Active Galactic Nuclei Feedback and Galactic Outflows

Ai-Lei Sun

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For my mom Jane and in memory of my dad Abel.

獻給我的父母孫實慶與韋素珍
Abstract

Feedback from active galactic nuclei (AGN) is thought to regulate the growth of supermassive black holes (SMBHs) and galaxies. The most direct evidence of AGN feedback is probably galactic outflows. This thesis addresses the link between SMBHs and their host galaxies from four different observational perspectives. First, I study the local correlation between black hole mass and the galactic halo potential (the $M_{\text{BH}} - V_c$ relation) based on Very Large Array (VLA) HI observations of galaxy rotation curves. Although there is a correlation, it is no tighter than the well-studied $M_{\text{BH}} - \sigma_*$ relation between the black hole mass and the potential of the galactic bulge, indicating that physical processes, such as feedback, could link the evolution of the black hole to the baryons in the bulge. In what follows, I thus search for galactic outflows as direct evidence of AGN feedback. Second, I use the Atacama Large Millimeter Array (ALMA) to observe a luminous obscured AGN that hosts an ionized galactic outflow and find a compact but massive molecular outflow that can potentially quench the star formation in $10^6$ years. The third study extends the sample of known ionized outflows with new Magellan long-slit observations of 12 luminous obscured AGN. I find that most luminous obscured AGN ($L_{\text{bol}} > 10^{46}$ ergs s$^{-1}$) host ionized outflows on 10 kpc scales, and the size of the outflow correlates strongly with the luminosity of the AGN. Lastly, to capitalize on the power of modern photometric surveys, I experiment with a new broadband imaging technique to study the morphology of AGN emission line regions and outflows. With images from the Sloan Digital Sky Survey (SDSS), this method successfully constructs images of the [O III]$\lambda$5007 emission line and reveals hundreds of extended emission line systems. When applied to current and future surveys, such as the Large Synoptic Survey Telescope (LSST), this technique could open a new parameter space for the study of AGN outflows. In summary, through multi-phase and multi-scale galactic outflows, AGN feedback can link the growth of SMBHs with the evolution of galaxies.
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Preface

This thesis is organized into five chapters and is based on three first author papers that have been accepted or submitted to The Astrophysical Journal and one project report. Chapter 1 is an introduction of the general topic. Chapter 2 and 3 are each based on one published paper. Chapter 4 is based on a submitted paper. Chapter 5 is a report on a project that has not been published. All of these works are completed under the guidance of my advisor Jenny Greene and with the support from many of my collaborators, including Nadia Zakamska, Nicole Nesvadba, Violette Impellizzeri, Cheng-Yu Kuo, James Braatz, and Sarah Tuttle.

Some of the research from this thesis has been presented at a series of conferences, including

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4. Dec 2014, Revolution in Astronomy with ALMA - The 3rd Year, Tokyo, Japan
5. Nov 2013, Workshop on AGN and Starburst-driven Outflows, Johns Hopkins, Baltimore, MA
6. Mar 2013, SnowPAC 2013 Black Hole Fingerprints: Dynamics, Disruptions and Demographics, Salt Lake City, UT

Chapter 2

In this chapter, I present Very Large Array (VLA) H I observations of the rotation curve for five nearby galaxies. This is to study the link between supermassive black holes and their host galaxies. With an up-to-date list of nearby galaxies with both dynamical measurements of black
hole masses and spatially-resolved rotational velocity, I compare the two correlations, $M_{\text{BH}} - \sigma_*$ and $M_{\text{BH}} - V_c$, and discuss the implications on black hole - galaxy coevolution. This project is my first semester project in Princeton and is later published in Sun et al. (2013).

Chapter 3

In this chapter, I present Atacama Large Millimeter/Submillimeter Array (ALMA) CO (1-0) and CO (3-2) observations of SDSS J1356+1026, a luminous obscured quasar driving 10-kpc scale ionized outflows (Greene et al., 2012, 2014). The goal of the observation is to look for evidence of AGN feedback in the form of molecular outflows. We find disturbed kinematics in CO that is indicative of outflows and discuss its energetics and the implication to the long-term evolution of the galaxy. This chapter is entirely based on the publication Sun et al. (2014).

