i.e. the narrow and the two broad components), that H\(_\alpha\) and [NII]\(\lambda 6548\) have the same redshift and width as [NII]\(\lambda 6583\) (the strongest line). Therefore, the velocity and velocity dispersion of each component of [NII]\(\lambda 6548\) and H\(_\alpha\) are the same as those of the corresponding components of [NII]\(\lambda 6583\). The amplitude of each [NII]\(\lambda 6548\) component was fixed at the theoretical value of 1/2.96 of that of the corresponding [NII]\(\lambda 6583\) amplitude. A similar approach was used to fit the [SII] doublet.

A simpler double peaked profile gives a better representation of the [FeVII] line which, as it lacks a detectable narrow component, was fitted with

\(^2\)IDL, or Interactive Data Language, is a programming language used for data analysis and visualization.
4.3 Emission line fitting

two Gaussians of the same width. Because of its high ionization potential
\((E = 125\, \text{eV}, \text{Corliss and Sugar} 1982)\), this line is believed to be produced
by a combination of hard UV continuum and hot collisionally ionized plasma
\((\text{Contini et al.} 1998)\). Given the high energies required for its production,
the [Fe VII] line is believed to originate close to the AGN (a few tens of pc,
\(\text{Ferguson et al.} 1997\)).

\textbf{Three Gaussians fit}: in order to determine the region over which the
three Gaussian fit is necessary, we require that for each component the line
amplitude is at least twice the standard deviation in the continuum adjacent
to the line. We also assume that the two broad components have the same
width (without this condition, the fit would be be underconstrained in many
spaxels, where the profiles are heavily blended). With this approach we fit
three Gaussian components to each of H\(\alpha\), [NII] and [SII] mostly within a
radius of \(\approx 1''\) from the nucleus, but also at larger distances, between 1''
and 2'' (the nucleus, denoted N, is identified with the continuum brightness
peak). Due to the lower S/N, three Gaussians were fitted to [OI] only for
a handful of pixels within \(\approx 0.7''\) from the center. An example of the three
components fit is shown in the top panel of Fig.4.3 for [NII] and H\(\alpha\).

\textbf{Two Gaussians fit}: broad components are still visible as a broad base
mainly between 1'' - 2'' from the nucleus. However, for many pixels the
two components are blended and the S/N is insufficient to justify fitting
three components. Therefore in this region we mostly fit two, represent-
ing the broad base and the narrow core, respectively. An example of a
two-components fit is shown in the middle panel of Fig.4.3. This fit was
performed with the goal of extracting the narrow component.

\textbf{Single Gaussian fit}: a single Gaussian fit was used beyond the central
2'' where the broad components become negligible and the two-components
fit failed. An example of single component fit is shown in the bottom panel
of Fig.4.3. A map showing the number of components fitted to the spectra
in a given spaxel is shown in Fig.4.4.

To determine accurate line intensity ratios representative of the various
kinematic components, five subregions of the FOV were identified (see ve-
locity map for the narrow and broad blue component in Fig.4.7b and 4.7c).
The subregions represent, respectively, the northern and southern “lobes”
(subregions A and B), regions associated with velocity residuals approxi-
4.3 Emission line fitting

Figure 4.4: Map showing the regions where one, two or three Gaussians were fitted to the emission lines. No significant \( \text{H}_\alpha \) emission was detected in the darker region labelled as “1\([\text{NII}]\)”. 

Approximately perpendicular to the axis of the lobes (see Section 4.5.2 for details), east and west of the nucleus (C and D), and the nucleus itself (N). The spectra obtained for sub-regions B, D and N are presented in Fig. 4.5; the spectra for subregions A and C are very similar to those of subregion B and D respectively.

The continuum and all the most prominent emission lines ([OI], H\(\alpha\), [NII], [SII]) were fitted simultaneously with the constraint that all the lines are characterized by the same redshift and the same width as the [NII]\(\lambda6583\) line. With these assumptions we fitted single Gaussians to the emission lines in the subregion B spectrum and two Gaussians to each line in subregion A. This was done to take into account the non-Gaussian base of the lines. In this case, the total flux of each line was considered to be the sum of the fluxes of the two components. Line emission is weak relative to the stellar continuum in subregions C and D, therefore stellar templates were fitted and subtracted. The templates, a subset of the models presented in Vazdekis [1999], represent an old stellar population of spectral type O-M and metallicity \( -0.7 \leq [\text{Fe/H}] +0.2 \). After this procedure, line profiles in subregion C and D were fitted with the same approach described for subregion A. The profiles of subregion N, which includes the nucleus, were fitted with three components: a narrow core and two broader Gaussians.
4.3 Emission line fitting

characterized by the same width. In order to minimize contamination from Hα, the blueshifted broad component was fitted to the blue side of the [NII]λ6548.

The stellar continuum was not removed prior to fitting the subregion A, B and N spectra as this did not produce any significant difference in the results.
4.3 Emission line fitting

Figure 4.5: Spectra extracted from the subregions specified in Fig. 4.7b and 4.7c. In order to correct for H\(\alpha\) absorption, a stellar template has been fitted and subtracted from subregion D.
4.3 Emission line fitting

Figure 4.6: Velocity [km s\(^{-1}\)], velocity dispersion [km s\(^{-1}\)] and flux [10\(^{-16}\) erg/s/cm\(^2\)/spaxel] as derived by fitting a single Gaussian to the [NII]\(\lambda 6583\) emission line. From the flux map it is evident that the strongest emission is mainly concentrated in an unresolved region within 1\(''\) from the nucleus and along the north-south direction. Low-level emission is nevertheless present over the entire FOV. A systemic velocity \(v_{\text{sys}} = 786\) km s\(^{-1}\) was derived from the modeling of the [NII] kinematics and was subtracted from the velocity map. The magenta cross marks the continuum peak.
4.4 Results

4.3.1 Uncertainties

Errors on the measured quantities were derived from Monte Carlo simulations. For each spaxel, we constructed one hundred realizations of the spectrum by adding Gaussian noise with amplitude comparable to the noise measured in the original spectrum. Mean values and standard deviations for the centroid velocities, velocity dispersions and fluxes were derived for each spaxel, with the standard deviation of the distribution in each parameter being taken as the uncertainty.

4.4 Results

4.4.1 Gas kinematics

4.4.1.1 Velocity and velocity dispersion

As [NII]λ6583 has the highest S/N, we use results obtained from the fits to this line to represent and model the gas velocity field. The velocities recovered from other emission lines are consistent within the errors.

We first show maps obtained by fitting a single Gaussian to the [NII] line throughout the entire FOV. Centroid velocity and velocity dispersion maps obtained with this approach are presented in Fig.4.6 after the subtraction of a systemic velocity $v_{sys} = 786 \text{ km s}^{-1}$ determined from the modeling of the gas kinematics (see Section 4.5.2 for details). The velocity map shows the characteristic pattern of a rotating disk upon which other components are superposed. There are two clear deviations from the rotation pattern: (i) a redshifted blob located at the nucleus and (ii) a blueshifted region to the north-west of the nucleus. Multicomponent fits and visual inspection of the corresponding spectra show that the nuclear redshifted blob is associated with a strong redward asymmetry in the line profile, see spectrum N in Fig.4.1. The blueshifted region north-west of the nucleus persists in maps obtained with multi-Gaussian fits and is discussed in Section 4.5.2.

The velocity dispersion map shows very clearly that the strongest line broadening occurs in the nuclear region and is roughly centered on the nucleus. A narrow band of high velocity dispersion is also observed either side of the nucleus, extending roughly 2'' to the south-east, 3'' to the north-west and 0''5 above and below it. This band is approximately perpendicular to the axis of the extended line emission, which is brightest in two lobes that
are observed north and south of the nucleus (Fig. 4.6). The greatest broadening, approximately 300 km s\(^{-1}\), is observed \(\approx 0'5\) east of the nucleus. The bright lobes of line emission coincide with regions of relatively low velocity dispersion with the smallest values \((\sigma \approx 50 \text{ km s}^{-1})\) occurring approximately along the direction north-south (roughly coincident with the lobes axis).

Centroid velocities and velocity dispersions for the narrow and the broad components derived from multi-Gaussian fits to the [NII] profiles are shown in Fig. 4.7a, 4.7b, 4.7c.

The centroid velocity, velocity dispersion and flux maps for the narrow component \((\sigma \approx 90 \text{ km s}^{-1})\) are derived from a combination of the three-, two- and single-Gaussian fits. The velocity map is very similar to that derived from the single-Gaussian fit alone, the main difference being the absence of the redshifted blob at the nucleus. The blueshifted region north-west of the nucleus is still apparent.

The centroid velocity, velocity dispersion and flux maps for the broad components \((\sigma \approx 200 \text{ km s}^{-1})\) are derived entirely from the three-Gaussian fit\(^3\). The red- and blue-shifted broad components are approximately co-spatial and dominate the line emission within the central \(\approx 1'\). However, it is notable that the brightest emission in the red-shifted broad component is shifted slightly \((\approx 0'5)\) north of the continuum brightness peak. The blue-shifted broad component is weaker overall, with the brightest emission slightly south-west \((\approx 0'5)\) of the continuum peak. Evidence for line splitting (in the sense that two broad components are required to fit the line profiles) in scattered spaxels extends well beyond the bright central region. In fact, weak double broad components can be found out to a distance of about 2' east and west of the nucleus, that is, in a similar orientation to that of the region of enhanced velocity dispersion derived from the single component fit.

The H\(\alpha\), [SII] and [OI] lines are characterized by the same features observed in [NII], i.e., two red- and blue-shifted broad components concentrated in the nuclear region and strong narrow-lines along the north-south direction.

The high velocity dispersion present in the narrow component map along the direction SE-NW, around the points \((-1'5, 0'5)\) and \((2'5, 0'6)\) in the

\(^3\)The broad component used in the two-Gaussian fit is not used; it may represent blending of red- and blue-shifted broad components.
4.4 Results

central panel of Fig. 4.7b, can be attributed to the blending of the broad and narrow components all the way to the edge of the FOV. Visual inspection, see for example spectrum C in Fig. 4.1, suggests a substantial decrease in the intensity of the narrow core with respect to the broad base. Therefore, in that region, a single Gaussian fit would be mainly tracing the velocity dispersion of the broad base. Despite a number of experiments, it was not possible to perform a fit producing a smooth transition in the velocity dispersion map and a perfect separation of the components.

Velocity and velocity dispersion maps for the [FeVII] line are presented in Fig. 4.8a and 4.8b. As in the case of the [NII] broad components, the blue- and red-shifted components of the [FeVII] line are approximately co-spatial, and the emission is concentrated within the inner 1″. From visual inspection of the datacube and the fits performed on individual spaxels, we consider that there is marginal evidence that the [FeVII] emission is elongated along the north-south direction. However the S/N beyond the central ≈0′′5 is too low to allow a robust fit to the lines.
Results

Figure 4.7a: [NII]λ6583 maps. Velocity [km s$^{-1}$], velocity dispersion [km s$^{-1}$], flux [10$^{-16}$ erg/s/cm$^2$/spaxel] for the redshifted broad component. A systemic velocity $v_{\text{sys}} = 786$ km s$^{-1}$ was derived from the modeling of the [NII] kinematics and was subtracted from the velocity maps.
4.4 Results

Figure 4.7b: [NII] λ6583 maps. Velocity [km s$^{-1}$], velocity dispersion [km s$^{-1}$], flux [$10^{-16}$ erg/s/cm$^2$/spaxel] for the narrow component. Though the narrow component flux map shows the brightest emission to be localized along the north-south direction, low-level emission is present over the entire FOV. Numbered boxes represent the subregions that were rebinned to extract the representative spectra shown in Fig.4.5. As evident from the left panel in Fig.4.7c, subregion N is representative of the spaxels where the broad components are stronger. A systemic velocity $v_{sys} = 786$ km s$^{-1}$ was derived from the modeling of the [NII] kinematics and was subtracted from the velocity maps. Maps shown here are a composite of the narrow component derived from three-, two- and single-gaussian fit. Maps corresponding to the broad component of the two-gaussians fit are not shown as the broad component in this case is believed to represent a blend of the blue- and red-shifted broad components included in the three-gaussians fit. The broad component was included in the two-gaussians fit only to permit accurate fitting of the narrow component.
4.4 Results

Figure 4.7c: [NII]λ6583 maps. Velocity [km s\(^{-1}\)], velocity dispersion [km s\(^{-1}\)], flux \([10^{-16} \text{ erg/s/cm}^2/\text{spaxel}]\) for the blueshifted broad component. Given our fitting constraints, the velocity dispersion maps of the blue- and red-shifted broad components are the same. As evident from the left panel, subregion N is representative of the spaxels where the broad components dominate. A systemic velocity \(v_{\text{sys}} = 786 \text{ km s}^{-1}\) was derived from the modeling of the [NII] kinematics and was subtracted from the velocity maps.
4.4 Results

4.4.1.2 Uncertainties

Velocity errors for the narrow component of the [NII] + Hα complex are highest in regions where two component fits were used: values range from 2 km s\(^{-1}\) in the region where the narrow component is strong and a broad base is clearly present, to > 50 km s\(^{-1}\) in a few regions where the broad base is weak. Errors are significantly smaller in regions where a single Gaussian fit was used. In particular, low values (2-5 km s\(^{-1}\)) are found along the direction north-south, where the emission in the narrow component is very strong and lines are narrow and single peaked. Larger values (up to 20 km s\(^{-1}\)) are characteristic of the outer regions, where the S/N decreases. Errors in the velocity dispersion of the narrow component have a similar behavior but the range of values obtained from the simulation is smaller: typical errors for the inner 2\(''\) vary in the range 10-20 km s\(^{-1}\).

Errors in the velocity of the broad component increase from the center outward, with the central arcsecond characterized by values close to 30 km s\(^{-1}\) increasing, at the very edge of the fitted region (approximately 2\(''\) from the nucleus), up to 150 km s\(^{-1}\) for the blue component and close to 80 km s\(^{-1}\) for the red component. The difference is due to the lower S/N of the blue broad component.

Errors derived for the [SII] velocity and velocity dispersion are very similar to those obtained for Hα and [NII]. Only two differences are evident: the first is that errors in the velocity of the blue broad component do not show the usual radial gradient, probably because of the weakness of the line. The second is that errors in the velocity dispersion of the red broad component are smaller than the corresponding errors derived from the [NII] with values ranging between 5 and 35 km s\(^{-1}\) and typical values of order 20 km s\(^{-1}\) (for comparison, errors derived from the [NII] line range between 5 and 60 km s\(^{-1}\) showing a steeper radial gradient increasing outward).

The [OI] velocity and velocity dispersion maps are affected by errors of order 1 km s\(^{-1}\) in the center of the south-western lobe, where the S/N is high, increasing to 10 km s\(^{-1}\) in the outskirt. The nucleus, where the S/N for [OI] is often not enough to allow a three component fit, is characterized by errors of order 20 km s\(^{-1}\). The north-eastern lobe, where the signal is lower than in the south-western lobe, has errors ranging from 4 km s\(^{-1}\), in the central region, to 20 km s\(^{-1}\) along the rim of the lobe where S/N decreases.
4.4 Results

Figure 4.8a: [FeVII]λ6086 maps for the redshifted component. Velocity [km s\(^{-1}\)], velocity dispersion [km s\(^{-1}\)], flux \([10^{-16} \text{ erg/s/cm}^2/\text{spaxel}]\). A systemic velocity \(v_{\text{sys}} = 786\) km s\(^{-1}\) was derived from the modeling of the [NII] kinematics and was subtracted from the velocity map.
4.4 Results

Figure 4.8b: [FeVII]λ6086 maps for the blueshifted component. Velocity [km s$^{-1}$], velocity dispersion [km s$^{-1}$], flux [$10^{-16}$ erg/s/cm$^2$/spaxel]. Note that the velocity dispersion is the same of the redshifted component by assumption. A systemic velocity $v_{\text{sys}} = 786$ km s$^{-1}$ was derived from the modeling of the [NII] kinematics and was subtracted from the velocity map.
4.4 Results

4.4.1.3 Channel maps

Channel maps were extracted in velocity bins of 50 km s$^{-1}$ along the [NII] profile. After subtracting a systemic velocity $v_{sys} = 786$ km s$^{-1}$ derived from kinematical modeling of the [NII] velocity field, to minimize H$\alpha$ contamination, negative velocities were derived from the blue side of the [NII]$\lambda$6548 line, whilst positive velocities were derived from the red side of the [NII]$\lambda$6583 line. The maps are shown in Fig. 4.9.

As [NII]$\lambda$6548 is a factor of three weaker than [NII]$\lambda$6583, and given that the broad blueshifted component is intrinsically weaker than the redshifted one, the blueshifted emission cannot be mapped beyond the $-400$ km s$^{-1}$ channel, whereas the redshifted emission can be mapped to $+800$ km s$^{-1}$.

Channel maps at high velocities $\leq -200$ km s$^{-1}$ and $\geq 400$ km s$^{-1}$ are clearly dominated by circum-nuclear emission. Interestingly, the emission in these channel maps is co-spatial despite the wide range of velocities involved. Maps for velocities within the range $-200 : 400$ km s$^{-1}$ seem to result from at least two kinematic features: (i) the strong emission at the nucleus which is isolated at extreme velocities and is due to the broad spectral components, (ii) a contribution from the narrow component associated with a large-scale rotating disk. The large-scale contribution takes the form of an off-center emission which is evident from $v = -200$ km s$^{-1}$ to $v = 300$ km s$^{-1}$.

4.4.2 Stellar kinematics

4.4.2.1 Velocity and velocity dispersion

In order to derive the stellar kinematics we fitted the stellar continuum and absorption lines using the Penalized Pixel Fitting technique (pPFX, Cappellari and Emsellem 2004) and a subset of the Vazdekis (1999) stellar templates that were computed for an old stellar population with spectral type in the range O-M and metallicity $-0.7 \leq [\text{Fe/H}] \leq +0.2$. Stellar centroid velocity and velocity dispersions were derived, for each spaxel, after masking the Na I $\lambda\lambda$5890,5896 absorption lines (which are affected by interstellar gas), the most prominent emission lines, and the O$\text{II} \lambda$6875 sky B band. Given the spectral resolution of the stellar templates, 1.8 Å, which is approximately the same as that of our observations, 1.9 Å at 6600 Å, we did not apply any additional correction to the velocity dispersion.
Figure 4.9: Channel maps derived from the [NII] emission lines. Corresponding velocities are shown in the top right corner of each map in km s\(^{-1}\). Flux units are Log 10\(^{-16}\) erg/s/cm\(^2\)/spaxel. To avoid contamination from H\(\alpha\), maps corresponding to negative velocities have been derived from the blue side of the [NII]\(\lambda6548\) line, whilst maps with positive velocities have been derived from the red side of [NII]\(\lambda6583\) line. A systemic velocity \(v_{\text{sys}} = 786\) km s\(^{-1}\) was derived from the modeling of the [NII] kinematics and subtracted from the maps. Contours are equally spaced flux contours.
4.4 Results

Although many pixels north of the nucleus were flagged during the fit we can see that, similarly to the gas kinematics, the stellar velocity field (left panel in Fig. 4.10) displays a rotation pattern in which the north-eastern side is receding. The stellar velocity dispersion (right panel in Fig. 4.10) reaches values close to 250 km s\(^{-1}\) near the center decreasing to 100 km s\(^{-1}\) toward the edges of the FOV. The small systematic increase, evident from south-east to north-west, is an artifact due to the decreasing S/N. The mean velocity dispersion within circles of increasing radii is fairly constant with \(\bar{\sigma} \approx 195\) km s\(^{-1}\) within an aperture of radius 2\(''\)5 (190 pc).

Previous estimates of the central stellar velocity dispersion have been determined by Dressler and Sandage (1983), Nelson and Whittle (1995) and Garcia-Rissmann et al. (2005). Dressler and Sandage obtained \(\sigma = 195 \pm 16\) km s\(^{-1}\) from spectra taken with the du Pont Las Campanas 2.5 m spectrographs in the spectral region 4800-5400 Å using a 2\(''\)×4\(''\) slit (FWHM\(^{4}\) \(\approx 180\) km s\(^{-1}\)). This value is consistent with our findings.

With a similar set up (aperture of 2\(''\)2×3\(''\)6 and optical spectra including the Mg \(b \lambda5175\) absorption line), Nelson and Whittle used the Royal Greenwich Observatory Spectrograph on the 3.9 m Anglo Australian Telescope (FWHM \(\approx 80\) km s\(^{-1}\)) obtaining a significantly smaller value of \(\sigma = 120 \pm 30\) km s\(^{-1}\). Garcia-Rissmann et al. used the Richey-Cretien spectrograph on the 4m Mayall telescope at Kitt Peak National Observatory with a slit width of 1\(''\)5. From the calcium triplet they derived the stellar velocity dispersion using two methods obtaining \(\sigma_1 = 123 \pm 3\) km s\(^{-1}\) and \(\sigma_2 = 133 \pm 3\) km s\(^{-1}\).

The origin of the discrepancy amongst the set of values summarized here is unclear.

4.4.2.2 Uncertainties

Typical uncertainties in the stellar velocity field range from 10 km s\(^{-1}\), in the nuclear region, up to 15 km s\(^{-1}\), in the outer part of the field. Errors on the stellar velocity dispersion are slightly larger, ranging from 15 km s\(^{-1}\) near the nucleus, up to 25 km s\(^{-1}\) toward the outskirts of the FOV.

\(^{4}\)Full width at half maximum = 2.36 \(\sigma\).
Figure 4.10: *Left:* velocity map as derived from the stellar absorption features excluding the [NaD] doublet. *Right:* stellar velocity dispersion. Units: km s$^{-1}$. A systemic velocity $v_{\text{sys},*} = 743$ km s$^{-1}$, as derived from modeling of the stellar kinematics, was subtracted from the velocity field.
### Table 4.1: LINE RATIOS AND ELECTRON DENSITIES

<table>
<thead>
<tr>
<th>Subr</th>
<th>[NII]6583/Hα</th>
<th>[OI]6366/Hα</th>
<th>[SII](6716 + 6731)/Hα</th>
<th>[SII]6716/6731</th>
<th>n_e cm⁻³</th>
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<td>narrow</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>2.45 ± 0.58</td>
<td>0.45 ± 0.09</td>
<td>1.07 ± 0.18</td>
<td>1.23 ± 0.18</td>
<td>200⁺⁻⁺⁴⁰</td>
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<tr>
<td>B</td>
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<td>0.22 ± 0.02</td>
<td>0.80</td>
<td>1.24 ± 0.01</td>
<td>190⁺⁻⁺⁴⁰</td>
</tr>
<tr>
<td>C</td>
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<td>0.46 ± 0.03</td>
<td>0.63 ± 0.2</td>
<td>1.2 ± 0.04</td>
<td>234⁺⁻⁺⁵⁰</td>
</tr>
<tr>
<td>D</td>
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<td>0.36 ± 0.05</td>
<td>0.65 ± 0.11</td>
<td>1.6 ± 0.03</td>
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<tr>
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<td>0.96 ± 0.02</td>
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<td></td>
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<td></td>
</tr>
<tr>
<td>N</td>
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<td>0.24 ± 0.02</td>
<td>2.81 ± 0.81†</td>
<td>...</td>
</tr>
<tr>
<td>red broad</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>N</td>
<td>1.29</td>
<td>0.17</td>
<td>0.57 ± 0.01</td>
<td>0.95 ± 0.02</td>
<td>752⁺⁻⁺⁵¹</td>
</tr>
</tbody>
</table>

Note. — See the velocity map derived from the narrow component in Fig. 4.7b and 4.7c for subregion IDs. Omitted errors are smaller than 0.01. †Exceeds high density limit.
4.4 Results

4.4.3 Line fluxes

The spatial distribution of the integrated \([\text{NII}]\lambda 6583\) line flux obtained from the single Gaussian fit to the \([\text{NII}]\) line over the whole FOV is shown in the right panel of Fig. 4.6. The strongest emission is observed within a circular region of radius \(r \approx 1''\) around the nucleus. The other main features are two elongated regions (the “lobes”) extending about 3″ north and south of the nucleus in a direction similar to that of the compact radio emission reported by Nagar et al. (1999) and Mundell et al. (2009). Weaker \([\text{NII}]\) emission is present over the entire FOV at a level of \(3 \times 10^{-17} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ spaxel}^{-1}\).

The spatial distribution of the integrated line flux obtained from the multi-Gaussian fit is shown in the right column of Fig. 4.7a, 4.7b and 4.7c for the broad and narrow components of the \([\text{NII}]\lambda 6583\) emission line. As evident from the figures, the multi-Gaussian decomposition shows that the narrow component originates from the lobes while the broad component is essentially confined to the nucleus.

Allowing for the lower spatial resolution of our data, the spatial distribution of the \([\text{NII}]\) flux is broadly consistent with the emission line morphologies observed in HST WFPC2 narrow band images in \(\text{H}\alpha + [\text{NII}]\) and \([\text{OIII}]\lambda 5007\) (Ferruit et al. 2000, see also Fig. 4.11). The HST images, however, resolve substructure in the lobes, revealing several bright knots embedded in more diffuse structures, with the two brightest knots being located approximately 0′′5 north and 1″ south of the nucleus, respectively. In the HST images, the \([\text{OIII}]\) emission has approximately same distribution as the \(\text{H}\alpha + [\text{NII}]\) emission, although the knots are more prominent in \([\text{OIII}]\) whereas the more diffuse structures are more prominent in \(\text{H}\alpha + [\text{NII}]\).

The HST images also reveal a “plume” of emission (present in both \(\text{H}\alpha + [\text{NII}]\) and \([\text{OIII}]\)) that extends approximately 1″ to the east and north of nucleus, and which appears to be distinct from the north-south lobes. This feature has no clear counterpart in our flux maps, but it corresponds to a handful of spaxels characterized by extreme line-blending, and it may be related to the region of enhanced velocity dispersion seen in Fig. 4.6. Indeed, in the version of the \(\text{H}\alpha + [\text{NII}]\) image presented by Ferruit et al. in their Fig. 5, a low surface brightness bar-like structure is present, crossing the nucleus from east to west, perpendicular to the lobes, and extending approximately 2″ on each side. The plume may represent the inner part of...
4.4 Results

this structure, which is approximately co-spatial with the region of enhanced velocity dispersion, and the velocity residuals discussed below in Section 4.5.2.

The bright central region of the $\text{H}\alpha + [\text{NII}]$ flux map is also resolved by the HST images, into an elongated structure approximately 0'5 long and oriented slightly west of north (see Fig.4 in Ferruit et al., the feature is also visible in the structure map in Fig.4.1). Close inspection shows that it is composed of two distinct components, to the north and south, respectively, which have higher excitation (as measured by the $\text{[OIII]}/\text{H}\alpha + [\text{NII}]$ line ratio derived by Ferruit et al. 2000) than the surrounding more diffuse emission. These HST components appear to be partially resolved in the flux maps derived from the broad kinematic components, corresponding to the asymmetric brightness distribution, relative to the continuum peak, of the broad red- and blue-shifted components of the line profiles.

The flux distribution of the blue- and red-shifted components of the $\text{[FeVII]}\lambda 6086$ emission line is shown in the right column of Fig.4.8a and 4.8b. As for the broad components of other lines, the redshifted component is brighter than the blueshifted one.
Figure 4.11: Left: [OIII]λ5007 image from HST observations (WFPC2-PC/F502N, proposal ID: 6419, PI: A. Wilson, Ferruit et al. 2000). Center: [OIII] contours overlaid on the [NII] redshifted broad component flux. Right: [OIII] contours overlaid on the [NII] narrow component flux. The images were aligned assuming a coincidence between the peak of the [OIII] emission and the continuum peak derived from our observation.
4.4 Results

4.4.4 Gas excitation

When we compute the [NII]/Hα ratio we find that the narrow component has values close to 1.6 approximately within the lobes and at the nucleus while the broad components have lower values, i.e. ≈ 1.1 for the broad blue component and ≈ 1.2 for the broad red component.

Line ratios derived from the simultaneous fit to the lines in the subregion spectra are given in Table 4.1 and plotted in the Baldwin-Phillips-Terlevich (BPT) diagrams [Baldwin et al. 1981] shown in Fig.4.12. As our spectral coverage does not include the [OIII] and Hβ emission lines, we estimated the [OIII]/Hβ ratio from Fig.10 in Weaver et al. [1991]. Over the whole FOV, the line ratios are well within the AGN photoionization region with the spectrum of subregion C showing ratios typical of LINERs and all of the others falling into the Seyfert region.

This is consistent with results obtained by Bennert et al. [2006] who performed long slit observations of NGC 1386, along the north-south axis of the [NII] lobes and the extended [OIII] emission, finding line ratios typical of HII regions only beyond 6′′ from the nucleus.

4.4.5 Electron density

Electron densities were derived from the intensity ratio [SII]λ6716/λ6731 assuming a temperature of 10^4K. The resulting maps are presented in Fig.4.13. For the narrow component, the highest densities are found along the direction SE-NW, in particular in the inner 1″ around the nucleus, reaching values ≈ 800 cm^{-3}. Beyond this region, to the north and south of the nucleus, the density of the emitting gas ranges between 150 and 300 cm^{-3}.

High densities are also evident in the broad component maps. Median values of ≈ 800 cm^{-3} are found for the blue broad component and ≈ 1100 cm^{-3} for the red broad component.

Values for the electron density derived from the spectra extracted from the subregions identified in Fig.4.1b and 4.1c are given in the last column of Table 4.1. It was not possible to derive the electron density for the blueshifted broad component of subregion N since the measured value of the [SII]λ6716/λ6731 ratio (2.8) is well above the high density limit (approximately 1.4, Osterbrock 1989); the high value seems to result from a poor fit due to heavy blending of the lines.
4.4 Results

Bearing in mind the different nature and modeling of the data, a consistent decrease in the density as a function of the distance from the nucleus was also derived from VLT-FORS1 long slit spectroscopy by Bennert et al. (2006).
Figure 4.12: BPT diagrams for the subregions specified in Fig. 4.7b and 4.7c. Values for the ratio [OIII] $\lambda$5007/H$\beta$ have been estimated from Fig. 10 in Weaver et al. (1991). Vertical error bars represent the range of values measured by Weaver et al. within the regions of interest. Typical errors along the abscissa are smaller than the symbol size with the exception of points from subregion A and C. The dashed boundary lines are taken from Kewley et al. (2006).
Figure 4.13: Electron density maps derived from the ratio $\text{[SII]}\lambda 6716/\lambda 6731$. *Left:* blueshifted broad component. *Center:* narrow component. *Right:* redshifted broad component. Units: cm$^{-3}$. The color scale is arbitrarily adjusted to highlight the features of the maps.
4.5 Discussion

4.5.1 The stellar velocity field

We fitted the stellar velocity field with a kinematic model describing circular orbits in a plane \( \text{van der Kruit and Allen, 1978; Bertola et al., 1991} \):

\[
v_{\text{mod}}(r, \psi) = v_{\text{sys}} + \frac{A r \cos(\psi - \psi_0) \sin \theta \cos^2 \theta}{\left( r^2 \sin^2(\psi - \psi_0) + \cos^2 \theta \cos^2(\psi - \psi_0) \right) + c_0^2 \cos^2 \theta}^{1/2}.
\]

This yields a velocity curve that increases linearly at small radii and becomes proportional to \( r^{(1-p)} \) at large radii. The parameter \( v_{\text{sys}} \) is the systemic velocity, \( A \) is the amplitude of the rotation curve, \( r \) and \( \psi \) are the radial and angular coordinates of a given pixel in the plane of the sky, \( \psi_0 \) is the position angle of the line of nodes (measured with respect to the \( x \)-axis of the image frame, increasing counterclockwise; \( \psi_0 - 65^\circ \) gives the value in degrees east of north), \( \theta \) is the disk inclination (\( \theta = 0 \) for face-on disks). The parameter \( p \) measures the slope of the rotation curve where it flattens, in the outer region of the galaxy, varying in the range 1-1.5. Finally, \( c_0 \) is a concentration parameter, which gives the radius at which the velocity reaches 70% of the amplitude \( A \).

Because of the limited size of the region analyzed, the parameter \( p \) is poorly constrained by the data, therefore we assume \( p = 1 \), which corresponds to an asymptotically flat rotation curve at large radii. The stellar velocity curve already seems to flatten at \( r \approx 1'' \) supporting this choice for \( p \). The inclination \( \theta \) is also poorly constrained. Assuming that the gas lies on a thin circular disk, we adopted the value \( \theta = 65^\circ \) given by NED and derived from the 2MASS K band axis ratio of the large-scale structure of the galaxy. The same value is also recovered from PAH emission within 15'' of the nucleus \( \text{Ruschel-Dutra et al., 2014} \).

We used a Levenberg-Marquardt least-squares algorithm to fit the rotation model to the velocity map with the fit determining values for the parameters \( A, v_{\text{sys}}, \psi_0, c_0 \) and the center of the rotation field \( (x_0, y_0) \). The fit was performed with a customized IDL routine which makes use of the fitting engine \textit{mpfit} \( \text{Markwardt, 2009} \). The values of the fitted param-
4.5 Discussion

eters are listed in Table 4.2 where results are reported for a fit in which the kinematical center is fixed at the continuum peak and for a fit in which the center is left a free parameter. Maps of the observed and best fit model velocity field are shown in Fig. 4.14 together with the residual map for the fit performed with a fixed center.

The fit performed with the kinematical center \((x_0, y_0)\) left as a free parameter returns a shift from the photometric nucleus which is \(0''2\) north and \(0''1\) west of the continuum peak. Considering our angular resolution \((0''9)\), this is negligible and we conclude that the stellar kinematical center coincides (within the uncertainties) with the photometric nucleus \((N)\).

The sparsity of data to the north of the nucleus in the velocity map (Fig. 4.14) might introduce a bias in the position angle of the line of nodes, \(\psi_0\), toward large values (eastward of north). To test this possibility, we repeated the fit to a symmetrized version of the stellar velocity map, which was created by masking out the pixels in such a way that the final mask was symmetric about the vertical axis passing through the center of the image. All of the fitted parameters, and in particular \(\psi_0\), showed negligible variations suggesting that the recovered value of \(\psi_0\) is not affected by the spatial distribution of the flagged pixels.

4.5.1.1 Stability of the solution

Dependence on the noise: to estimate the uncertainties in the recovered parameters due to the observed noise level, we fitted the velocity maps recovered from the Monte Carlo simulation described in Section 4.3.1. Standard deviations for the distribution of the recovered parameters were computed and are given in Table 4.2. The estimated uncertainties for the amplitude of the velocity curve, \(A\), and the systemic velocity, \(v_{sys}\), were smaller than 1 km s\(^{-1}\).

Dependence on the initial guess: to test the dependence of the recovered parameters on the initial guess, we performed 200 fits of the stellar velocity map where the initial guess for each parameter was randomly drawn from a uniform distribution. To avoid unreasonable initial guesses that would generate obviously bad fits, the limits of the initial guess distribution for each parameter were determined from visual inspection of the map to be fitted. The range of values allowed for the initial guess is given in the rightmost column of Table 4.2.
4.5 Discussion

Table 4.2: FITS TO THE OBSERVED STELLAR VELOCITY FIELD

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Notes</th>
<th>Initial guess</th>
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</thead>
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<td><strong>Fixed center</strong></td>
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<tr>
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<td>geocentric‡</td>
</tr>
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</tr>
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<td>0:5</td>
</tr>
<tr>
<td>$p$</td>
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<td></td>
</tr>
<tr>
<td>$\theta$ [deg]</td>
<td>65 fixed</td>
<td></td>
</tr>
<tr>
<td>$x_0$ [arcsec]</td>
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<td></td>
</tr>
<tr>
<td>$y_0$ [arcsec]</td>
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</tr>
<tr>
<td><strong>Free center</strong></td>
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</tr>
<tr>
<td>$A$ [km s$^{-1}$]</td>
<td>$117 \pm 1$...</td>
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<tr>
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</tr>
<tr>
<td>$\psi_0$ [deg]</td>
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<td>60:135</td>
</tr>
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<td>0:5</td>
</tr>
<tr>
<td>$p$</td>
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<td></td>
</tr>
<tr>
<td>$\theta$ [deg]</td>
<td>65 fixed</td>
<td></td>
</tr>
<tr>
<td>$x_0$ [arcsec]</td>
<td>$+0.2$ †</td>
<td>from N -1:1</td>
</tr>
<tr>
<td>$y_0$ [arcsec]</td>
<td>$+0.1$ †</td>
<td>from N -1:1</td>
</tr>
</tbody>
</table>

†The formal uncertainty estimated for this coefficient is much smaller than 0 ′. ‡The heliocentric systemic velocity is $v_{sys,*} = 754$ km s$^{-1}$.

The procedure was performed with both the center as a free parameter and the center fixed at the nucleus. In both cases all the fits converged exactly to the same solution and none of the coefficients reached the boundaries allowed for the fit.

**Dependence on the value adopted for $p$:** when $p$ is fixed at values larger than 1 (implying a velocity curve which decreases at large radii), the amplitude increases steadily, reaching a value of 300 km s$^{-1}$ when $p = 1.5$. A similar increase is found for the parameter $c_0$ (as expected from its definition) while the other fitted parameters, $v_{sys}$ and $\phi_0$, are almost insensitive to the value adopted for $p$.  

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4.5 Discussion

4.5.2 The gas velocity field

The velocity map derived from the narrow component covers the whole FOV and shows a pattern typical of rotation plus some distortion (see Fig. 4.7b, first column, second row). In order to isolate non-rotational motions and also to determine the properties of the rotation, we fitted the kinematic model described by eq. 4.1 to the gas velocity field. The model, in this case, represents gas rotating in a plane with circular orbits.

Pixels with errors in excess of 50 km s$^{-1}$ were masked prior to performing the fit. The derived parameters are given in Table 4.3 for three realizations of the model: in the first case, model 1GK, the position angle of the line of nodes was fixed at the value recovered from the stellar kinematics and the center was fixed at the continuum peak (which coincides with the kinematical center derived from the stellar velocity field); in the second case, model 2GK, the position angle of the line of nodes was a free parameter and the center was fixed; in the third realization, model 3GK, both the position angle of the line of nodes and the center were free to vary. As for the fit to the stellar kinematics, for all models the parameters $p$ and $\theta$ were held fixed at values of 1 and 65$^\circ$ respectively.