Chapter 4

In this chapter, I present Magellan IMACS long-slit spectroscopy of 12 luminous nearby type 2 AGN at similar redshifts and luminosities as SDSS J1356+1026 discussed in Chapter 3. This project is inspired by the discovery of 10-kpc scaled ionized outflows among luminous AGN (Greene et al., 2011; Liu et al., 2013; Harrison et al., 2014). Combining our data with the sample by (Liu et al., 2013), I constrain the occurrence rate and the size distribution of these ionized outflows over a range of AGN luminosity. This work is submitted to The Astrophysical Journal.

Chapter 5

In this chapter, I experiment on a new technique to image AGN emission line regions with photometric data from the Sloan Digital Sky Survey (SDSS). This is an attempt to increase the sample size of AGN extended emission line regions and ionized outflows capitalizing on the large area covered by current and future surveys, e.g. the Subaru HyperSuprime Camera (HSC) survey and the Large Synoptic Survey Telescope (LSST). I present preliminary results and discuss the future possibilities of this technique to open a new parameter space for AGN feedback studies. This work is not published.
Bibliography


Contents

Abstract iv

Acknowledgments v

Preface vii

Bibliography ix

1 Introduction 1

1 Indirect Evidence of AGN Feedback 2

2 Modes and Phases of AGN Feedback 4

3 Combining Observations and Theories 6

Bibliography 8

2 Refining the $M_{BH} - V_c$ Scaling Relation with HI Rotation Curves 13

1 Introduction 14

2 HI Observations 16

3 Analysis 18

3.1 Non-parametric Moment-0 and Moment-1 Maps 20

3.2 Parametric Fitted Velocity Fields 23

3.3 Rotation Curves 26

4 $M_{BH} - V_c$ Relation 28

4.1 The Sample 28

4.2 Fitting Method 36

4.3 Fitting Results 37

4.4 Comparison with the Literature 39
Introduction

Since the discovery of the supermassive black hole (SMBH) at the center of our Milky Way (Eckart & Genzel, 1997; Ghez et al., 1998), astronomers have come to realize that black holes are not only a common constituent of the universe (Kormendy & Gebhardt, 2001) but can also play an important role in the evolution of galaxies. The hypothesis that SMBH regulate the growth of their host galaxies is motivated by several puzzles in galaxy evolution, including the need for a physical mechanism to quench the star formation in high mass galaxies (e.g., Thomas et al., 2005), and the observed tight correlation between the mass of the black hole and the galaxy potential (e.g., Gebhardt et al., 2000; Ferrarese & Merritt, 2000). The mass accretion on to supermassive black holes is a natural source of energy to explain these phenomena. The term Active Galactic Nuclei (AGN) Feedback encapsulates the entire range of impacts that growing black holes can have on their host galaxies. Recent developments from both the theoretical and observational side further highlight the importance of AGN feedback. Simulations have established that AGN feedback can quench star formation and explain the red sequence (e.g., Croton et al., 2006; Bower et al., 2006). Observations have also revealed cases where the AGN drives massive galactic outflows that could potentially expel the galactic gas reservoir (e.g., Greene et al., 2011; Veilleux et al., 2013).

However, as AGN feedback is a very complex phenomenon, much of its details and the effect on galaxies remain unknown. In order to build a self-consistent model of galaxy evolution, we need to understand how outflows are driven, how they interact with galaxies, and how common they are. In this thesis, I present four observational studies that look at AGN feedback from four different perspectives. This chapter provides a general introduction.


1 Indirect Evidence of AGN Feedback

Star formation and the growth of supermassive black holes are the two major activities that govern the evolution of galaxies. They both are transformations of gas, mostly in dense and cold forms, into compact objects that could release gravitational or nuclear energy. The energy so released, in the form of radiation, supernova explosions, or AGN winds, can in turn impact the reservoir of cold gas that the star formation and AGN feeds on. These mechanisms in principal create a feedback loop that could potentially regulate themselves. Moreover, the formation of stars and the growth of black holes are tied together through their mutual interactions with the galactic interstellar medium.