Assuming $p = 1$ implies a flat rotation curve at large radii. Schulz and Henkel (2003) obtained single-slit observations of NGC 1386, and used the H$\alpha$ and [NII]$\lambda$6583 emission lines to derive the rotation curve out to 15$''$ from the nucleus, along the galaxy major axis. From their Fig. 4 it is evident that the rotation curve is still rising within the region probed in our analysis. It is therefore clear that neither $p$ nor the amplitude, $A$, can be well constrained by our data. Nevertheless, the main goal of fitting a rotation curve to the observed velocity field is to isolate radial motions close to the nucleus, rather than to characterize the galaxy-scale rotation curve (which would require data from a wider range of radii).

In model 1GK the amplitude reaches a high value ($308$ km s$^{-1}$) which is strongly dependent on the position angle assumed for the line of nodes, e.g. a variation of 1$^\circ$ in the adopted value for $\psi_0$ corresponds to a variation of 10 - 15 km s$^{-1}$ in $A$.

The systemic velocity derived from this model is about 40 km s$^{-1}$ higher than the value obtained from the stellar kinematics. This difference could be due to the presence of gaseous radial motions superposed on the rotation pattern. The channel maps in Fig. 4.9 seem to suggest a systemic velocity,
4.5 Discussion

$v_{cm}$, which is about 70 km s$^{-1}$ higher than derived from the modeling of gas kinematics. This would make the channel maps kinematically symmetric with respect to the zero velocity map. Nevertheless, $v_{cm}$ is clearly not consistent with the double peaked velocity distribution of the narrow component (i.e. the distribution of the velocity values is not symmetric with respect to $v_{cm}$).

Models 2GK and 3GK produce relatively small residuals ($\lesssim 30$ km s$^{-1}$) over most of the FOV (with the exceptions noted below) indicating that the gas velocity field is consistent with a rotating disk at a position angle $\psi_0 = 88^\circ$ (middle and bottom rows of Fig.4.15). This differs by $15^\circ$ with respect to the position angle obtained from the fit to the stellar kinematics. Offsets of comparable size have been found in several other Seyfert galaxies and appear to be more common in Seyfert than in quiescent galaxies, perhaps indicating that weak non-axisymmetric perturbations are more prevalent in the former (Dumas et al., 2007).

In model 3GK, where the coordinates of the kinematical center are free parameters in the fit, the recovered center is offset 1" north of the nucleus. Offsets of similar size, although in different directions, were also found by Weaver et al. (1991), Schulz and Henkel (2003) and Bennert et al. (2006). It is possible that this offset is related to the distortion in the velocity field that is clearly visible as the blueshifted residuals (discussed below) north-west of the nucleus. The distortion is not due to misfits related to the presence of the two broader components, it seems to be a genuine feature of the narrow component.

In model 2GK, we assume that the kinematical center is that recovered from the fit to the stellar velocity field, which is consistent with the continuum peak, and hence the fit was performed with the center fixed at the continuum peak, (0,0). It is likely that the gas kinematical center is affected by the presence of inflows or outflows, while the stellar kinematical center should be a more reliable tracer of the true gravitational kinematical center. Therefore, we consider the parameters recovered from model 2GK to be more reliable than those derived from model 3GK.

The overall pattern of the residuals obtained from models 2GK and 3GK is similar to that produced by model 1GK. However, there are differences in the relative amplitudes in the sense that for 2GK and 3GK, residuals in
the outer regions (beyond 2″ from the nucleus) are weaker relative to those in the inner (within 2″) regions. An interesting feature in the residual maps obtained from these models is a blueshifted region 2″ - 3″ to the north-west of the nucleus, where the residual velocities reach amplitudes of 50 - 70 km s\(^{-1}\). This region is most prominent in model 2GK, but is clearly present in model 1GK. There is evidence of a redshifted counterpart to the east of the nucleus. Unfortunately, the H\(\alpha\) + [NII] lines are heavily blended over much of this region (black pixels) preventing a satisfactory line profile decomposition (Section 4.3). Nevertheless, redshifted residuals are present around the edges of the blended area in all models, strongly suggesting that a redshifted counterpart is indeed present. The combination of blue and red-shifted residuals together indicate the present of a distinct kinematical component spanning the nucleus, approximately along the galaxy minor axis.

Comparison with the velocity dispersion map presented in Fig.4.6 indicates that this residual is associated with the region of high velocity dispersion extending from -2″ to +3″ along the SE-NW direction (i.e., roughly along the galaxy minor axis) and smoothly transitioning to lower velocity dispersions. As noted in Section 4.4.3, these kinematic features are approximately co-spatial with a low surface brightness bar-like structure seen in the HST H\(\alpha\) + [NII] image of Ferruit et al. (2000).

The velocity dispersion map presented in Fig.4.6 shows that these residuals are associated with a region of high velocity dispersion extending from -2″ to +3″ along the SE-NW direction and smoothly transitioning to lower velocity dispersion values.

As evident from the velocity maps in Fig.4.7a and 4.7c the two broad components are systematically blue- and redshifted with respect to the larger-scale narrow component, suggesting the presence of either an inflow or an outflow. Their mean velocities relative to the systemic velocity derived from the kinematics of the narrow component are -140 km s\(^{-1}\) and 250 km s\(^{-1}\) respectively. These broad components appear co-spatial in our flux maps, but it seems reasonable to identify at least the central part of the region emitting them with the two components (northern and southern) of the bright central feature in the HST emission line images of Ferruit et al. (2000). However, evidence for line splitting, in the sense that two broad
components are required to fit the line profiles, extends well beyond the bright, unresolved central region. In fact, weak double broad components can be found out to a distance of approximately 2″ east and west of the nucleus, that is, in a similar orientation to that of the region of enhanced velocity dispersion derived from the single-component fit.

The [FeVII] line profile is also dominated by blue- and red-shifted components, although with more extreme mean velocities (-250 and 270 km s\(^{-1}\), Fig. 4.8a and 4.8b). This line originates closer to the AGN, therefore velocities higher than those derived for the low-ionization species are expected. The emission in this line is also centrally concentrated (within 1″ of the nucleus) and again, it seems reasonable to identify the blue- and red-shifted kinematic components with the central structures visible in the HST image.

### 4.5.2.1 Stability of the solution

**Dependence on the noise:** as previously described for the stellar kinematics, we fitted the velocity maps recovered from the Monte Carlo simulation described in Section 4.3.1. Standard deviations for the distribution of the recovered parameters were computed and are given in Table 4.3 as an estimate of the uncertainty.

**Dependence on the initial guess:** as for the stellar kinematics, we tested the dependence of the recovered parameters on the initial guesses and again we find that using initial guesses drawn randomly from the range specified in Table 4.3 the solution is always stable converging to the same values.

**Dependence on the value adopted for p:** the amplitude, \(A\), and the concentration parameter, \(c_0\), are the most sensitive to the value adopted for \(p\). We assumed \(p = 1\), which is justified by the flattening of the rotation curve at large radii (Schulz and Henkel 2003). When \(p\) is larger than 1, the amplitude immediately reaches high values (i.e. larger than 400 km s\(^{-1}\) for model 1GK and larger than 280 km s\(^{-1}\) for models 1GK and 2GK). The systemic velocity and \(\psi_0\) are almost insensitive to \(p\).

### 4.5.2.2 Comparison with previous work

Although parameters like the amplitude, \(A\), and \(c_0\) may not be reliable due to the limited spatial extent of our data, we believe that the other
parameters are reliably and accurately determined. Perhaps the most important of these parameters is the systemic velocity. Recall that the systemic velocity derived from stellar kinematics should be the most reliable measure of the galaxy recessional velocity as the value derived from gas kinematics may be affected by non-rotational motions, such as inflows or outflows.

Various estimates of the systemic velocity have been made at lower spatial resolution using the gas kinematics derived from long-slit observations of the Hα and [NII]λ6583 emission lines (e.g. Weaver et al. 1991; Storchi-Bergmann et al. 1996; Schulz and Henkel 2003). All of these measurements produce values in the range 868-890 km s\(^{-1}\), while the heliocentric systemic velocity derived here is \(v_{\text{sys, gas}} = 797 \pm 1\) km s\(^{-1}\) (from model 2GK).

A contribution to the discrepancy comes from our decision to fix the gaseous kinematical center at the stellar kinematical center. Indeed, the discrepancy decreases when the center is fitted as a free parameter, but there is still a difference \(\Delta v > 50\) km s\(^{-1}\) with previous measurements. In addition, the lower resolution of previous studies would have made it more difficult to disentangle the rotating velocity field from the additional components. However it should be noted that Schulz and Henkel derive a systemic velocity of 877 km s\(^{-1}\) relying solely on the outer portion of their velocity curve, i.e. using data between 8″ and 15″, where the curve flattens. When measuring the velocity at the brightness peak, they obtain a value \((v_{\text{sys}} = 789 \pm 15\) km s\(^{-1}\)) consistent with our findings.

The kinematics of the coronal line [FeVII]λ6086 in NGC 1386 have previously been investigated by Rodríguez-Ardila et al. (2006). They performed single slit observations of the galaxy, with the slit aligned along the north-south direction. As in this work, they detected a double peaked emission line with the redshifted component stronger than the blueshifted one. They observed emission up to about 106 pc (1\″4) north and south of the nucleus (the spatial scale has been adjusted to our adopted distance). The maps presented in Fig.4.8a and 4.8b show a smaller spatial extension. Visual inspection of the datacube suggests that emission is present over a scale comparable with that proposed by Rodríguez-Ardila et al., however the S/N is not high enough to allow a robust fit to the spectra. As proposed by Rodríguez-Ardila et al. the presence of this emission, roughly aligned with the bright lobes visible in the flux maps, and probably associated with
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the bright nuclear knots revealed by Ferruit et al. (2000), is suggestive of a bipolar outflow along the radiation cone.
Figure 4.14: *Left:* velocity map [km s$^{-1}$] as derived from the stellar absorption features excluding the [NaD] doublet. *Center:* rotation model fit. *Right:* residual. The black cross represents the continuum peak. The magenta cross is the kinematical center derived from the fit.
Figure 4.15: *Top:* model 1GK, the center is fixed at the continuum peak and the line of nodes is fixed at the value derived from stellar kinematics. *Middle:* model 2GK, the line of nodes is a free parameter and the center is fixed at the continuum peak. *Bottom:* model 3GK, line of nodes and center are free parameters. *Left:* velocity map [km s$^{-1}$] as derived from the narrow component of the [NII]λ6583 emission line; pixels with errors larger than 50 km s$^{-1}$ are masked. *Center:* rotation model fit [km s$^{-1}$]. *Right:* residual [km s$^{-1}$]. Magenta cross: kinematical center. Black cross: continuum peak. Maps are shown after subtraction of the systemic velocity derived from each fit. The fit parameters are given in Table 4.3.
4.5 Discussion

Table 4.3: FITS TO THE OBSERVED GASEOUS VELOCITY FIELD

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<tr>
<th>Parameter</th>
<th>Notes</th>
<th>Initial guess</th>
</tr>
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<tbody>
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<td><strong>Geometry from stellar kinematics (model 1GK)</strong></td>
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<td>$A$ [km s$^{-1}$]</td>
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<td>$v_{\text{sys}, \text{gas}}$ [km s$^{-1}$]</td>
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</tr>
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</tbody>
</table>

| **Fixed center (model 2GK)** | | |
| $A$ [km s$^{-1}$] | 226 ± 1 | 180:300 |
| $v_{\text{sys}, \text{gas}}$ [km s$^{-1}$] | 786 ± 1 | geocentric‡ |
| $\psi_0$ [deg] | 88 ± 0.3 | 60:100° |
| $c_0$ [arcsec] | 3.08 ± 0.02 | 0:5 |
| $p$ | 1 | fixed |
| $\theta$ [deg] | 65 | fixed |
| $x_0$ [arcsec] | 0 | fixed at N |
| $y_0$ [arcsec] | 0 | fixed at N |

| **Free center (model 3GK)** | | |
| $A$ [km s$^{-1}$] | 213 ± 1 | 180:300 |
| $v_{\text{sys}, \text{gas}}$ [km s$^{-1}$] | 810 ± 1 | geocentric‡ |
| $\psi_0$ [deg] | 88 ± 0.1 | 60:100° |
| $c_0$ [arcsec] | 2.57 ± 0.02 | 0:5 |
| $p$ | 1 | fixed |
| $\theta$ [deg] | 65 | fixed |
| $x_0$ [arcsec] | + 0.4 † | from N |
| $y_0$ [arcsec] | + 0.9 † | from N |

†The estimated uncertainty for this coefficient is much smaller than 0″1.
‡The heliocentric systemic velocity is $v_{\text{sys}, \text{gas}} = 797$ km s$^{-1}$. 
4.6 Interpretation

Our analysis of the IFS data cube has revealed multiple components of line-emitting gas characterized by distinct kinematic properties. In particular, we identify three main kinematic components: (1) a low velocity dispersion ("narrow") component that extends over the entire FOV, (2) a higher velocity dispersion ("broad") component observed within approximately 2′′ of the nucleus, but mostly concentrated within 1′′ and apparently coincident with the two nuclear knots resolved in the HST observation of Ferruit et al. (2000), and (3) a region of enhanced velocity dispersion, associated with red- and blue-shifted velocity residuals and with a faint emission structure seen in previous HST imaging (Ferruit et al., 2000), points to the presence of a distinct kinematic component roughly perpendicular to the galaxy disk.

The velocity field of the narrow component is consistent with gas predominantly rotating in circular orbits with inclination consistent with the galaxy disk. However, fits to the velocity field reveal residuals indicating that significant deviations from rotation about the axis of the large-scale disk are also present.

4.6.1 The narrow component - disk rotation

The presence of multiple components of emission lines is evident from the total flux map presented in Fig. 4.6, as well as from the flux distributions in the third column of Fig. 4.7a, 4.7b, and 4.7c, and the channel maps of Fig. 4.9. The bright lobes extending along the direction north-south, and the low-level emission present over the entire FOV, are associated with the narrow kinematic component. They show rotational motion and low velocity dispersion. Therefore, although the double-lobed morphology of the narrow component is suggestive of an outflow, the velocity field does not support this interpretation. The morphology and kinematics can be reconciled if we interpret the bright lobes as due to emission from photoionized gas in the regions of the galaxy disk that are intersected by the biconical AGN radiation field that is predicted by the AGN unified model (e.g., Antonucci, 1993). Our interpretation is based on the model proposed for NGC 4151 by Robinson et al. (1994): if the edge of the radiation cone emerges from the disk at a shallow angle, then the intersection with the disk surface traces an
ellipse, which would result in an elongated surface brightness distribution similar to what is observed (see Section 4.6.5 and Fig.4.17).

Fig.4.11 shows that the [OIII] λ5007 emission matches very well the flux distribution observed for the [NII] emission and the other low-ionization species included in our observation. It therefore seems reasonable to assume that the extended [OIII] emission has the same origin as the low-ionization lines.

4.6.2 The broad component - nuclear outflow

The second kinematic component – the broad component – is associated with the strong nuclear line emission responsible for the central “blob” in the flux distribution maps. It is mostly confined within 1″ from the nucleus, but shows some extension out to approximately 2″. This component is actually double, and appears in the emission-line profiles as two components, one blueshifted and the other redshifted relative to the systemic velocity. They are co-spatial and have a relatively large velocity dispersion (σ ≈ 220 km s\(^{-1}\)). A reasonable interpretation is that they represent the approaching and receding sides of an outflow.

Spectra presented in Fig.4.3 and the flux maps in the right column of Fig.4.7a and 4.7c show that the red broad component is brighter than the blue. This type of asymmetry (redshifted gas brighter than blueshifted gas) is not what would usually be expected in an outflow. Indeed, emission line blueshifts or blue asymmetries are usually considered evidence for outflows (e.g. Zamanov et al., 2002). Here we suggest that the origin of the asymmetry in the brightness of the two components is due to the combination of the dust distribution and morphology of the outflow: we propose that the broad components originate from outflowing discrete clouds containing dust. These clouds are photoionized by radiation from the AGN around which they are distributed, which implies that the ionized face of each cloud is always directed toward the AGN. Therefore blueshifted clouds preferentially present to the observer their non-ionized side; on the other hand, the redshifted clouds present their ionized faces to the observer, thus appearing brighter.

The picture outlined above also explains the asymmetry in the velocity of the broad components (\(\bar{v}_{blue} \approx -140 \text{ km s}^{-1}\), \(\bar{v}_{red} \approx 250 \text{ km s}^{-1}\)): blueshifted clouds with maximal line-of-sight velocity are those at small
4.6 Interpretation

Projected distances from the AGN, e.g. cloud 1 in Fig. 4.16. According to our proposed scenario, radiation from these clouds is strongly attenuated as they show the observer their non-ionized face. Blueshifted clouds located at larger projected distances, and therefore characterized by smaller line-of-sight velocities, contribute a greater fraction of the blueshifted emission as their ionized face is partially visible, e.g. cloud 2 in Fig. 4.16. On the other side, redshifted clouds at small projected distances from the AGN (and therefore characterized by maximal line-of-sight velocities) always show the observer their ionized faces. As a result, the average velocity measured for the blueshifted clouds is smaller than the velocity measured for the redshifted counterparts.

It seems reasonable to identify the blue- and red-shifted broad components of the line profile with the two components (northern and southern) of the bright central feature in the HST emission line images of Ferruit et al. (2000). If this association is correct, it suggests that the kinematic components are the approaching and receding sides of a bipolar outflow that is aligned with the radiation cone axis.

Maps for the [FeVII] emission lines are consistent with those derived for the [NII] broad component, however there is marginal evidence that the emission is extended along the radiation cones. This is consistent with the idea that the blue- and red-shifted broad components come from a bipolar outflow aligned with the AGN radiation cones.

4.6.2.1 Mass outflow rate

We estimate the mass outflow rate as the ratio between the mass of the outflowing gas and the dynamical time at the nucleus. The gas mass associated with the broad component is estimated as:

\[ M_g = m_p N_e V f \]  \hspace{1cm} (4.2)

where \( m_p \) is the proton mass, \( N_e \sim 1200 \text{ cm}^{-3} \) and \( V \) are the electron density and the volume of the region where broad components are detected, \( f \) is the filling factor. The filling factor and volume are eliminated by combining eq. (4.2) with the following expression for the H\( \alpha \) luminosity:
4.6 Interpretation

Figure 4.16: Outflowing clouds (circle 1 and 2) are ionized by the AGN accretion disk (ellipse on the left). Blueshifted clouds preferentially show to the observer their non ionized face (in black). Their line emission is attenuated by dust embedded in the cloud. Clouds at large projected distances from the nucleus (large values of $\alpha$, corresponding to small line-of-sight radial velocities, $v_r$) are brighter as their ionized face is partially visible to the observer. As a result, the average velocity measured for the blueshifted clouds is skewed toward small values.

\[ L_{\text{H}\alpha} \sim N_e^2 j_{\text{H}\alpha}(T) V f \]  
with $j_{\text{H}\alpha}(T) = 3.534 \times 10^{-25} \, \text{cm}^3 \, \text{erg} \, \text{s}^{-1}$ at $T=10000 \, \text{K}$ (Osterbrock 1989). Therefore the gas mass is expressed as:

\[ M_g = \frac{m_p L_{\text{H}\alpha}}{N_e j_{\text{H}\alpha}(T)}. \]  

In the previous section we argued that emission from the blueshifted broad component is attenuated by dust embedded within the emitting clouds, whilst clouds responsible for the redshifted broad component show the observer their ionized side. Therefore, we assume that the red broad component gives a better representation of the intrinsic emission produced by the outflowing gas and we estimate the total H\alpha luminosity due to the outflow as twice the H\alpha luminosity from the red broad component, yielding $L_{\text{H}\alpha} = 2.5 \times 10^{40} \, \text{erg} \, \text{s}^{-1}$. The mass of the ionized gas is, therefore, $M_g \sim 5 \times 10^4 \, M_\odot$. This represents the amount of gas responsible for the H\alpha emission from the two “broad” components.

We estimate the dynamical time as the ratio of the radius of the region...
4.6 Interpretation

**Figure 4.17:** The proposed configuration for the nuclear region of NGC 1386 (see Section 4.6.5). **Left:** the narrow component of the emission lines originates from ionized gas rotating (long-dashed arrow) and inflowing (short-dashed blue and red arrows) in the plane of the galaxy (large grey disk). The yellow cones schematically represent the AGN radiation field which escapes the torus in bicones aligned with the torus axis. The radiation cone axis is inclined at $38^\circ$ to the disk plane, $76^\circ$ to the line of sight, and the cones have a half-opening angle of $34^\circ$. **Center:** the bright lobes visible in the flux maps are due to photoionization of the disk gas where the radiation cones (omitted for clarity) intersect the disk. **Right:** within the central $\approx 1''$, the broader emission line components arise mainly from dusty clouds (green blobs) participating in a bipolar radial outflow (blue and red dashed arrows) aligned with the radiation cone axis. Blue- and red-shifted velocity residuals, which are associated with increased velocity dispersion, suggest that rotation (solid green arrow) and/or outflow (short black arrows) is occurring on larger scales (2 - 3'') in a plane approximately perpendicular to the radiation cone axis (thin green disk). The large-scale disk associated with the narrow emission line component is omitted for clarity. Cartoon created using the *Shape* program (Steffen et al., 2011).

where broad components are observed ($\approx 2''$ or 152 pc) to the mean velocity of the outflow (250 km s$^{-1}$). This gives $T_d \sim 6 \times 10^5$ yr. The corresponding mass outflow rate is $\dot{M} \sim 0.1 \ M_\odot \ yr^{-1}$ (note that this is a lower limit as it represents the outflowing mass associated with only the ionized side of the clouds). For comparison, the mass accretion rate implied by the bolometric luminosity is $\dot{M}_{\text{acc}} = L_{\text{bol}}/\eta c^2 \sim 3 \times 10^{-4} M_\odot \ yr^{-1}$, where we assume a mass-to-energy conversion efficiency $\eta = 0.1$, $L_{\text{bol}} \approx 90L_{[OIII]}$ (Dumas et al., 2007) and $L_{[OIII]} \approx 2 \times 10^{40}$ erg s$^{-1}$ from the flux measurement in Storchi Bergmann and Pastoriza (1989).
4.6 Interpretation

4.6.3 Equatorial rotation or expansion?

In general, the narrow component velocity field is dominated by circular rotation consistent with the rotation of the large-scale galactic disk. However, there is strong evidence for a distinct kinematic component extending 2" - 3" either side of the nucleus, and approximately oriented along the minor axis of the large scale disk. This component appears to be associated with a low surface brightness bar-like structure that is seen crossing the nucleus east to west in the HST WFPC2 image obtained by Ferruit et al. (2000) and discussed in Section 4.4.3. It is characterized by increased velocity dispersion and blue- and red-shifted velocity residuals to the west and east of the nucleus, respectively. Notably, the orientation of this structure is roughly perpendicular to the axis of the AGN radiation bicone.

The velocity residuals can be interpreted as either radial outflow or rotation. In the first case, outflow is favored over inflow on the basis of geometrical arguments: the blue residual is associated with the near side of the galaxy disk. In the second case, the rotation is about an axis approximately coincident with the axis of the AGN radiation cone. In either case, the outflow/rotation appears to be occurring in a plane inclined at large angle with respect to the large-scale disk and roughly perpendicular to the AGN radiation bicone. We propose that this is the equatorial plane of the torus. It is possible that the residuals result from a combination of rotation and outflow. Several models (e.g. Krolik and Begelman, 1986; Elitzur and Shlosman, 2006; Dorodnitsyn et al., 2008; Keating et al., 2012; Wada, 2012; Dorodnitsyn and Kallman, 2012) propose that the torus itself is formed in an approximately equatorial magneto-hydrodynamical wind or that a wind is blown off the torus. The observed residuals, the enhanced velocity dispersion, and the circum-nuclear surface brightness structure, could conceivably originate from an extension to larger scales (or from a remnant) of such a wind. A cartoon illustrating the proposed scenario is shown in Fig.4.17.

4.6.4 Velocity residuals in the large-scale disk

In the outer regions of the FOV, at distances of 2" - 5" from the nucleus, we find blueshifted residuals in the E-NE arc, while redshifted residuals are found to the N-NW and W-SW. This system is most prominent in the residual maps obtained from model 1GK, where the line of nodes and the
4.6 Interpretation

Kinematical center are fixed at the values determined from stellar kinematics, but can also be discerned at much lower amplitude in the residual maps obtained from the other two models (2GK and 3GK). The blueshifted velocities appear in the far side of the galaxy (the south-eastern side, see Fig. 4.1), while the redshifted velocities appear in the near side, and are spatially coincident with the arc-like dust lanes highlighted in the structure map presented in Fig. 4.1. The dust lanes appear to trace part of a nuclear spiral, and we suggest that these velocity residuals may trace gas streaming inwards along the spiral.

4.6.5 The geometry and kinematics of the nuclear region

Here we attempt to place the various components of the circum-nuclear ionized gas in NGC 1386, as characterized by distinct kinematics and spatial distributions, in the context of an overall structure for the nuclear region. We also consider the relationship of these components to the classical emission line regions of AGN, namely the narrow line region (NLR) and the extended narrow line region (ENLR). Our proposed configuration for the nuclear region of NGC 1386 is shown schematically in Fig. 4.17.

The gas emitting the narrow kinematic component resides in a disk, which rotates approximately in the plane of the galaxy. The line emission from this component extends over the entire FOV (690 $\times$ 530 pc), but is brightest in a double-lobed structure that results from photoionization of the disk gas where the AGN radiation cones intersect the disk (Fig. 4.17, left and center). The geometry of the radiation cones can be constrained by requiring (1) that the disk surface area bounded by the intersection with the cones approximately matches the extension and orientation of the bright lobes, and (2) that the line of sight to the nucleus does not pass within the radiation cone (i.e., the line of sight must intercept the torus, since NGC 1386 is a Seyfert 2). With these constraints, we find that the observed morphology is approximately reproduced when the radiation cone axis is inclined at 38° to the disk plane, 76° to the line of sight, and the cones have a half-opening angle of 34°. These values should be considered illustrative rather than tightly constrained. However, we note that recent modeling of a NUSTAR X-ray spectrum of NGC1386 by Brightman et al. (2015) yielded a value for the torus opening angle of approximately 33°, consistent with our value for the opening angle of the radiation cones.
4.6 Interpretation

The extended emission-line lobes, therefore, do not represent a physical (matter bounded) structure, such as an outflow or, as suggested by Schulz and Henkel (2003), an edge-on disk; they are merely those parts of a disk rotating in the galactic plane that are illuminated (and photoionized) by the AGN radiation emerging from the torus opening. In this respect, they are similar to the $\sim$ kpc scale “extended narrow line regions” that are present in many Seyfert galaxies (i.e., interstellar gas clouds photoionized by the anisotropic AGN radiation field, Unger et al. 1987). The overall similarity between the morphologies of the extended (> 1$''$ north and south of the nucleus) [OIII]$\lambda 5007$ and H$\alpha$ + [NII] emission in HST images (Ferruit et al. 2000) and the flux distributions in the narrow component of the [NII] (and H$\alpha$) emission lines, derived from our IFS data, implies that the extended [OIII] emission has the same origin. The sub-structure in the “lobes” revealed by the HST images presumably reflects the non-uniform distribution of gas clouds in the disk.

It is worth noting that Chandra observations of NGC 1386 presented by Li and Wang (2013) show the presence of elongated X-ray emission, extending over few kpc, with an orientation consistent with that of the radiation cones inferred here.

As noted in Section 4.6.4, the pattern of velocity residuals suggests that inward spiral streaming motions may also be present in the disk, although the amplitudes are dependent on whether or not the gas disk is assumed to be co-planar with the stellar rotation.

We consider the gas emitting the broad double component to be participating in a nuclear outflow, the blue- and red-shifted components representing the approaching and receding sides of the flow, respectively. Our data do not have sufficient spatial resolution to strongly constrain the geometry of the outflow. However, the brightest emission is concentrated within the central 1$''$ and may be associated with the elongated double structure which is visible in both the structure map presented in Fig 4.1 and in the HST WFPC2 [OIII] and H$\alpha$ + [NII] images of Ferruit et al. (2000). If this is the case, the morphology suggests a bipolar outflow approximately aligned with the radiation cone axis. The southern HST component would then be identified with the approaching, blueshifted, side and the northern component with the receding, redshifted side.
The characteristic properties of the broad component gas, in particular its proximity to the nucleus, electron density (≈1000 cm$^{-3}$), velocity dispersion (≈200 km s$^{-1}$) and its complex kinematics, lead us to identify it as the NLR in NGC 1386. In our illustrative cartoon, this is represented by the green blobs in the right panel of Fig. 4.17, each one representing a distribution of outflowing clouds.

In addition to the two main kinematic components, that is, rotation in the plane of the galaxy and a nuclear outflow, there is strong evidence for another component that involves rotation and/or outflow in the equatorial plane of the torus, and extends to approximately 2 - 3″ (∼200 pc) either side of the nucleus. We speculate that this structure (represented by the green disk in the right panel of Fig. 4.17) may be evidence for the accretion-disk winds that have been proposed to explain the formation of the torus. The excitation mechanism for the relatively faint line emission associated with this kinematic component is unclear. The gas is (of necessity) located outside the AGN radiation cones. However, the line ratios in subregions C and D, which sample the emission west and east, respectively, of the nucleus, are generally consistent with AGN photoionization, although subregion C in particular, exhibits lower excitation characteristic of LINERs. Thus, it is possible that this gas is photoionized by an attenuated AGN radiation field “leaking” through a clumpy torus. Alternatively, the enhanced velocity dispersion in this region suggests that shock ionization could also play a role.

### 4.7 Summary and Conclusions

Using the GMOS integral field unit we observed the inner 690 pc of the nearby Seyfert 2 spiral galaxy NGC 1386 in the spectral range 5600 - 7000 Å which includes a number of prominent emission lines ([OII]λ6300, [FeVII]λ6086, [NII]λλ6548,6583, Hα, [SII]λλ6716,6731). We modeled the profiles of these lines to produce velocity, velocity dispersion and flux maps with a spatial resolution of 68 pc and a spectral resolution of 66 km s$^{-1}$.

The emission-line flux maps, as well as flux distributions in channel maps, are characterized by two elongated structures to the north and south of the nucleus, a bright nuclear component with FWHM ≈ 0″9, and low-level emission extending over the whole FOV. We argue that the elongated structures
are due to emission from gas in the galaxy disk photoionized by AGN radiation via a geometry in which the AGN radiation bicone intercepts the galactic disk at a shallow angle. Fainter emission consistent with AGN photoionization is also observed beyond the elongated structures suggesting that some radiation from the AGN escapes through the obscuring torus.

The gas has three distinct kinematic components.

1. A low velocity dispersion component \( \sigma \approx 90 \text{ km s}^{-1} \), which is consistent with gas rotating in the galaxy disk and includes the bright elongated structures (the “lobes”) observed in the flux map. There is no kinematic evidence that these structures are distinct from the galaxy disk gas; they are participating in the general rotation and, as noted above, can be explained by partial illumination of the disk by the AGN radiation cones. However, subtraction of rotation models reveals velocity residuals in the outer regions of the FOV that suggest inflow, perhaps in the form of streaming along dusty nuclear spirals.

We estimate the electron density from the \([\text{SII}]\) doublet, finding that the narrow component has \( n_e \approx 1000 \text{ cm}^{-3} \) at the nucleus and \( \approx 200 \text{ cm}^{-3} \) in the bright extended lobes.

2. A higher velocity dispersion component \( \sigma \approx 220 \text{ km s}^{-1} \) characterized by blueshifted and redshifted sub-components at average velocities of \(-140\) and \(+250 \text{ km s}^{-1}\), respectively. This component corresponds to the bright nuclear emission observed in our flux maps and is attributed to a compact \( (\lesssim 1''\) bipolar outflow aligned with the radiation cone axis. It appears to be resolved into two bright knots by HST observations, which can be identified with the approaching and receding sides of the outflow. We identify it as the narrow line region in NGC 1386. The broad components have electron densities of \( n_e \approx 800 \text{ cm}^{-3} \) for the blueshifted and \( \approx 1100 \text{ cm}^{-3} \) for the redshifted components, respectively. Using the H\(\alpha\) luminosity we estimate a lower limit for the mass outflow rate of \( \dot{M}_{\text{out}} \approx 0.1 \text{ M}_\odot \text{ yr}^{-1} \), which is much larger than the accretion rate necessary to sustain the AGN bolometric luminosity, that is \( \dot{M}_{\text{acc}} \approx 3 \times 10^{-4} \text{ M}_\odot \text{ yr}^{-1} \).

3. There is strong evidence for a third kinematical component in the form of velocity residuals that are spatially coincident with a region of enhanced velocity dispersion and a faint, bar-like emission structure
revealed by HST imaging. This component extends 2′′-3′′ either side of the nucleus, approximately perpendicular to the major axis of the galaxy disk. The presence of blueshifted residuals on the near (west) side and redshifted residuals on the far (east) side of the galaxy is consistent with outflow and/or rotation in a plane that is approximately perpendicular to the AGN radiation cone axis. We speculate that this is a wind which is both outflowing in a plane roughly coincident with the equatorial plane of the torus, and rotating about the axis of the radiation cones.

In some respects, the structure and kinematics of the circum-nuclear region of NGC 1386 are consistent with the “classical” AGN unification model in which a hydrostatic, optically thick torus prevents isotropic escape of the UV-optical radiation from the AGN. In particular, the bright extended lobes of line emission can be explained by AGN photoionization where biconical beams of ionizing radiation intersect the galaxy disk. There is also good evidence for a compact bipolar outflow along the axis of the AGN radiation cones; such outflows appear to be a common feature of Seyfert galaxies (e.g. Fischer et al., 2013).

However, we also find features that are not easily explained in the context of the “classical” unification model. The emission line ratios are generally consistent with AGN photoionization over the whole FOV, even for the faint emission outside the inferred boundaries for the AGN radiation cones. This suggests that attenuated AGN ionizing radiation is able to escape at large angles from the radiation cone axis, favoring models in which the torus consists of an ensemble of discrete, optically thick clumps (e.g. Nenkova et al., 2008b).

Perhaps more intriguing, however, is the evidence that rotation and/or outflow is also occurring in the equatorial plane of the torus. In recent years, our group has found evidence for the presence of similar compact (∼100 pc) equatorial outflows, i.e. perpendicular to the axis of the radio jet or to the axis of the ionization cones, in several other active galaxies (Couto et al., 2013, Schnorr-Müller et al., 2014b, Riffel et al., 2014); an equatorial outflow has also been suggested by Su et al. (1996) to explain the features observed in the radio emission of NGC 5929. Perhaps we are finding evidence of torus winds similar to those predicted by recent models (e.g. Keating et al., 2012, Dorodnitsyn and Kallman, 2012, and references therein). These observations
4.7 Summary and Conclusions

hint that equatorial outflows on \( \sim 100 \) pc scales may be a common feature of AGNs. However, to investigate their nature and ubiquity among the AGN population, high spatial resolution spectroscopy of a larger sample and detailed modeling to determine the kinematic and physical properties of the gas will be required.
CHAPTER 5

GAS KINEMATICS IN THE SEYFERT 1 GALAXY NGC 1365

5.1 Introduction

NGC 1365 is an archetypal barred galaxy, classified as SB(s)b by de Vaucouleurs et al. (1991). Jones and Jones (1980) identify the galaxy as a member of the Fornax cluster. It is known to host a Seyfert-like AGN which is classified as Seyfert 1.8 by Véron-Cetty and Véron (2006). However, the nuclear region is a composite star-forming/AGN region with a number of peculiarities which challenge simple AGN unification models. The coexistence of AGN and stellar photoionization, in the vicinity of the nucleus, has been nicely mapped with integral field observations by Sharp and Bland-Hawthorn (2010).

Signs of nuclear activity have been identified mainly at X and optical wavelengths: Iyomoto et al. (1997) observe a strong FeK emission line, and a point-like hard X-ray source consistent, in position, with the nucleus; a powerlaw component was judged necessary to perform a satisfactory fit of nuclear X-ray spectra in Komossa and Schulz (1998). Risaliti et al. (2005) report on extreme X-ray variability of the hard X-ray continuum. This was later interpreted as the result of variations in the distribution of discrete absorbers along the line of sight (e.g. Braito et al. 2014 and references therein). Such findings lend support to the hypothesis that the hard X-ray emission in the nucleus of NGC 1365 is a genuine AGN signature.
5.1 Introduction

Optical spectroscopy revealed the presence of broad Balmer emission lines, line ratios typical of AGNs (e.g. Veron et al., 1980; Edmunds and Pagel, 1982; Schulz et al., 1999), and the presence of [NeV] and HeII (Phillips and Frogel, 1980) suggesting the presence of a hard extreme-UV continuum, which is typical of AGNs. Interferometry and narrow-band imaging showed a fan-shaped [OIII]λ5007 emission extending about 10″ (∼ 1 kpc) south-eastward of the nucleus (Edmunds et al., 1988; Storchi-Bergmann and Bonatto, 1991; Kristen et al., 1997).

Evidence of AGN activity at radio wavelengths is scarce: Sandqvist et al. (1995) report the presence of a 5″ radio jet extending south-eastward of the nucleus, similarly to the [OIII] extension discovered by Storchi-Bergmann and Bonatto. However, Stevens et al. (1999) consider evidence for a radio jet to be marginal at best, suggesting that star formation dominates the energetics at radio, optical, and soft X-ray wavelengths.