Unsurprisingly, star formation and AGN activity have similar cosmological histories that peak at around $z \approx 2$, the time when galaxies received much more cold gas supply than they do today (see review by Madau & Dickinson, 2014). The first piece of indirect evidence for the link between galaxy and black hole growth is inefficient star formation, especially in massive galaxies. Observations of local galaxies find that the star formation rate is only about 1% of what we would expect from the dynamical time of the molecular clouds and the amount of cold gas available (see review by Kennicutt & Evans, 2012). Integrated over cosmic time, this inefficient star formation is especially severe in low- and high-mass halos, as suggested by the discrepancy between the stellar mass function and the halo mass function at these extremes (see review by Somerville & Davé, 2015). Part of this discrepancy can be explained by star formation feedback. In particular, in low mass galaxies, supernova explosions, that shock and remove the gas in their vicinity, are thought to be capable of suppressing star formation (Mac Low & Ferrara, 1999; Kauffmann et al., 2003). But supernova or any other type of stellar feedback is not energetic enough to expel gas from the deep potential of massive galaxies. Active galactic nuclei, on the other hand, release energy of about $\sim 0.1m_{\text{BH}}c^2$ over their lifetimes, that is a factor of 10 to 100 than enough to unbind the entire galaxy ($m_{\text{gal}}\sigma_\star^2$). This makes AGN a natural candidate to explain the suppressed star formation in massive, especially elliptical, galaxies. Also, massive elliptical galaxies tend to have an early but short episode of star formation as indicated by the $[\alpha/\text{Fe}]$ abundance ratio (Thomas et al., 2005), that could be due to a violent quenching event by a bursty AGN.
Chapter 1: Introduction

The second piece of evidence is that the black hole masses are found to be tightly correlated with the properties of their host galaxies (for a recent review see Kormendy & Ho, 2013). The best-understood correlation is the one between the black hole mass and the stellar velocity dispersion of the host galaxy ($M_{\text{BH}} - \sigma_*$, Ferrarese & Merritt, 2000; Gebhardt et al., 2000; Tremaine et al., 2002; Gültekin et al., 2011; McConnell & Ma, 2013) which has a small scatter of $\sim 0.3$ dex over three orders of magnitude in the black hole masses. This may be a surprising result at first glance, as the black hole is a negligible part of the galaxy, accounting for only $\sim 0.1\%$ of its mass, but the correlation was actually predicted based on the expectations of AGN feedback even before its observational discovery (Silk & Rees, 1998). The idea is that if the power of the AGN feedback is proportional to the black hole mass, as one would expect from Eddington limit arguments, then overly massive black holes are powerful enough to drive outflows that can escape the galactic potential, stopping the further growth of the black hole itself. This sets an upper limit on the black hole mass based on the surrounding galactic potential, and the observed values lie close to this predicted relation.

There are other theories that attempt to explain the scaling relations without the presence of feedback. For example, theories that involve collisional dark matter particles (Ostriker, 2000), assume an isothermal sphere as the black hole progenitor (Adams et al., 2001), or consider stars captured by the AGN accretion disk (Miralda-Escude & Kollmeier, 2005) have been proposed. Cen (2015) suggests that the scaling relations could arise from the proportional distribution of the cold gas supply to the black hole and the stellar component. Peng (2007), Jahnke & Macciò (2011), and Kulier et al. (2015) suggest that a correlation with the dark matter halo would arise naturally after a large number of mergers based on the central limit theorem. The importance of the dark matter halo in shaping the scaling relations is also emphasized in some of the feedback simulation work (Booth & Schaye, 2010). To test the predictions of the merger scenario, we revisit the relation between the black hole masses and their galactic halos in Chapter 2.

The black hole scaling relations are still under active research. Recent studies have found that the tight $M_{\text{BH}} - \sigma_*$ relation for normal galaxies may not hold for the lower-mass megamaser galaxies (Greene et al., 2010; Läsker et al., 2016), and elliptical and spiral galaxies may follow slightly different paths on the scaling relations (McConnell & Ma, 2013). These details are crucial
to understand not only the seeding of the black holes and the growth history of the black holes, but also the interactions between black holes and their host galaxies. Advances in observational techniques, including with the Atacama Large Millimeter/submillimeter Array (ALMA) and the next-generation optical telescopes, such as the Thirty Meter Telescope (TMT), have the potential to extend the black hole mass measurements to a wider variety of galaxies (Do et al., 2014; Barth et al., 2016) to help us answering these important questions of black hole - galaxy connections.

2 Modes and Phases of AGN Feedback

AGN feedback can take various forms. One well-studied form of feedback is through powerful radio jets, referred to as radio-mode or maintenance-mode feedback in the literature. These highly collimated jets can penetrate the interstellar or the intergalactic medium on Mpc scales, and are thought to deposit their energy and keep the hot halo gas from cooling and forming stars (see review by McNamara & Nulsen, 2007). For a long time, this radio mode was also thought to be the major mode by which AGN disturb gas on galactic scales (see review by Veilleux et al., 2005). Very extended emission line regions were first found in radio loud galaxies (e.g., Stockton & MacKenty, 1987) and kpc-scale outflows are often associated with radio jets (e.g., Colbert et al., 1996). However, even if jets can entrain gas along its path, it is not clear that they can effectively expel the galactic gas reservoir and quench star formation given their narrow opening angle and low occurrence rate (10% among AGN). Also, it is not clear whether radio-mode feedback can explain the black hole scaling relations, as jets are often associated with AGN accreting at a low rate instead of close to the Eddington limit (see review by Heckman & Best, 2014).

Feedback from AGN radiation, referred to as the radiative mode or quasar mode feedback, provides another promising mechanism to regulate star formation. Observations of quasar broad absorption lines (BAL) (reviewed by Weymann et al., 1981), X-ray ultra fast outflows (e.g., Pounds et al., 2003), and simulations of AGN disk winds (e.g., Proga et al., 2000) have established that the intense radiation pressure in quasars is capable of driving high velocity winds ($\sim 0.1c$) through line opacity on sub-pc scales. Radiation pressure can also act on dust grains at larger scales beyond the dust sublimation radius ($R_{\text{subl}} \sim \text{pc}$). It is natural to speculate that such
a wind can work in a similar way as starburst-driven winds to drive wide-angle galactic outflows. But for a long time there was little observational evidence to support such AGN wind driven outflows on galactic scales.

Narrow emission lines from AGN ionized nebula, e.g., [O III]λ5007, [N II]λ6584, and Hα lines, are ideal for probing the impact of AGN on the galactic scales. For its strength and ubiquity, the [O III]λ5007 line is particularly common in spatially resolved spectroscopic studies to look for signs of AGN wind driven outflows. Low luminosity radio-quiet AGN exhibit few signs of disturbed kinematics on kpc scales. For luminous ULIRG AGN, although they may host ionized outflows, it is not clear whether those outflows are AGN or star formation driven (see review by Veilleux et al., 2005). The first robust evidence of galactic-scale ionized outflows driven by AGN winds appeared after the discovery of a population of luminous obscured type 2 AGN with the SDSS (Zakamska et al., 2003; Reyes et al., 2008). The occultation of the bright nucleus makes it much easier to see the fainter emission lines throughout the galaxy. With long-slit spectroscopy, Greene et al. (2011, 2012) found that SDSS J1356+1026, a radio quiet type 2 AGN with very high bolometric luminosity ($L_{\text{bol}} \sim 10^{46}$ ergs s$^{-1}$), hosts a spectacular 20 kpc-scaled outflow with a deprojected velocity of $\sim 1000$ km s$^{-1}$ capable of escaping the galaxy. This prototypical object will be discussed in more detail in Chapter 3. After this discovery, a number of IFU studies, including Liu et al. (2013); Harrison et al. (2014); McElroy et al. (2014); Karouzos et al. (2016), further found that kpc-scale outflows seem to be ubiquitous among luminous type 2 AGN, providing compelling evidence that quasar mode feedback can be effective at perturbing, if not expelling, the interstellar medium on galactic scales. With ever larger spectroscopic coverage in the SDSS survey, the growing size of the type 2 AGN sample (Mullaney et al., 2013; Yuan et al., 2016) presents an excellent opportunity to study AGN feedback. Not only can we examine detailed outflow physics in the most extreme systems, but also we can survey the outflow demographics from Seyfert- to quasar-luminosity AGN. In Chapter 4, we present a new long-slit spectroscopy study of these type 2 AGN to investigate the dependence of outflow properties on the AGN luminosity.

The search for AGN-driven outflows is not limited to optical emission lines. Using multi-wavelength observations astronomers have found that AGN outflows are very complex
phenomenon with multi-scaled (10 pc - 10 kpc) and multi-phased (10 K - 10^7 K) structures (see review by Fabian, 2012). While the warm ionized gas phase (10^4 K) has been the easiest to observe, the hot X-ray emitting wind fluid (10^7 K) is likely the momentum carrying piston, and the cold molecules (10^{1-2} K) probably dominate the mass load. In particular, as stars form in dense molecular clouds, it is important to understand how the molecular gas reacts to the intense radiation and wind from the AGN.