Evidence that star formation plays a major role in the nucleus of the galaxy was, perhaps, first identified by Morgan (1958) who reported the presence of “hot spots”, i.e. bright HII regions. Later observations showed that different hot spots are characterized by different spectral properties (Alloin and Kunth, 1979) revealing the presence of a young stellar population (Phillips and Frogel, 1980) distributed in a circumnuclear ring (e.g. Sandqvist et al., 1982; Saikia et al., 1994; Forbes and Norris, 1998; Sakamoto et al., 2007). Detailed studies of the hot spots have been performed, e.g.: using data from ground telescopes and HST-FOC images, Kristen et al. (1997) identified a number of compact sources suggested to be super star clusters. They estimate that the most luminous of them might contain about 10^4 O-stars with a supernovae rate of ∼ 10^{-3} per year. Young and massive star clusters with evidence of associated outflows have been identified in these environments by Galliano et al. (2012). Elmegreen et al. (2009) proposed a scenario for the formation of such agglomerates within the framework of the large scale gas kinematics.

Being a nearby galaxy, isolated, with a prominent bar and spiral arms, and having an intermediate inclination with respect to the observer’s line of sight, the gas kinematics in NGC 1365 have been extensively studied. This line of investigation started when Burbidge and Burbidge (1960) and Burbidge et al. (1962) used long slit spectroscopy to derive the rotation curve from Hα and [NII] observations. Significantly different kinematics
5.1 Introduction

were derived by [Phillips et al. (1983)] from observations of higher excitation lines, namely \([\text{OIII}]\) and \(\text{HeII}\). Jorsater and van Moorsel (1995) used high resolution observations of neutral hydrogen to map the large-scale velocity field. They determined the inner disk \((120'' \lesssim r \lesssim 240'')\) inclination to be 40°. They also found non-circular motions associated with the bar, and a central reservoir of molecular gas. In the central region of the galaxy, a strongly disturbed velocity field was also revealed with the aid of optical observations by [Lindblad et al. (1996)] while a biconical outflow model was proposed by [Hjelm and Lindblad (1996)] to explain the \([\text{OIII}]\) velocity field.

More recently, measurements of the large-scale 2D velocity field of \(\text{H}\alpha\), and a new analysis of archival HI data were presented in [Zánmar Sánchez et al. (2008)]: while the I-band light distribution was found to be remarkably symmetric, strong asymmetries were found in the distribution of gas, dust and kinematical features, in both \(\text{H}\alpha\) and HI. In particular, a number of kinematically peculiar HII regions were identified, in the east side of the bar, between approximately 30'' and 60'' from the nucleus. The disturbances in the kinematics of HI observed in outer regions could be due to the proper motion of the galaxy within the cluster. However, a minor merger, or the accretion of a gas cloud, seem necessary to explain the peculiarities observed toward the inner part of the galaxy.

The galaxy NGC 1097 shares a number of similarities with NGC 1365, including morphology, distance, and inclination. It is not by chance that a number of authors have studied the two galaxies in parallel (e.g. [Burbidge and Burbidge, 1960], [Ondrechen and van der Hulst, 1989], [Ondrechen et al., 1989], [Beck et al., 2005]). In a previous work, [Fathi et al., 2006], members of our team have identified, in NGC 1097, gas inflows along a nuclear spiral which leads down to a few parsecs from the unresolved AGN. It seems therefore natural to look for similar inflows in NGC 1365.

While previous spectroscopic studies have focused on the large-scale kinematics of NGC 1365, here we present optical integral field spectroscopy for the inner 6''. We adopt the distance of 18.6 ± 0.6 Mpc, as determined from Cepheid variables by [Madore et al. (1999)], which results in the scale \(s = 90.2\ \text{pc/arcsec}\).

This chapter is organized as follows: data analysis, with details on the emission lines fitting procedures, is presented in Section 5.3. Results are
5.2 Observations

NGC 1365 was observed on November 3, 2012 and January 18 2013 with the Integral Field Unit (IFU) of the Gemini Multi-Object Spectrograph (GMOS; Allington-Smith et al. 2002; Hook et al. 2004) mounted on the Gemini South Telescope (program ID: GS-2012B-Q73). Two adjacent fields were observed, each covering $7 \times 5$ arcsec$^2$, resulting in a total angular coverage of $13 \times 6$ arcsec$^2$ with $0''2$ sampling, centered on the nucleus, and roughly aligned with the nuclear bar (position angle PA = 125° east of north). The observed field-of-view (FOV) is indicated in the top left panel of Fig.5.1 continuum images are shown in the right panels.

In order to account for dead fibers in the IFU, $\pm 0''35$ spatial dithering was applied along both axes. This resulted in four exposures of 2700
5.3 Emission line fitting

Figure 5.2: Representative spectra from the spaxels A, B and N, as indicated in the continuum image.

seconds each. From the unresolved broad line region, visible at the nucleus in the continuum images, we determined that the seeing limited the spatial resolution to 0.6 ± 0.1. Adopting the cosmology corrected scale given on NED (102 pc/arcsec), this corresponds to 61 ± 10 pc.

In order to cover the wavelength range 5600-7000 Å, which includes the emission lines [OI]λ6300, Hα+[NII]λλ6548,6583, [SII]λλ6716,6731 and several stellar absorption features, we used the IFU in two-slits mode with the grating GMOS R400 in combination with the r(650 nm) filter, this yields a spectral resolution R = 1918 or σ ≈ 66 km s$^{-1}$. A portion of the spectrum including the most prominent emission lines is shown in Fig.5.2 for some representative positions in the FOV.

The typical accuracy in the wavelength calibration is 0.14 Å (or 6 km s$^{-1}$ at λ = 6583 Å). Flux calibration was performed against the standard star LTT 3218, of spectral type DA (white dwarf with strong Balmer hydrogen lines), and it is expected to be accurate to ≈ 10%.

5.3 Emission line fitting

We used customized IDL routines to model the continuum and the profiles of the most prominent emission lines (Hα, [NII]λλ6548,6583, [SII]λλ6716,
6731, [OI]λ6300). Gaussian profiles were fitted to the lines in order to derive centroid velocities, velocity dispersions and fluxes. Three separate runs were performed to fit the Hα + [NII] lines, the [SII] doublet, and the [OI] line. The continuum adjacent to the lines was modeled with a first order polynomial.

To fit the Hα+[NII] emission lines we assumed that Hα and [NII]λ6548 have the same width as [NII]λ6583. In addition, the amplitude of the [NII]λ6548 was fixed at the theoretical value of 1/2.96 of the [NII]λ6583 amplitude (e.g. Osterbrock and Ferland 2006). A similar approach was used to fit the [SII] doublet.

Over most of the FOV, emission lines are well represented by a simple Gaussian profile, e.g. top left panel in Fig.5.3, however a bright broad Hα line is present at the nucleus and the emission lines exhibit asymmetric bases over certain regions of the FOV. The strategies adopted to fit the emission lines profiles are described below for each case.

The broad line region (BLR): the central 1″ is dominated by unresolved emission from the BLR which manifests itself in the form of a broad Hα emission line. At the nucleus it dominates the underlying narrow component, while it slowly fades away at larger radii becoming visible as a broad base up to 2″ from the nucleus (the extended and faint broad base traces the wings of the PSF).

As the BLR is unresolved, we fitted it with a combination of two Gaussians for which only the flux was left as a free parameter. We used three spaxels located about 0.5′′ from the nucleus to determine the width, velocity and relative flux of the two gaussians. In these spaxels the narrow emission lines associated with [NII] and Hα are strong enough with respect to the broad component to robustly constrain the fit of the line profile. The mean values of the parameters derived from these fits are shown in Table 5.1. A fit performed at the nucleus using these parameters is shown in the top right panel of Fig.5.3. The underlying narrow emission lines corresponding to [NII] and Hα were fitted simultaneously.

Asymmetries (Gauss-Hermite polynomial fit): asymmetric line profiles are present in some regions of the FOV. To map the spatial distribution of the asymmetry we fitted the emission lines with a truncated Gauss-Hermite
5.3 Emission line fitting

polynomial (GHP):

\[ f_{gh}(\lambda) = F e^{-k^2/2} \frac{1}{\sqrt{2\sigma^2}} (1 + h_3 H_3 + h_4 H_4) \] (5.1)

\[ H_3 = \frac{1}{\sqrt{\sigma}} \left( 2\sqrt{2}k^3 - 3\sqrt{2}k \right) \] (5.2)

\[ H_4 = \frac{1}{\sqrt{24}} (4k^4 - 12k^2 + 3) \] (5.3)

\[ k = \frac{\lambda - \bar{\lambda}}{\sigma}, \] (5.4)

where \( F \) is the amplitude, \( \sigma \) the line width (or velocity dispersion), and \( \lambda \) is the peak wavelength. Departures from symmetry are quantified by the value of the coefficient \( h_3 \), a proxy for the skewness: a negative (positive) value of this coefficient indicates the presence of a blueshifted (redshifted) tail. The coefficient \( h_4 \), a proxy for the kurtosis, measures the degree of “peakiness” of the emission line: a negative (positive) value of this coefficient indicates a rectangular (centrally-peaked) line profile. An example of a spectrum fitted with a GHP is shown in the bottom left panel of Fig.5.3.

It is reasonable to argue that asymmetries in the line profile originate from a superposition of multiple kinematical components (e.g. gas rotating in a disk plus gas experiencing in/outflow). While the GHP allows us to derive accurate fluxes for the total line profile, it does not disentangle the multiple components. To achieve this goal, we fit the asymmetric line profiles with two Gaussians.

Asymmetries (two Gaussians fit): to derive flux, velocity dispersion and velocity for the kinematical component responsible for the observed asymmetry, we fitted two Gaussians to those lines where the skewness coefficient satisfies the condition \(|h_3| ≥ 0.05\). The condition was determined by trial and error to select those lines where the asymmetry is strong enough to allow a robust fit with two Gaussians. An example of a two-components fit is shown in the bottom right panel of Fig.5.3.

5.3.1 Uncertainties

To estimate the errors on the measured quantities we performed Monte Carlo simulations: for each spaxel, we constructed one hundred realizations of the spectrum by adding Gaussian noise with amplitude comparable to
5.4 Results

Table 5.1: THE BROAD COMPONENTS

<table>
<thead>
<tr>
<th>component</th>
<th>vel [km s(^{-1})]</th>
<th>(\sigma) [km s(^{-1})]</th>
<th>relative flux (amplitude)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-143 ± 1</td>
<td>394 ± 1</td>
<td>1 (1)</td>
</tr>
<tr>
<td>2</td>
<td>-51 ± 2</td>
<td>1113 ± 2</td>
<td>0.893 (0.411)</td>
</tr>
<tr>
<td>tot</td>
<td>-100 ± 2 (^*)</td>
<td>1181 ± 2</td>
<td>...</td>
</tr>
</tbody>
</table>

Note. — \(^*\)This is a flux weighted average of the velocities derived for the two components. All velocities have been computed after subtracting a systemic velocity of 1671 km s\(^{-1}\). \(\dagger\)This value is computed as \(\sqrt{\sigma_1^2 + \sigma_2^2}\). Fluxes are free parameters with a different value for each pixel. As a reference, for both Gaussians the median flux per pixel within a radius of 0\(\arcsec\)3 from the continuum peak is 1.2 \(\times\) 10\(^{-14}\) erg s\(^{-1}\) cm\(^{-2}\), where 1 pixel \(\equiv\) 0\(\arcsec\)1 \(\times\) 0\(\arcsec\)1.

The noise measured in the original spectrum. Mean values and standard deviations for the centroid velocities, velocity dispersions and fluxes were derived for each spaxel, with the standard deviation of the distribution in each parameter being taken as the uncertainty.

5.4 Results

5.4.1 Gas kinematics

5.4.1.1 Velocity and velocity dispersion

The centroid velocity and velocity dispersion derived from the narrow [NII]\(\lambda\)6583 emission line are shown in Fig. 5.4. The maps were produced by combining results from the single-Gaussian fit and the multiple component fit of the spectra where a broad H\(\alpha\) line is present.

The velocity field shows a pattern which could originate either from rotation or streaming motions along a bar. The velocity dispersion values range between 60 and 130 km s\(^{-1}\) with a mean value of 80 km s\(^{-1}\) (approximately coincident with the median).

Hints that an addition kinematical component is superposed on the velocity field derived from the narrow component come from asymmetries in the base of the line profiles. A map of the skewness of the emission lines, the \(h_3\) coefficient derived from Gauss-Hermite polynomial fits, is presented...
5.4 Results

Figure 5.3: Fit of the [NII]λλ6548,6583 and Hα emission lines. Top left: example of single Gaussian fit. The horizontal blue lines mark the continuum level before it was subtracted. Top right: fit at the continuum peak. Two Gaussians were used to model the broad Hα (blue dot-dashed and orange short-dashed). The green long-dashed Gaussians represent the underlying narrow components. The red solid line shows the summed fit. Bottom left: example of a fit with Gauss-Hermite polynomials. Bottom right: same spectrum shown in the previous panel with two Gaussians fitted to extract the velocity of the component associated with the asymmetry (blue dot-dashed Gaussian).
5.4 Results

in the top panel of Fig. 5.5. A comparison of this map with the velocity field in Fig. 5.4 makes it clear that the asymmetry is reversed with respect to the velocity field of the narrow component, i.e. the asymmetry is blueshifted (redshifted) where the emission lines are redshifted (blueshifted) with respect to the systemic velocity. In regions where \(|h_3| \geq 0.05\) each line was modeled with two gaussians. The centroid velocity and velocity dispersion for the component associated with the asymmetry are presented in Fig. 5.6. The velocity dispersion ranges between 86 and 156 km s\(^{-1}\) with a mean value of 114 km s\(^{-1}\) (approximately coincident with the median).

The BLR is assumed to be unresolved, therefore the kinematical parameters used to fit the broad H\(\alpha\) components were not allowed to vary over the FOV. Values for the velocity and velocity dispersion adopted for each Gaussian component are listed in Table 5.1.

Centroid velocities derived from the fit of the H\(\alpha\) emission line are consistent with the values derived from [NII], however the maps derived for the [SII] doublet and the [OI] emission line present an additional prominent kinematical feature: an excess of blueshifted velocities extending from the nucleus to \(\approx 2''5\) south-east. The velocity map derived for the [OI] line is shown in the top panel of Fig. 5.7. As will be shown in Section 2.5 this feature is also present in the [NII] velocity map, although it is less evident, and it is clearly seen only after the subtraction of a velocity map representing gas rotating along circular orbits.

5.4.1.2 Uncertainties

Errors on the velocity and velocity dispersion derived from the fit were estimated with a Monte-Carlo simulation, as explained in Section 5.3.1. Values derived for the single Gaussian fit are typically lower than 1 km s\(^{-1}\) for the centroid velocity of the [NII] and H\(\alpha\) narrow lines. Errors are slightly larger for the [SII], but still below 5 km s\(^{-1}\). Similar values were obtained for the velocity dispersion.

Typical errors for the asymmetric component are approximately 1 km s\(^{-1}\) for both the velocity and velocity dispersion in the right side of the FOV, where the asymmetry is stronger. In the left side, where the asymmetry is weaker, typical errors are approximately 10 km s\(^{-1}\).

Errors for the velocity and velocity dispersion of the broad Gaussians

195
5.4 Results

Figure 5.4: Maps derived by fitting a Gaussian profile to the narrow component of the [NII] emission line. **Top:** velocity. **Center:** velocity dispersion. **Bottom:** flux. The velocity map is shown after subtracting a systemic velocity of 1671 km s$^{-1}$ (derived from the modeling described in Section 5.3.1). The cross at (0,0) marks the continuum brightness peak.
5.4 Results

used to model the broad Hα are given in Table 5.1.

5.4.2 Line fluxes

Flux maps for the [NII], Hα and [SII] emission lines are not significantly different than the continuum maps presented in Fig.5.1. The integrated flux distribution for the [NII]λ6583 emission line is shown in the bottom panel of Fig.5.4: the nucleus is dominated by unresolved emission from the AGN, and two bright blobs are visible ≈ 5″ north-east and south-west of the nucleus.

The flux map for the asymmetric component fitted to [NII] and Hα is shown in the bottom panel of Fig.5.6. Maps for the broad Hα are not shown as they reproduce the bright, unresolved emission at the nucleus.

The flux map derived from the fit of the [OI] emission line is presented in the bottom panel of Fig.5.7. With the caveat that the line is weak, especially south of the nucleus, we note that the flux presents a fan-shaped morphology reminiscent of the [OIII] flux distribution. The enhanced flux south of the nucleus corresponds however to an increase in the width of the fitted Gaussians (the velocity dispersion), and visual inspection suggests that this is due to a low S/N and a consequent poor fit.

5.4.2.1 Uncertainties

Uncertainties on the fluxes, as derived from the fitting procedure, have been estimated with the Monte Carlo simulation described in Section 5.3.1. For the [NII] and Hα emission lines flux errors are ≈ 0.05 × 10^{-17} erg s^{-1} cm^{-2} spaxel^{-1} over most of the FOV. Because of the blending of the lines, within 0″5 from the nucleus errors increase, ranging between ≈ 0.1 and 0.9 ×10^{-17} erg s^{-1} cm^{-2} spaxel^{-1}. Similar values have been obtained for the [SII] doublet, with the difference that uncertainties at the nucleus show lower values, approximately 0.1×10^{-17} erg s^{-1} cm^{-2} spaxel^{-1}. This is due to the fact that the [SII] emission lines are not blended at the nucleus showing a profile which is simpler than the one of Hα and [NII].

5.4.3 Electron density

The electron density is shown in Fig.5.8. It was derived from the intensity ratio [SII]λ6716/λ6731 assuming a temperature of 10^4K (Osterbrock and Ferland, 2006).
5.4 Results

The map shows values in the range 100 - 200 ± 60 cm$^{-3}$ over most of the FOV. The density increases to a mean value of 600 ± 100 cm$^{-3}$ within a radius of ≈ 0′5 from the nucleus. High values (≈ 500 ± 100 cm$^{-3}$) are present east and south-east of the nucleus, in a region coincident with the cone of [OIII]λ5007 emission reported by Storchi-Bergmann and Bonatto (1991). Similar high densities are present in the bright blobs, already identified in the flux maps, located about 5″ north-east and south-west of nucleus.

It was not possible to perform a robust fit of the [SII] doublet with two Gaussians, therefore a density map for the asymmetric component was not derived.

5.4.4 Line ratios

Maps for the line ratios [NII]λ6583/Hα, [SII]$(\lambda 6716 + \lambda 6731)$/Hα and [OI]λ6300/Hα are presented in Fig. 5.9.

Maps of the [NII]/Hα and [SII]/Hα ratio show large values in an elongated region, roughly centered on the nucleus, extending from -4 to +4″ along the NE-SW direction, and approximately 1.5″ above and below the nucleus in the orthogonal direction. In this region typical values range between 0.8 (Log: -0.1) and 1.2 (Log: 0.08) for [NII]/Hα, and between 0.25 (Log: -0.6) and 0.36 (Log: -0.4) for [SII]/Hα. A decrease in the flux ratios is visible in both maps within 0″5 from the nucleus, but it is more pronounced for the [SII]/Hα ratio, where values drop in the range 0.15 - 0.24 (Log: -0.8, -0.6). Low values are also visible in a large region approximately west of the nucleus. Values are in the range 0.26 - 0.4 (Log: -0.6,-0.4) for the [NII]/Hα ratio, and in the range 0.12 - 0.17 (Log: -0.9,-0.8) for the [SII]/Hα ratio. In both maps, intermediate values are present north, east and south of the nucleus. Although the enhancement in the line ratio is fairly well defined and evident, it doesn’t have any clear corresponding feature in the velocity or the density maps.

The [OI] line is weaker than [NII], Hα and [SII], resulting in a low S/N map for the [OI]/Hα ratio. Because of the sparsity of the data it was not possible to identify any trend. The median value (approximately coincident with the mean) is 0.03 with the 25th and 75th percentile being 0.02 and 0.04 respectively.
5.4 Results

Figure 5.5: Maps of the Gauss-Hermite coefficients $h_3$ and $h_4$. Negative (positive) values of $h_3$ trace the presence of a blueshifted (redshifted) asymmetry. Negative (positive) values of $h_4$ trace the presence of a flattened (peaked) line profile core. The central region was flagged because of the presence of a broad H$\alpha$ component which did not allow a reliable fit with Gauss-Hermite polynomials. As a reference, a spectrum extracted from the region close to (4$''$5,1$''$), where the asymmetry reaches the maximum, is presented in the bottom panel of Fig.5.3.
5.4 Results

Figure 5.6: Maps derived by fitting two gaussians to the [NII]6583 emission lines characterized by a skewness $|h_3| \geq 0.05$. Maps shown here represent the asymmetric component. Top: velocity. Center: velocity dispersion. Bottom: flux. The velocity map is shown after subtracting a systemic velocity of 1671 km s$^{-1}$. 
5.4 Results

Figure 5.7: As in Fig. 5.4 for [OI]. Caveat: the enhanced flux south of the nucleus, corresponding to higher velocity dispersions, is likely due to poor fits because of a low S/N.
5.4 Results

Figure 5.8: Electron density map derived from the flux ratio [SII]6716/6731 assuming a temperature $T = 10^4$ K.

Figure 5.8: Electron density map derived from the flux ratio [SII]6716/6731 assuming a temperature $T = 10^4$ K.
5.4 Results

Figure 5.9: Flux ratio $\frac{[\text{NII}]\lambda 6583}{\text{H}\alpha}$, $\frac{([\text{SII}]\lambda 6716 + \lambda 6731)}{\text{H}\alpha}$ and $\frac{[\text{OI}]\lambda 6300}{\text{H}\alpha}$. Spaxels where the relative error on the ratio is equal to or larger than 50% have been masked out (blank pixels). A contour corresponding to $\frac{[\text{NII}]}{\text{H}\alpha} = 0.6$ is plotted in the top panel; $\frac{[\text{NII}]}{\text{H}\alpha} > 0.6$ (Log 0.6 = -0.2) is characteristic of AGN photoionization.
Figure 5.10: BPT diagrams for line ratios computed over a circular region of 3\" in radius centered at the nucleus, and 2\" east and west of the nucleus. Values for the [OIII]/H\beta ratio have been taken from Schulz et al. (1999). [OI] fluxes have been derived before the application of the Monte-Carlo mask.
5.5 Discussion

5.5.1 Non-circular motions in the gas velocity field

Following the method already described for NGC 1386, Section 4.5.1, I attempted to highlight non-circular motion in the [NII] velocity field by subtracting from the observed velocity map a kinematic model describing circular orbits in a plane.

The circular-orbit model fitted to the observed [NII] is given by eq. 4.1. As shown in Zánmar Sánchez et al. (2008) and other previous studies, the velocity curve is still rising within the region probed by our observations, therefore the parameters \( p, A \) (and therefore \( c_0 \)) are poorly constrained by the data. We assume \( p = 1 \), which corresponds to an asymptotically flat rotation curve at large radii. We keep \( A \) and \( c_0 \) as free parameters, however these should not be taken to characterize the large-scale rotation curve of the galaxy. The model fitted here has the sole goal of isolating motions which deviate from a model representing gas rotating in circular orbits.

The inclination \( \theta \) has been estimated in previous works from both photometry (\( \theta = 51^\circ \), e.g. Lindblad 1978; Zánmar Sánchez et al. 2008) and the large-scale kinematics (\( \theta = 41^\circ \), e.g. Jorsater and van Moorsel 1995; Zánmar Sánchez et al. 2008). We assumed a fixed value \( \theta = 41^\circ \). Both Jorsater and van Moorsel and Zánmar Sánchez et al. show that the photometric value produces a poor fit to the kinematics suggesting that the discrepancy is likely due to the strong spiral features located close to the major axis (e.g. Barnes and Sellwood, 2003).

As for NGC 1386, to determine the parameters \( (A, v_{sys}, \psi_0, c_0) \) and the center of the rotation field \( (x_0, y_0) \), we fitted the rotation model in eq. 4.1 to the [NII] velocity map. The derived parameters are listed in Table 5.2. Maps of the observed and the best fit model velocity field are shown in Fig. 5.11 together with the residual map.

The position angle of the line of nodes that we derived from the fit (250° east of north) is substantially different than the value derived from the large-scale kinematics (220°, Jorsater and van Moorsel 1995; Zánmar Sánchez et al. 2008). This is not surprising because the galaxy is strongly barred and we probed a much smaller region than the one studied by Jorsater and van Moorsel and Zánmar Sánchez et al. However, a visual comparison between the [NII] velocity map obtained here and the large-scale Hα velocity...
5.5 Discussion

map presented in Fig.4 of Zánmar Sánchez et al. suggests that we obtain consistent results for the gas kinematics in the inner 6″.

The systemic velocity that we obtained from the fit of the kinematical model is $1671 \pm 6$ km s$^{-1}$. This value is significantly different than the value derived from the large-scale gas kinematics ($1632$ km s$^{-1}$, Jorsater and van Moorsel, 1995; Zánmar Sánchez et al., 2008). However, it is consistent with the average systemic velocity derived from the optical measurements listed on the Hyperleda extragalactic database that is $1657 \pm 10$ km s$^{-1}$.

We found that the kinematical center is offset 0.5 south-east of the continuum peak. This is smaller than the PSF FWHM (0′6), therefore we consider this offset to be negligible. From the large-scale gas kinematics Zánmar Sánchez et al. found an offset of a few arcseconds.

The velocity residuals have a distribution well represented by a Gaussian approximately centered at 1 km s$^{-1}$ with a FWHM of 27 km s$^{-1}$. Interpretation of the residual distribution is not straightforward: the bottom panel in Fig. 5.11 shows that a number of deviations from circular motion are present over the field. Most of such deviations take the form of blobs with a typical size of about 1″ and an amplitude in the range 10 - 20 km s$^{-1}$. There is no clear correspondence between the residuals and the spatial flux distribution of the H$\alpha$ emission line. In particular, the bright knots NE and SW of the nucleus do not correspond to features in the velocity residual map. Therefore, the residuals do not appear to be associated with the circum-nuclear star forming regions.

The most interesting feature is a negative residual extending south-eastward from the continuum peak down to the edge of the FOV. This extended blueshifted residual derived from the [NII] velocity field coincides with the region of blueshifted velocities directly visible in the [OI] and [SII] velocity maps, and it is also located within the well known [OIII] ionization cone (e.g. Storchi-Bergmann and Bonatto 1991; Sharp and Bland-Hawthorn 2010).

5.5.1.1 Uncertainties

Uncertainties due to the noise on the parameters presented in Table 5.2 are negligible.

\[^1\text{http://leda.univ-lyon1.fr/}\]
5.5 Discussion

Table 5.2: FITS TO THE OBSERVED GASEOUS VELOCITY FIELD

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Notes</th>
<th>Initial guess</th>
</tr>
</thead>
<tbody>
<tr>
<td>A [km s(^{-1})]</td>
<td>218</td>
<td>100:400</td>
</tr>
<tr>
<td>(v_{\text{sys}}) [km s(^{-1})]</td>
<td>1671 ± 6 heliocentric, *</td>
<td>800:2400</td>
</tr>
<tr>
<td>(\psi_0) [deg]</td>
<td>15 (\dagger)</td>
<td>10:60(\circ)</td>
</tr>
<tr>
<td>(c_0) [arcsec]</td>
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<td>0:10</td>
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<tr>
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<td>(\theta) [deg]</td>
<td>41 fixed</td>
<td>…</td>
</tr>
<tr>
<td>(x_0) [arcsec]</td>
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<td>-2:2</td>
</tr>
<tr>
<td>(y_0) [arcsec]</td>
<td>-0.5</td>
<td>-2:2</td>
</tr>
</tbody>
</table>

Note. — \*The systemic velocity derived from the narrow lines at the continuum peak is 1659 ± 6 km s\(^{-1}\) (the quoted error is due to wavelength calibration uncertainties). \(\dagger\)This value corresponds to 250\(\circ\) east of north.

We tested the dependence of the recovered parameters on the initial guess and we found that, using initial values drawn randomly from the range specified in Table 5.2, the solution was stable converging, almost always, to the same values. In only a few cases (5/200) did the algorithm recover a solution which was clearly not acceptable. It seems, therefore, that the solution is robust against a fairly large range of initial guesses.

The main source of uncertainty seems to be the wavelength calibration, which only affects the systemic velocity. As already stated in Section 2.3, the random error was estimated to be 6 km s\(^{-1}\). In addition, the calibration can be affected by systematics which are difficult to assess because of the lack of suitable sky lines within the observed spectral range.

5.5.2 Evidence for an outflow?

Since the early observations of NGC 1365 (e.g. Burbidge and Burbidge 1960; Burbidge et al. 1962) it has been clear that the circum-nuclear gas kinematics is complex and that outflows could be present. Two decades later Phillips et al. (1983) observed split [OIII] lines a few arcseconds from the nucleus and, inspired by the work that Axon and Taylor (1978) had recently published on M82, they proposed a model where the [OIII] emission originated from material outflowing along the walls of a hollow cone. A one-sided fan-shaped morphology was observed in [OIII] by, e.g., Edmunds et al.
Figure 5.11: Top: observed velocity field as derived from the [NII]λ6583 emission line. Center: model. Bottom: residual. The velocity map is shown after subtracting a systemic velocity of 1671 km s$^{-1}$, derived from the fit. The thick cross at (0,0) marks the continuum brightness peak. The thin cross marks the kinematical center derived from the fit.
A number of observations were performed to confirm and understand the line splitting, and a number of models were proposed (e.g. Edmunds et al. 1988; Jorsater et al. 1984; Hjelm and Lindblad 1996). The current consensus is that the velocity field derived from [OIII] and other high-ionization emission lines is the combination of a rotating disk (the one mapped by Hα and other low-ionization lines), and a biconical outflow. According to the model proposed in Hjelm and Lindblad (1996), the cone has a half opening angle of 50°, the axis is within 5° of the galaxy rotation axis, and the outflow is radially accelerated with higher velocities close to the cone axis. See Lindblad (1999) for an illustration of the proposed geometry.

Evidence for an outflow coincident with the extended [OIII] emission is not obvious in the velocity field derived from the [NII] emission. However, as described in the previous section, the [NII] velocity residual map (Fig.5.11) shows an extended, blueshifted residual with amplitude as large as −30 km s\(^{-1}\) localized within the conical [OIII] emission mapped in previous works. The BPT diagrams shown in Fig.5.10 and the line ratio maps in Fig.5.9 suggest that the residual is located within, or adjacent to, a region dominated by AGN photoionization. However, to reach a definitive conclusion it is necessary to obtain spatially resolved, single-epoch observations of all emission lines used in the BPT diagrams (the [OIII] and H\(\beta\) emission lines were not covered in our observation). The residual could be due to unresolved spectral features generated by the outflowing gas. The same feature is immediately evident in the velocity maps derived from [OI] and [SII], see top panel in Fig.5.7 for the [OI] velocity map.

As already discussed in Section 5.3, visual inspection of the spectra revealed the presence of a line asymmetry, which we mapped by fitting GH polynomials to the emission lines, see Fig.5.5. Blueshifted asymmetries are the spectral signatures expected to arise from outflowing gas moving toward the observer. It is therefore natural to ask whether they were observed in correspondence with the blueshifted residual. Unfortunately, the region where the extended blueshifted residual was identified could not be fitted with GH polynomials because of the presence of the broad Hα emission line.

The spatial distribution of the asymmetries is somewhat puzzling: the
strongest blueshifted asymmetries are present over the entire right side of the FOV (south-west and south-east of the nucleus), in correspondence with the receding side of the galaxy (see Fig.5.1 to compare with near and far side of the galaxy). Conversely, mostly redshifted asymmetries, but with smaller amplitude than the blueshifted counterparts, are localized on the left side of the FOV (north-west and north-east of the nucleus). No evidence of significant asymmetries is recovered south-east of the nucleus, where the conical [OIII] emission has been observed.

The velocity field associated with the asymmetry is also puzzling. With the goal of disentangling the rotating gas from the gas responsible for the asymmetry, we fitted the lines with two Gaussians. The velocity map for the component associated with the asymmetry is presented in the top panel of Fig.5.6. With the exception of few pixels, the right side of the FOV is characterized by positive velocities with a Gaussian distribution of mean value approximately equal to 50 km s\(^{-1}\). Conversely, the left side of the FOV, where only few pixels were fitted with two Gaussians, shows typical velocities of -25 km s\(^{-1}\). No obvious relation with the presence of a biconical outflow can be drawn for such features.

As described in Section 5.4.3, we used the [SII] doublet to derive the electron density. Remarkably, Fig.5.8 shows that the blueshifted residual corresponds to a region of increased electron density.

In previous works, non-circular motions in NGC 1365 have been mapped via the modeling of split line profiles in [OIII] and other high-ionization species. Split lines are not resolved within our FOV, nevertheless from visual inspection of the datacube it is obvious that a second blueshifted component is present, in H\(\alpha\), [NII] and [SII], in a handful of pixels near the edge of the FOV. More precisely, this region is characterized by (i) an enhancement in the velocity dispersion located around the point (4\(\arcsec\), -3\(\arcsec\)), see middle panel in Fig.5.4 (ii) by an evident decrease in the GH coefficient \(h_4\), a proxy for the line kurtosis, indicating line profiles with a flat top, see bottom panel in Fig.5.5. The same region has enhanced blueshifted velocity residuals as large as -27 km s\(^{-1}\), see bottom panel in Fig.5.11.

In summary: features suggestive of outflowing gas have been so far observed in high-ionization species. Here we found similar evidence also in a number of low-ionization species, i.e. [OI], [NII], H\(\alpha\) and [SII]: we observed blueshifted velocity residuals in a fan-shaped region with the apex at the
5.5 Discussion

Figure 5.12: Map of the observed features suggestive of outflowing gas: fan-shaped blueshifted velocity excess coincident with enhanced electron density and characterized by AGN-like line ratios (light gray), evidence for unresolved split lines (dark grey), flat-topped line profiles suggestive of unresolved split lines (black and dark grey). The solid line corresponds to $[\text{NII}]/H\alpha = 0.6$, as in Fig.5.9. Points inside the contour are characterized by $[\text{NII}]/H\alpha \geq 0.6$, suggestive of AGN photoionization.

nucleus, oriented as the $[\text{OIII}]$ conical emission, with line ratios suggestive of AGN photoionization, and enhanced electron density; evidence for line splitting was identified in an adjacent area. Fig.5.12 provides a comprehensive map of the spatial distribution of these features.

5.5.3 Is there any evidence for gas inflows?

Large-scale bars are among those dynamical features that funnel gas toward the inner region of their host galaxies. NGC 1365 has a strong bar with a projected major axis extending over about 200$''$ (e.g. Zánmar Sánchez et al., 2008). Our observation, with an FOV of 13$''$ x 6$''$ centered on the nucleus, probed only a very small fraction of the bar. According to the hydrodynamical models of NGC 1365 presented in Lindblad et al. (1996a), this region falls entirely within the inner Lindblad resonance, which is located at a radius of $r \approx 30''$. Their model predicts the presence of spiral gas inflows within this region, however it must be acknowledged that it relies on a number of simplifying assumptions and, similarly to other studies (e.g. Zánmar Sánchez et al. 2008, Piñol-Ferrer et al. 2012), it attempts
to reproduce the main features of the large-scale kinematics. The spatial resolution is therefore not ideal for a direct comparison with our results.

The velocity residuals derived from the [NII] emission line do not show any obvious pattern which could be associated with gas inflows. It is worth recalling that a distinctive trait of the narrow emission lines is the presence of an asymmetric base. This is systematically blueshifted with respect to the line peak in the right-hand (south-western) portion of the FOV and redshifted in the left side. The change in sign is not correlated with the orientation with respect to the observer: the near side of the galaxy corresponds, approximately, with the upper (western) part of the FOV. The origin of the asymmetry remains, therefore, unclear. However, it is possible that this feature is related to the presence of gas inflows.

5.6 Summary and conclusion

We observed the Seyfert 1.8 galaxy NGC 1365 using the GMOS integral field unit on the GEMINI South telescope. The FOV was centered on the nucleus and aligned with the large-scale bar covering \(1173 \times 541\) pc\(^2\). Our observation covered the spectral range 5600 - 7000 Å which includes a number of emission lines ([OI]\(\lambda 6300\), [NII]\(\lambda \lambda 6548,6583\), H\(\alpha\) and [SII]\(\lambda \lambda 6716,6731\)). We modeled the profiles of these lines to produce velocity, velocity dispersion and flux maps with a spatial resolution of 54 pc and a spectral resolution of 66 km s\(^{-1}\).

The flux maps are dominated by unresolved emission at the nucleus, while several bright knots, probably HII regions, are present elsewhere. The bright unresolved emission at the nucleus is due to a prominent broad component in the H\(\alpha\) emission line; because of the PSF wings, this is observed within a radius of approximately 2\(''\) of the nucleus. The broad component is very prominent at the nucleus and we modeled it with a combination of two Gaussians from which we derived a flux-weighted velocity of -100 km s\(^{-1}\) (with respect to a systemic velocity of 1671 km s\(^{-1}\), as derived from the [NII]\(\lambda 6583\) emission line) and a combined velocity dispersion of 1181 km s\(^{-1}\).

Strong narrow emission lines are present over the entire FOV with velocity dispersion in the range 60 - 130 km s\(^{-1}\) and median value \(\sigma \approx 80\) km s\(^{-1}\).
5.6 Summary and conclusion

The velocity fields derived from the [NII]λ6583 emission line and, independently, from Hα are consistent with gas rotating in the large-scale disk; however, extended blueshifted velocity residuals suggest the presence of an additional kinematical component. The same excess of blueshifted velocities is directly evident from the velocity maps derived from [OI] and [SII]. The excess has a fan-shaped morphology with the apex at the nucleus; it is located within a region where previous authors observed a more extended conical [OIII] emission (e.g. Storchi-Bergmann and Bonatto [1991]); it corresponds to a sharp increase in the electron density (from 150 to 500 cm$^{-3}$), and it is characterized by line ratios typical of AGN photoionization ([NII]/Hα > 0.6). Close to this region of interest we find evidence for line splitting. These features, previously observed at larger radii and for higher ionization species, are consistent with the hypothesis of a conical outflow suggested in previous works (e.g. Hjelm and Lindblad [1996]).

Finally, although NGC 1365 shows overall morphological similarities with NGC 1097, we found no evidence for gas inflows along nuclear spirals, like those observed in NGC 1097 by Fathi et al. [2006], neither did we find obvious evidence for gas inflows along the bar.