With the far-infrared spectroscopy provided by *Herschel*, Veilleux et al. (2013) finds ubiquitous blue-shifted OH absorption lines in ULIRG AGN, suggesting the presence of common and wide-angled molecular outflows. Although it is not trivial to infer the outflow size and thus the mass outflow rate from absorption line studies, the comparison with radiative transfer models suggests that these outflows are ~ 100 pc in size with high mass outflow rates of hundreds of $M_\odot$/yr (Sturm et al., 2011). Molecular emission lines at sub-mm wavelengths, such as CO and HCN, provide a complimentary method to directly image and constrain the sizes of the outflows. With IRAM PdBI CO spatially resolved observations, Cicone et al. (2014) compiled a sample of 19 nearby luminous ULIRG AGN and find outflow properties broadly consistent with the OH observations, although in this case the mass estimate is affected by the uncertain mass conversion factor $X_{\text{CO}} = M_{\text{mol}}/L_{\text{CO}}$. Recently, the unprecedented resolution and sensitivity offered by ALMA makes it possible to resolve small-scale outflows in nearby AGN (e.g., 10 pc at NGC 1068, Garcia-Burillo et al., 2014) or detect outflows at high redshift ($z = 6$, Cicone et al., 2015). It is important to apply these new capabilities of ALMA to the luminous type 2 AGN sample to learn about the interplay between the AGN wind, ionized outflows, and the molecular reservoir in these extreme AGN feedback systems. In Chapter 3, we present a new ALMA study on the type 2 AGN outflow prototype SDSS J1356+1026.

### 3 Combining Observations and Theories

Observations have certain limitations. The tracer used at various wavelengths, e.g., [O III] or CO lines, can only probe certain phases of gas, and the total energetics can be very uncertain because of outflow masses are in general hard to measure. Also, observations only capture a snapshot of
Chapter 1: Introduction

the event. How to link these instantaneous outflows to the star formation rate history on Gyr
time scales is unclear. At the same time, AGN feedback is also invoked to explain an even wider
range of phenomena, including the metallicity enrichment of the inter-cluster medium (e.g.,
Fabjan et al., 2010), and the flattening of the dark matter halo core (e.g., Kormendy et al., 2009).
We need theoretical understanding to link the microscopic physics of outflow propagation to the
macroscopic effects on galaxy evolution, in order to have a complete picture of AGN feedback.
Modern simulations of galaxy evolution have successfully reproduced the quenching of star
formation by including AGN feedback (e.g., Springel et al., 2005; Di Matteo et al., 2005; Choi
et al., 2015), and simultaneously raised more questions on the details of the feedback processes.

AGN feedback is often treated with sub-grid physics – for example, by assigning a certain
fraction of the AGN radiated energy or momentum to nearby gas particles/grids (see review by
Somerville & Davé, 2015). This approach requires parameter tuning that is not necessarily
physically motivated and does not capture important processes in feedback. Without realistic
AGN feedback models, fine-tuned modern cosmological simulations, such as the Illustris
simulation, still deviates from observations in the number of high-z AGN predicted (Sijacki et al.,
2015).

The first important question that needs to be answered is whether the energy from AGN winds
is delivered to large scale outflows or is lost through radiative cooling, which determines the
efficiency of the feedback. In the momentum-conserving limit, where the energy is lost through
radiation, the outflows can barely escape the nucleus, whereas in the energy-conserving limit,
most of the wind energy is transferred to the outflow that helps it to propagate to $\sim 10$ kpc in size
(King & Pounds, 2014). Tombesi et al. (2015) combines X-ray and OH molecular line
observations to support the energy-conserving scenario in the case of a ULIRG AGN, but more
observations are needed to examine if outflows experience a transition between the momentum-
and energy-conserving phase, as suggested by King (2005). The second question is to understand
how these molecular clouds survive (or not) in the presence of feedback. One would expect that
the strong shocks, radiation, and Rayleigh-Taylor instabilities could easily destroy molecular
clouds, raising questions about how to form the observed massive molecular outflows. Third, to
calibrate different outflow models, we would like to compare the observations and theory
predictions of the outflow sizes and energetics, ideally over a large range of AGN luminosities and host galaxy properties. Such an observational data set does not yet exist. In Chapter 5, I test a new photometric technique to find and characterize outflows over large samples provided by current and future large photometric surveys.