In conclusion, at the small scales probed with our observation, we found evidence for the conical outflow previously identified by other groups from the study of higher ionization species, however we did not find any obvious evidence of gas inflows. These could be revealed by observations performed over a larger FOV including the whole bar and the prominent dust lanes located at its boundaries.
CHAPTER 6

SUMMARY AND CONCLUSION

In this dissertation I presented two observational studies in which I investigated aspects of the growth and coevolution of supermassive black holes (SBHs) and their host galaxies. The first study is a search for SBHs recoiling in the aftermath of an SBH-binary merger. The second is a study of the ionized gas kinematics in the central kiloparsec of two nearby active galactic nuclei (AGNs): NGC 1386, a Seyfert 2 (obscured AGN) galaxy, and NGC 1365, a barred Seyfert 1 (non-obscured AGN).

6.1 Recoiling SBHs

In Chapter 2 I presented results from a photometric analysis of 14 massive elliptical galaxies imaged with the Hubble Space Telescope. The goal of the study was to measure the spatial offset between the nuclear point source (the SBH) and the photometric center of the galaxy as defined by the old stellar population of the inner 2 - 3 kpc. Given the regular nature of the galaxies, most of which are remarkably featureless in their photometric properties, the photocenter was assumed to locate the minimum of the large-scale potential well, the expected equilibrium position of the SBH.

For fifty years it has been implicitly assumed that SBHs reside at the galactic center to within ~ 1 parsec or less. Yet, in the last decade, advances in numerical relativity led astronomers to believe that this might not be the case in massive galaxies that have experienced major mergers. The
6.1 Recoiling SBHs

The current standard cosmological model predicts that massive galaxies acquired their mass via a succession of mergers. At the same time, observations strongly support the hypothesis that SBHs are ubiquitous in the centers of all galaxies above a certain mass threshold. It is therefore natural to expect that a history of galactic mergers implies a similar history of mergers for their SBHs. Asymmetries in the merging SBHs (i.e. different masses and spin configurations) are expected to produce asymmetric emission of gravitational waves. The asymmetric removal of linear momentum imparts a kick to the merged SBH which can be ejected from the galaxy, in the most extreme cases, or recoil to large distances from the nucleus. N-body simulations predict that SBHs which do not escape the galaxy will oscillate for long periods of time (~ 1 Gyr) in the low-density nuclei of massive ellipticals leading to spatial offsets as large as the core radius of their host galaxy (a few 100 pc).

Looking for evidence of recoiling SBHs, we made the first systematic search for SBH displacements in massive nearby elliptical galaxies hosting low luminosity AGNs.

In the following sections I will summarize the most important conclusions of our study. I will start with the most robust ones, in Section 6.1.1 and Section 6.1.2, for which model assumptions play a negligible role, and I will recall the more speculative ones, in Section 6.1.3, Section 6.1.4 and Section 6.1.5, where model assumptions do play a major role. Concluding remarks and future directions will be given in Section 6.1.6.

6.1.1 Is there evidence that SBHs are offset from the center of their host galaxies?

Out of 14 galaxies, we identified 10 with significant spatial offsets of projected amplitude in the range 3 - 10 pc. Six of these are considered robust against irregularities in the surface brightness distribution of the host galaxies. In most cases the offsets correspond to sub-pixel scales. When considered individually, the observed offsets are consistent with residual oscillations resulting from a recoil event; however, a few other mechanisms are capable of producing such offsets: asymmetric jets, SBH-binaries, and massive perturbers. We reviewed the data available in the literature for each galaxy and we proposed a list of the most plausible mechanisms responsible for the offset observed in each case.
6.1 Recoiling SBHs

We found no case in which the SBH is offset from the photocenter by a significant fraction of the core radius. In massive ellipticals characterized by a core – a central light deficit – SBHs reside within a few parsecs of the photometric center defined by the old stellar population of the inner 2 - 3 kpc. All of the measured offsets are a small fraction (1% - 10%) of the core radius, which on average is approximately 300 pc for the studied galaxies.

6.1.2 The role of powerful radio jets

Powerful kpc-scale radio jets (FRI-like) are present in four of the 14 galaxies analyzed: NGC 1399, 4261, 4486, and IC 4296, with the jet being evident in the optical images only in NGC 4486 (M87). In three of these galaxies (NGC 1399, 4486, IC 4296) we measured a spatial offset between the SBH and photocenter which is approximately aligned with the jet (within 20°). While the brightness of the jets is fairly symmetric in NGC 1399, this is not the case for NGC 4486 and IC 4296. In these galaxies the SBH is offset in the direction of the fainter jet.

Simulations of SBH binary coalescence suggest a statistical tendency for recoil offsets to be approximately aligned with the jet (or counter-jet) direction (e.g. [Lousto et al., 2010]). However, a net thrust, resulting from an intrinsic asymmetry in jet power, could also displace the SBH from its equilibrium position, if sustained over timescales of the order of $10^8$ yr (e.g. [Kornreich and Lovelace, 2008] and references therein). Studies of large samples to test this prediction have never been performed and, before the study presented here, this mechanism had been invoked to explain the spatial offset of the nuclear point source in two galaxies only (both of which belong to our sample): NGC 4261 ([Ferrarese et al., 1996] and NGC 4486 ([Batcheldor et al., 2010]). Our results support the hypothesis that asymmetries in powerful radio jets may indeed displace their SBHs. It must be noted that asymmetries in the jet brightness are usually explained in terms of relativistic Doppler beaming, implying that jets are intrinsically symmetric (e.g. [Sparks et al., 1992]). However, we estimate that only a small degree of asymmetry (of the order of 1% of the accretion luminosity) is sufficient to offset the SBH by a few parsecs.

To draw a firm conclusion, it is clear that the problem must be tackled by studying a large sample so that the relation between spatial offsets of the SBH, direction of the jet, and asymmetry of of the jet can be assessed on a
6.1 Recoiling SBHs

statistical basis.

6.1.3 Do massive ellipticals really grow via mergers?

The current standard cosmological model, the “A cold dark matter” (ΛCDM) cosmological model, assumes that galaxies dwell in dark matter halos. Both the galaxies and the halos grow, over cosmic time, through a series of mergers. This is often referred to as the “hierarchical” assembly scenario (e.g. Springel et al., 2005c). Some observations, however, suggest that massive present-day galaxies formed at high redshift, perhaps from the merger of gas clouds, and then evolved passively, with mergers with other stellar systems playing only a minor role in their evolution. This is often referred to as the “monolithic” assembly scenario (e.g. Matteucci, 2003).

To which scenario do our results lend support? The small offsets observed seem to favor the monolithic scenario. From the model described in Section 2.5.3 we estimated that our results are reproduced by a galaxy merger rate which is much lower than the values currently found in the literature. Typically such values are estimated by comparing some observed quantity, such as the number of close galaxy pairs, with the results of ΛCDM simulations and are, therefore, model dependent.

The ΛCDM cosmological model is known for reproducing well the large-scale structure of the universe and it has become a paradigm of modern astrophysics. However, it exhibits a number weaknesses when it comes to smaller scales and it has been put to severe scrutiny by only a few authors (e.g. Kroupa et al., 2012). With the caveat that our model is very simplistic and relies also on predictions of general relativistic simulations of merging binaries, and N-body simulations of the dynamical evolution of SBHs, it is possible that our results are in conflict with a key prediction of the ΛCDM model: the galaxy merger rate.

6.1.4 The configuration of SBH-binaries at the time of merger

General relativistic simulations predict that the recoil velocity for an SBH created by the merger of two SBHs depends on two parameters: (1) the binary mass ratio; (2) the individual spins, more specifically, their amplitude and their relative orientation with respect to the orbital angular momentum. Large recoils are attained for maximally spinning SBHs and large (>1:10)
mass ratios.

The model described in Section 2.5.3 predicts that, with the assumed merger rate, recoil velocity distribution and SBH oscillation damping time, we should have observed larger spatial offsets. It is therefore possible that the discrepancy between observations and the model prediction arises from the adopted recoil velocity distribution. This distribution, derived by Lousto et al. (2012), in turn relies on assumptions for the distribution of the SBH-binary mass ratio, spin amplitude and direction: quantities which are weakly constrained.

For a given mass ratio, certain spin configurations can boost the recoil velocity by one order of magnitude. During the merger of two galaxies the SBHs mass ratio does not vary significantly through the inspiral and merger phases. However, the spins are affected by gas accretion events. We can, therefore, speculate that the small spatial offsets measured in our analysis could be due to the fact that the SBHs reach the merger stage with a spin configuration which minimizes the recoil velocity, e.g. with a low spin amplitude and spin direction aligned with the orbital angular momentum. Alternatively, it is possible that the SBHs in our sample were assembled via the merger of low mass-ratio binaries ($<1:10$). If SBH masses are representative of their host galaxy mass, then this would imply that large ellipticals were assembled via the merger of a large number of small galaxies (a scenario consistent with hierarchical evolutionary paths).

### 6.1.5 The gas content of massive ellipticals

The model that we used to estimate the probability to observe a given spatial offset, cf. Section 2.5.3, assumes a galaxy merger rate or, equivalently, an SBH-binary merger rate, recoil velocity distribution and a prescription for the SBH oscillation damping time. In the previous sections I speculated that the origin of the discrepancy between observations and predictions was due to an overestimate of the merger rate, Section 6.1.3, or to the fact that SBH-binaries merge in a configuration which produces small ($< 250 \text{ km \ s}^{-1}$) recoil velocities, Section 6.1.4. Another possibility is that the damping time for the SBH oscillations was overestimated. Shorter damping times would cause a faster decrease in the SBH oscillation amplitude, decreasing the probability to observe a spatially offset AGN.

The damping times used in our model were estimated from a relation
6.1 Recoiling SBHs

derived by Gualandris and Merritt (2008) from high-accuracy N-body simulations. They modeled the oscillations of recoiling SBHs in the nuclei of galaxies with a core-Sérsic light profile (similarly to the galaxies in our sample). These simulations do not account for the presence of gas. Shorter damping times are instead produced in hydrodynamical simulations of recoiling SBHs in gas-rich galaxies (e.g. Sijacki et al., 2011). It is difficult to derive quantitative constraints, however we can speculate that the lack of large SBH offsets may be indicating that the cores of large elliptical galaxies do contain enough gas to significantly affect the evolution of a recoiling SBH. In other words, they can not be modeled accurately as “dry” systems.

6.1.6 Concluding remarks and future directions

We undertook the first systematic study of a small sample of large elliptical galaxies hosting low-luminosity AGNs to look for spatial offsets between the nuclear point source and the photocenter of the host galaxy. We found that the nuclear point source (a proxy for the SBH powering the AGN) resides within 10 pc of the photocenter (a proxy for the minimum of the potential well, where the SBH is expected to reside). Our results for the sample as a whole do not support the hypothesis that in massive ellipticals the SBH undergoes long-lasting oscillations of amplitude comparable with the core radius, where the oscillations are induced by the anisotropic emission of gravitational waves produced during the merger of an SBH-binary.

In most cases the small offsets correspond to sub-pixel displacements. Although we applied a number of criteria to penalize the significance of offsets in those galaxies where dust was obviously present, or where the isophotal structure exhibited small irregularities, it is legitimate to maintain a certain degree of doubt about their nature and it is desirable to obtain independent confirmations of their presence.

Individually, the small offsets measured in these galaxies could still have been caused by gravitational recoils. However it is difficult to distinguish recoils from other plausible mechanisms. For example, recoiling SBHs are expected to generate kinematically peculiar broad line regions (BLRs); in other words, the BLR is located within the sphere of gravitational influence of the recoiling SBH, therefore, depending on the recoil velocity, a fraction of the BLR remains bound to SBH during its travel through the galaxy. As a result, the gas in the BLR is expected to be characterized by shocks and
6.1 Recoiling SBHs

...to have a different systemic velocity than that characteristic of the gas in the narrow line region, which is influenced by the large-scale potential of the galaxy. However the galaxies in the sample have weak or absent emission lines (i.e. they have small amounts of ionized gas, if any). Broad lines, if present, are revealed only after the subtraction of stellar templates, a process which can mimic the presence of a broad line because of over subtraction of an absorption feature. In addition, even when these spectral features are present, kinematical differences between broad and narrow lines can be due to presence of non-gravitational motions, such as gas inflows and outflows. As a result spectroscopic studies of the ionized gas, when possible, are not promising, or at least, not free of ambiguities.

More promising to understand the nature of offset nuclear sources is the study of a larger sample of galaxies and its statistical interpretation. Spatial offsets due to jet thrusts are expected to be aligned with the jet, with the displacement amplitude being proportional to the degree of asymmetry of the jet power. On the other hand, when the offset is due to the anisotropic emission of gravitational waves, the spatial offset is expected to be aligned (or counter-aligned) with the orbital angular momentum of the SBH-binary showing, therefore, a weaker correlation with the jet direction and no correlation with the jet brightness asymmetry. If gas accretion is effective in the alignment of the SBH spins with the angular momentum of the SBH-binary, then projected offsets due to the presence of a binary-SBH are expected to be consistent with a parent distribution of offsets orthogonal to the jet axis. No correlations are expected with the properties of the radio jets when offsets are due to interactions with massive perturbers. It is therefore clear that quantifying the relation between spatial offsets and jet properties (such as direction and degree of asymmetry) in a large sample of galaxies will allow for more robust conclusions. Toward this goal, we recently obtained a grant to perform an archival study of a large sample of galaxies imaged with HST.

To complement this investigation, efforts could be made to reach a better understanding of the 2D velocity and light profile of the inner kiloparsec of galaxies hosting recoiling SBHs. The large-scale velocity field for gas and stars in disk galaxies hosting recoiling SBHs has been simulated by Kornreich and Lovelace (2008), however it seems that no further studies have been done to probe the circum-nuclear region. Because of inflows and out-
flows, the gas kinematics can be extremely complex in the nuclei of active galaxies. However, the stellar kinematics should be relatively unaffected by the processes of AGN feeding and feedback providing, therefore, useful insights into the dynamics of recoiling SBH-galaxy core systems. Integral field spectroscopy would be the obvious tool to investigate the predictions. Concerning the light profile, we already know that an SBH-binary is expected to deplete the central few 100 pc of the host galaxy creating a light deficit: 3-body interactions are expected to eject stars intersecting the orbit of the binary creating a mass deficit of the same order of magnitude as the combined mass of the SBH-binary (e.g. Merritt and Milosavljevic, 2005); we also know that a recoiling SBH sloshing around within the nucleus of a galaxy will transfer kinetic energy to the surrounding stars causing the core to expand (e.g. Boylan-Kolchin et al., 2004; Gualandris and Merritt, 2008). However no theoretical work seems to have been done to predict in detail the isophotal features of a galaxy nucleus hosting a recoiling SBH. Such a study would be extremely useful and probably relatively easy to test: studies of the 2D light profile of galaxies have been done for decades and are relatively easy to perform.

Our search for recoiling SBHs was at the limit of what could be done with the Hubble Space Telescope. Powerful new instruments, with great promise, are about to rise above the horizon, such as the Thirty Meter Telescope and the Giant Magellan Telescope among the others. They will certainly cast light on our findings, allowing for a deeper look into the hearts of galaxies.

6.2 Gas kinematics

In Chapters 3, 4 and 5 I presented a detailed study of the ionized gas kinematics in the inner few 100 pc of two nearby isolated AGNs: NGC 1386, a Seyfert 2 (obscured AGN), and NGC 1365, a Seyfert 1 (non-obscured AGN) barred galaxy. We found evidence for complex kinematics consistent with a combination of rotation in the large-scale disk of the galaxies, outflows with different morphologies, and perhaps inflows.

SBHs grow via mergers of SBH-binaries, but they also grow via accretion of gas. In so doing, they power AGNs. However, gas must lose more than 99% of its angular momentum to be transferred from kpc-scales down to sub-
pc scales where it can be accreted by the SBH. The emerging picture is that a number of mechanisms occur at different spatial scales for this to happen: at several kpc scales, inflows may be triggered either by galactic interactions and mergers, or by the formation of large-scale bars induced by the secular evolution of isolated galaxies; bars funnel gas from kpc-scales down to the central few hundreds of parsecs; nested gravitational instabilities, such as bars-within-bars and nuclear spirals, funnel the gas from 100 pc-scales to pc and maybe sub-pc scales where outflows can carry away further angular momentum, transferring mass and kinetic energy to the interstellar medium. This chain of events is still not fully understood. For example, simulations of structure formation which include AGN feedback (i.e. outflows) commonly assume that some fraction of the accreted rest-mass energy (typically about 0.5%) is available for feedback (e.g. Springel et al., 2005b). Given the key role that AGN feedback seems to play in galaxy evolution (e.g. Di Matteo et al., 2005), it is desirable to set robust constraints on the fraction of accreted rest-mass energy which is injected back in the large-scale interstellar medium via outflows. Detailed studies of the gas kinematics in AGNs will help constrain this parameter. Toward this goal, there is great interest in probing, at high spatial resolution, the 2D gas kinematics in nearby galactic nuclei.

With the long-term goal of studying the relation between gas kinematics and SBH accretion rate, our team assembled a sample of about 50 nearby AGNs selected on the basis of either their nuclear hard X-ray luminosity (a proxy for the SBH accretion rate), or the presence of nuclear dusty spirals (features believed to trace inflows). At the time of writing some of the galaxies are still in the process of being observed with the Gemini Multi-Object Integral Field Unit. In this dissertation I discussed results obtained for NGC 1386 (from the dusty spirals sample) and NGC 1365 (from the X-ray selected sample). In the following sections I will summarize the most important results obtained for these two galaxies (Section 6.2.1 and Section 6.2.2). The energy budget of AGNs will be discussed in Section 6.2.3. In Section 6.2.4 I will comment on what we learnt about the structure of active galaxies, in particular about the torus (Section 6.2.4.1) and the narrow line region (Section 6.2.4.2). Finally, Section 6.2.4 concludes by sketching the general picture emerging when we account for similar studies conducted on nearby Seyferts and LINERs.
6.2 Gas kinematics

6.2.1 NGC 1386

The galaxy was known for the complex gas kinematics of its nuclear region and we confirm this trait. We performed the first IFU study of this galaxy observing the central $9'' \times 7''$ (684 $\times$ 532 pc) at a spatial resolution of $0.9''$ (68 pc), and we covered the spectral range 5700-7000 Å at a resolution $R = 1918$ ($\sigma \approx 66$ km s$^{-1}$). We found that the stellar kinematics is consistent with rotation, however the gas kinematics is remarkably complex.

In terms of flux, the line emission is dominated by a bright central component, with two lobes extending $\approx 3''$ north and south of the nucleus. As for the gaseous kinematic components, we can clearly identify two. The first has low velocity dispersion ($\bar{\sigma} \approx 90$ km s$^{-1}$) and extends over the whole field-of-view. This is interpreted as gas rotating in the galaxy disk. We interpret the lobes as resulting from photoionization of disk gas in regions where the AGN radiation cones intercept the disk. The second kinematic component has higher velocity dispersion ($\bar{\sigma} \approx 200$ km s$^{-1}$) and it is observed in the inner 150 pc around the continuum peak. This component exhibits double peaked line profiles, with redshifted and blueshifted components separated by $\approx 500$ km s$^{-1}$, suggesting a nuclear outflow. Using HST imaging, Ferruit et al. (2000) resolved the central bright emission associated with the broad component into two knots approximately aligned with the large-scale lobes. Our spectroscopic data, together with the features revealed by Ferruit et al., are strongly suggestive of a bipolar outflow, for which we estimate a mass outflow rate of $\dot{M} \gtrsim 0.1$ M$_{\odot}$ yr$^{-1}$.

Additional kinematic components, revealed by velocity residuals and increased velocity dispersion along the east-west axis, suggest that outflow and/or rotation is occurring in a plane approximately perpendicular to the axis of the radiation cone. Spatially coincident with these features, is a faint bar-like emission revealed by the HST imaging of [NII] + H$\alpha$ emission reported by Ferruit et al.

The velocity residuals also show evidence for a fourth kinematical feature that we identify with gas inflowing along nuclear spirals. However, unlike the residuals coincident with the region of enhanced velocity dispersion, these residuals are strongly dependent on the rotation model fitted to the observed velocity field. As a result, we consider the evidence for inflows to be less robust than the evidence for an equatorial outflow.
6.2 Gas kinematics

6.2.2 NGC 1365

This is one of the most studied galaxies in the southern hemisphere. It has a number of characteristics which make it an interesting target: it is nearby, it is isolated, it has a large-scale bar, and it has an active nucleus. Integral field observations of NGC 1365 have previously been performed by, for example, Zánmar Sánchez et al. (2008) and Sharp and Bland-Hawthorn (2010), however the previous work covered larger FOVs at lower spatial resolution. We performed an IFU study of the circum-nuclear region, observing the inner $13'' \times 6''$ ($1173 \times 541$ pc) at a spatial resolution of $0.6''$ (54 pc), and we covered the spectral range 5600 - 7000 Å at a resolution $R = 1918$ ($\sigma \approx 66$ km s$^{-1}$).

The emission line flux maps are dominated by the bright unresolved nucleus (as expected for a Seyfert 1 galaxy, where the AGN is exposed to the direct view of the observer). Several bright clumps are also present in the circum-nuclear region, mostly corresponding to a line ratio $[\text{NII}]6583/\text{H}\alpha < 0.6$, suggesting that the AGN is not the dominant source of photoionization for the clumps; they are likely star-forming regions. This is not surprising, as several previous studies have shown the co-existence of AGN and stellar photoionization in the nucleus of NGC 1365 (e.g. Sharp and Bland-Hawthorn, 2010).

The H$\alpha$ emission line has a prominent broad component (a characteristic which defines Seyfert 1 galaxies). This spectral feature is believed to originate from the so-called “Broad Line Region”, a distribution of clouds orbiting close ($r << 1$ pc) to the SBH (e.g. Krolik, 1999). We modeled the H$\alpha$ broad component by superimposing two Gaussians, deriving a velocity $v \approx -100$ km s$^{-1}$ (with respect to a systemic velocity of 1671 km s$^{-1}$) and a velocity dispersion $\sigma \approx 1180$ km s$^{-1}$. The photometric counterpart of this spectral feature is the unresolved emission mentioned in the previous paragraph.

In addition to the nuclear broad component, a narrow velocity component ($\sigma \approx 80$ km s$^{-1}$) is present over the whole field. Using the velocity field of the [NII] emission line, we showed that this is consistent with gas rotating in the large-scale disk of the galaxy, however velocity residuals show an excess of blueshifted velocities in an elongated fan-shaped pattern extending south-east and with its apex located at the AGN. This feature is directly visible in the velocity maps for [OI] and [SII], it corresponds to a sharp
increase in the electron density (from approximately 150 to 500 cm$^{-3}$), it is mostly confined within the region photoionized by the AGN ([NII]/H$\alpha > 0.6$), and it is spatially coincident with the extended fan-shaped [OIII] emission mapped in previous studies (e.g. Edmunds et al. 1988, Storchi-Bergmann and Bonatto 1991, Kristen et al. 1997). In agreement with previous authors, we interpret this as evidence for a biconical outflow (the counterpart being observable only at larger radii, outside the FOV probed by our observation).

Near the southern edge of the conical feature described above, we see evidence for line splitting. This was previously observed, at larger radii, but along the same direction, by other authors and it was interpreted as emission coming from gas outflowing along the walls of a hollow cone (e.g. Phillips et al. 1983, Edmunds et al. 1988, Jorsater et al. 1984, Hjelm and Lindblad 1996). To the best of my knowledge, this is the first time that the features described above have been observed on these scales and in low-ionization species.

With its prominent kpc-scale bar, NGC 1365 is considered an archetypal barred galaxy. Bars are amongst those non-axisymmetric distortions in the gravitational potential of the galaxy which are able to funnel gas from kpc-scales down to a few hundreds of parsecs from the nucleus (Section 1.3.1). It is therefore natural to look for evidence for gas inflows. We do not, in fact, find any obvious kinematical signature of inflow. However, we find evidence for a puzzling spectral feature which could be related to such inflows: an asymmetry in the base of the emission lines which is blueshifted south-west of the nucleus, and redshifted north-west. Unfortunately its interpretation remains unclear.

6.2.3 The energy budget of AGN feedback

As stated above, simulations suggest that AGN feedback has important effects on galaxy evolution (e.g. Di Matteo et al. 2005). It is usually assumed that 0.5% of the accreted rest mass energy is available for AGN feedback. However, this parameter is poorly constrained by observations. For example, in a sample of six galaxies, Müller-Sánchez et al. (2011) estimated that the ratio between outflow kinetic power and AGN bolometric luminosity (a proxy for the SBH accretion rate) ranges between $10^{-4}$ and 0.05.
6.2 Gas kinematics

Despite the complexity of NGC 1386, this galaxy offers an ideal scenario to estimate this fraction. This is because the outflowing gas is associated with a spectral component which is fairly well separated from the one due to gas rotation – at least according to our interpretation. For NGC 1365 the same approach is not possible, as the outflowing gas component is not as evident as in NGC 1386, and it is revealed only in the velocity residuals obtained after the removal of a velocity field representing gas rotating in circular orbits.

In Section 4.6.2, I used the \( H_\alpha \) luminosity to estimate the mass outflow rate in NGC 1386, obtaining \( \dot{M}_{\text{out}} \sim 0.1 \, M_\odot \, \text{yr}^{-1} \). This turns out to be approximately 300 times larger than the SBH mass accretion rate necessary to sustain the bolometric luminosity estimated from the [OIII] emission. Similar results have been obtained, for other galaxies, by Veilleux et al. (2005), Storchi-Bergmann et al. (2010), and Müller-Sánchez et al. (2011), who found mass outflow rates as large as \( 10^2 - 10^3 \) times the SBH accretion rate. If we estimate the kinetic power associated with the outflowing gas as \( \dot{E}_{\text{out}} = 1/2 \dot{M}_{\text{out}} (v^2 + 3\sigma^2) \), with \( v = 250 \, \text{km s}^{-1} \) and \( \sigma = 200 \, \text{km s}^{-1} \) as, respectively, the average velocity and velocity dispersion of the outflowing gas, we obtain \( \dot{E}_{\text{out}} \approx 1.33 \times 10^{40} \, \text{erg s}^{-1} \). The bolometric luminosity of NGC 1386, as estimated in Section 4.6.2, is \( L_{\text{bol}} = 1.8 \times 10^{42} \, \text{erg s}^{-1} \). This implies that, for NGC 1386, the kinetic power of the outflow amounts to approximately 0.7% of the bolometric luminosity. Considering that this is an order of magnitude estimate, the result is consistent with the value commonly adopted in the simulations.

6.2.4 The structure of active nuclei

The essential constituents of active galactic nuclei are an SBH, an accretion disk, the broad line region (BLR), an equatorial obscuring medium (the torus), and the narrow line region (NLR). In this section I will review what we learnt about some of these elements from our study of NGC 1386 and NGC 1365.

\[ ^1 \text{For comparison, note that Müller-Sánchez et al. (2011) computes the kinetic power as} \dot{E}_{\text{out}} = 1/2 \dot{M}_{\text{out}} (v^2 + \sigma^2) \text{ which, for NGC 1386, produces} \dot{E}/L_{\text{bol}} = 0.2\%. \]
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6.2.4.1 The torus

In Section 1.2, I outlined our current understanding of the obscuring torus in AGNs. The current general consensus is that this is a clumpy distribution of dusty clouds with cylindrical symmetry and reflection symmetry with respect to the equatorial plane; the inner edge is defined by the dust sublimation radius and is, therefore, dependent on the luminosity of the AGN. Near-IR reverberation mapping studies have so far produced values in the range 0.01 - 1 pc (e.g. Oknyanskij and Horne, 2001; Minezaki et al., 2004; Koshida et al., 2014). The outer radius is not so well defined. What can we infer about the torus in NGC 1386 and NGC 1365?

Existence. Although the torus is a standard constituent of the AGN unification model, its presence should not be taken for granted. Some models, e.g. Elitzur and Shlosman (2006), predict that it is only present above a certain threshold luminosity. Let’s therefore open this discussion by asking whether there is any evidence for the presence of a torus in the nuclei of NGC 1386 and NGC 1365.

NGC 1386 is a Seyfert 2 galaxy; according to the AGN unification model this means that the nucleus (the accretion disk around the SBH) is hidden from the observer at optical wavelengths, as the line of sight intercepts the torus. If a torus is indeed present, then the AGN radiation is expected to escape along the torus axis of symmetry generating a bi-polar illumination pattern. This is clearly observed in the flux maps presented in Section 4.4.3. These maps also show bright unresolved emission at the nucleus. How do we reconcile the presence of this emission with a torus? HST imaging shows that the emission is resolved in two knots separated by \( \approx 0.5 \) (38 pc, Ferruit et al., 2000). It is likely that these are clouds located along the torus axis and directly illuminated by the AGN. In summary, the flux features observed in NGC 1386 can be understood in terms of a geometrical model in which a torus with an opening angle of 34\(^\circ\), with the axis oriented at approximately 76\(^\circ\) with respect to the line of sight, intercepts the galaxy disk at an angle of about 38\(^\circ\) (Fig. 4.17).

NGC 1365 is a Seyfert 1 galaxy; according to the AGN unification model this means that the SBH accretion disk is directly observable, therefore the torus axis is inclined at a small or intermediate angle with respect to the line of sight. In this case the flux morphology can be both approximately
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circular (if the AGN is viewed face on), or bipolar (if the AGN is viewed at intermediate inclinations). Our observations reveal blueshifted velocity residuals and enhancement in the electron density in a fan-shaped region with the apex at the nucleus. These features are also located within the fan-shaped emission observed in [OIII] by previous authors (e.g. Storchi-Bergmann and Bonatto, 1991). Together with the presence of a counter-cone, observed by other authors at distances larger than those probed by our observations, these features do suggest that a torus is indeed present.

A promising approach in the modeling of the torus is one in which the torus consists of dusty clouds that are outflowing within a hydromagnetic wind (e.g. Elitzur and Shlosman, 2006, and references therein). As anticipated at the beginning of this section, such models predict that the torus forms at bolometric luminosities larger than $L_{\text{bol}} \sim 10^{42} \text{ erg s}^{-1} \text{ cm}^{-2}$. There is some observational support for this prediction (e.g. Chiaberge et al., 1999; Whysong and Antonucci, 2004; Maoz et al., 2005). How do the results presented here compare with this prediction? The bolometric luminosity of NGC 1365 is $L_{\text{bol}} \sim 10^{44} \text{ erg s}^{-1}$ (Vasudevan et al., 2010) and observations are consistent with the presence of a torus, as predicted. The bolometric luminosity for NGC 1386 is $L_{\text{bol}} \sim 10^{42} \text{ erg s}^{-1}$ (Section 4.6.2.1), corresponding to the transition threshold. This object, therefore, does not provide a “clean” test of the model. At any rate, as stated above, the features observed in NGC 1386 are consistent with the presence of a torus, suggesting therefore that tori can still be formed at $L_{\text{bol}} \sim 10^{42} \text{ erg s}^{-1}$.

**Morphology.** What can we infer about the torus morphology? Our analysis of NGC 1386 suggests that the torus is clumpy. We found that the emission line ratios are consistent, over the whole FOV, with AGN photoionization. This suggests that, if a torus is present, then it must be “leaky”; in other words, it must be made of clumps which allow the escape of photons even in the direction perpendicular to the torus axis.

To explain the features observed in the flux of NGC 1386 we proposed a configuration where the AGN is inclined at an angle with respect to the galactic disk. This allowed us to estimate the inclination and opening angle of the torus obtaining $38^\circ$ for the angle between the torus axis and the galactic disk, $76^\circ$ for the inclination with respect to the line of sight, and $34^\circ$ for the half opening angle. These values are not strongly constrained.
by our data, for example they depend on the assumed thickness of the
galactic disk. However, a very similar value for the half-opening angle was
recently obtained by Brightman et al. (2015), based on modeling of the
X-ray spectrum.

In NGC 1365 the scenario is complicated by the presence of intense
star-formation producing line ratios typical of star-forming regions even at
the very nucleus of the galaxy where the AGN is expected to dominate.
Nevertheless, we measure line ratios typical of AGN photoionization 2″ (152
pc) east of the nucleus (within the fan-shaped region where we identify
the outflow) and we measure line ratios typical of stellar photoionization 2″
west of the nucleus; this second region should correspond to the counter-cone
which, however, would be behind the galaxy disk. This dichotomy suggests
that a torus is present, shielding certain regions from the AGN ionizing
radiation. The fact that line ratios characteristic of AGN photoionization
are confined to the outflow region could imply that the torus in NGC 1365
is less clumpy than the torus in NGC 1386; however, unlike the nucleus of
NGC 1386, the nucleus of NGC 1365 is densely populated by star forming
regions which give a major contribution to the radiation field. It is therefore
difficult to identify any torus leakage and to comment on its structure.

**Origin.** Several authors propose that the torus is a magnetically driven
wind (e.g. Konigl and Kartje 1994, Elitzur and Shlosman 2006, Wada
2012, Dorodnitsyn and Kallman 2012). HST imaging of NGC 1386 shows
the presence of an elongated faint emission-line structure approximately perp-
endicular to the AGN radiation cone extending about 2″ (152 pc) south-
east and north-west of the nucleus (Ferruit et al., 2000). Our analysis shows
that the same region corresponds to enhanced velocity dispersion, velocity
residuals suggestive of outflow and/or rotation, and line ratios typical of
AGN photoionization or shocks. It is therefore possible that we are indeed
observing the outer layers of the same wind which, at smaller radii, obscures
the AGN.

6.2.4.2 The narrow line region

Broadly speaking, the NLR is understood as a clumpy distribution of
clouds extending over scales in the range $\sim 10^2 - 10^3$ pc and photoionized
by the AGN; these clouds emit permitted and forbidden lines with typical
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FWHM ≈ 500 km s\(^{-1}\), their typical electron density and temperature are estimated to be respectively \(n_e \sim 10^2 - 10^4\) cm\(^{-3}\) and \(T \sim 10^4\) K (Osterbrock and Ferland, 2006). Being photoionized by the AGN, gas in the NLR often shows biconical or elongated morphologies (e.g. Mulchaey et al., 1996a,b; Schmitt et al., 2003a,b). The kinematics is often complex, displaying features suggestive of bipolar outflows and disturbed rotation (e.g. Müller-Sánchez et al., 2011).

It is commonly assumed that the NLR is traced by the emission of \([\text{OIII}] \lambda 5007\) and other species (such as H\(\alpha\) and \([\text{NII}] \lambda 6583\), e.g. Mulchaey et al. 1996a,b; Schmitt et al. 2003a,b). Following this custom, it is tempting to identify the NLR of NGC 1386 with the two extended lobes plus the nuclear emission. However, we showed that gas in the lobes is merely interstellar gas illuminated by the AGN and rotating in the galaxy disk. Despite its relatively small extension (approximately 230 pc each side of the nucleus) it seems more appropriate to consider the gas in the lobes to be part of the “extended narrow line region”, a component that Unger et al. (1987) defined as gas photoionized by the AGN at distances up to 20 kpc from the nucleus with a velocity field consistent with the galactic rotation and FWHM < 45 km s\(^{-1}\). We propose that the actual NLR of NGC 1386 consists of the compact bipolar outflow extending approximately 80 pc each side of the nucleus.

We suggest that a proper identification of the NLR requires not only imaging of the line emitting gas (typically \([\text{OIII}] \lambda 5007\) and H\(\alpha\)), but also a careful understanding of its kinematics. It is therefore likely that the actual NLR has been mis-identified in a number of galaxies. A better understanding of the processes of AGN feeding and feedback will be achieved by studying relations between the actual NLR and other components of galactic nuclei.

6.2.5 Concluding remarks and future directions

In this dissertation I presented a study of the 2D gas kinematics for the ionized gas in the inner kiloparsec of two nearby AGNs: NGC 1386 (Seyfert 2) and NGC 1365 (Seyfert 1). The two galaxies belong to the Fornax cluster, however they are non-interacting galaxies. Therefore the kinematics can be considered the result of secular evolution. I found that the kinematics can be explained by (1) a combination of gas rotating in the large-scale disk of the galaxies, (2) outflows with velocities of the order of 100 km s\(^{-1}\), and
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(3) perhaps inflows (along nuclear spirals in NGC 1386). In NGC 1386, where the outflowing gas was clearly identified with a well-defined spectral component, for the bipolar outflow I estimated a mass outflow rate of the order of $0.1 \, M_\odot \, yr^{-1}$. Kinematical and photometric features suggest the presence of an equatorial wind which may represent the outer regions of a torus-forming wind.

These results are in agreement with the general picture emerging when other studies are taken into account (e.g. Knapen et al., 2000; Fathi et al., 2006; Storchi-Bergmann et al., 2007; Riffel et al., 2008; Müller-Sánchez et al., 2009; Davies et al., 2009; Müller-Sánchez et al., 2011; Riffel and Storchi-Bergmann, 2011; Schnorr, Müller et al., 2011; Riffel et al., 2013; Combes et al., 2014; Davies et al., 2014; Schnorr-Müller et al., 2014a,b). These studies show that the gas kinematics in the inner kiloparsec of Seyfert galaxies can usually be interpreted as a combination of rotation, inflows and outflows. Mass inflow and outflow rates are estimated to be in the range $0.1 - 1 \, M_\odot \, yr^{-1}$ (yet these numbers are affected by large uncertainties), with typical outflow velocities of few $100 \, km \, s^{-1}$. A range of morphologies have been inferred for the outflows: bipolar, quasi-spherical, and even equatorial, that is perpendicular to the axis of the radio jet or to the axis of the AGN radiation cone. Inflows have been claimed along nuclear dusty spirals and bars.

Although we understand some aspects of the kinematics, it must be acknowledged that the detailed picture (regarding, for example, the morphology of these compact inflows and outflows) is not free of confusion and ambiguities: spectral and photometric features are often complex, unresolved or only partially resolved, with the interpretation being model-dependent and not-unique. Certainly, a sharper picture will emerge with extensive observations with recent and future instruments such as ALMA, MUSE, JWST, and the forthcoming generation of ground-based extremely large telescopes. Probing the gas kinematics over scales of 1 - 10 pc will soon become routine. In the mean time, as I have shown here, there is still much to be learned from the wealth of data delivered by the current facilities.


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