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Chapter 2

Refining the $M_{\text{BH}} - V_c$ Scaling Relation with HI Rotation Curves

abstract

Black hole - galaxy scaling relations provide information about the coevolution of supermassive black holes and their host galaxies. We compare the black hole mass - circular velocity ($M_{\text{BH}} - V_c$) relation with the black hole mass - bulge stellar velocity dispersion ($M_{\text{BH}} - \sigma_*$) relation, to see whether the scaling relations can passively emerge from a large number of mergers, or require a physical mechanism, such as feedback from an active nucleus. We present VLA H I observations of five galaxies, including three water megamaser galaxies, to measure the circular velocity. Using twenty-two galaxies with dynamical $M_{\text{BH}}$ measurements and $V_c$ measurements extending to large radius, our best-fit $M_{\text{BH}} - V_c$ relation, $\log M_{\text{BH}} = \alpha + \beta \log(V_c/200 \text{ km s}^{-1})$, yields $\alpha = 7.43^{+0.13}_{-0.13}$, $\beta = 3.68^{+1.23}_{-1.20}$, and intrinsic scatter $\epsilon_{\text{int}} = 0.51^{+0.11}_{-0.09}$. The intrinsic scatter may well be higher than 0.51, as we take great care to ascribe conservatively large observational errors. We find comparable scatter in the $M_{\text{BH}} - \sigma_*$ relations, $\epsilon_{\text{int}} = 0.48^{+0.10}_{-0.08}$, while pure merging scenarios would likely result in a tighter scaling with the dark halo (as traced by $V_c$) than baryonic ($\sigma_*$) properties. Instead, feedback from the active nucleus may act on bulge scales to tighten the $M_{\text{BH}} - \sigma_*$ relation with respect to the $M_{\text{BH}} - V_c$ relation, as observed.
Chapter 2: Refining the $M_{\text{BH}} - V_c$ Scaling Relation with HI Rotation Curves

1 Introduction

The observed scaling relations between supermassive black hole (BH) mass and properties of the host galaxy, intensively studied over the past decade, suggest that black hole growth is tied to the growth of the surrounding host galaxy. These galaxy properties include the bulge/spheroid stellar velocity dispersion $\sigma_*$ (e.g., Ferrarese & Merritt, 2000; Tremaine et al., 2002; Gültekin et al., 2009; Beifiori et al., 2012; McConnell & Ma, 2013), the mass and luminosity of galaxy bulges (e.g., Marconi & Hunt, 2003; Häring & Rix, 2004; McConnell & Ma, 2013), and the circular velocity $V_c$ (e.g., Ferrarese, 2002; Kormendy & Bender, 2011; Beifiori et al., 2012), which is the rotation velocity measured at large radius to probe the dark matter halos potential. It is intriguing that these power-law relations, especially the $M_{\text{BH}} - \sigma_*$ relation, hold over several orders of magnitude in BH mass with small scatter, even though the black hole accounts for only a few thousandths of the mass of the galaxy (e.g., Häring & Rix, 2004).

There are a wide array of theories attempting to explain the BH-galaxy scaling relations (e.g., Silk & Rees, 1998; Ciotti & Ostriker, 2001; Murray et al., 2005; Hopkins et al., 2006; Peng, 2007). Two of the most popular models include variants of feedback from active galactic nuclei (AGN) and scenarios in which merging alone can lead to BH-galaxy scaling laws. In AGN feedback models, the central BH accretes mass and grows until it is massive enough to expel gas from the galaxy potential well and quench its own growth. BH growth in this picture is regulated by the depth of the galaxy potential well (Silk & Rees, 1998; Fabian, 1999; Di Matteo et al., 2005; Robertson et al., 2006). On the other hand, the pure merging scenario suggests that the correlation between linear quantities, for example the BH mass $M_{\text{BH}}$ and the halo mass $M_{\text{DM}}$, can emerge from a large number of mergers based on the central limit theorem, even without a physical mechanism linking the two (Peng, 2007; Hirschmann et al., 2010a; Jahnke & Macciò, 2011).

Although both the feedback and merging phenomena may occur in galaxy evolution, it is unclear whether either of the mechanisms is essential in establishing the scaling relations. The most important physical scale for feedback is also a matter of debate (Booth & Schaye, 2010a; Debuhr et al., 2010). Furthermore, we do not know how the AGN output couples to the gas,
Chapter 2: Refining the $M_{\text{BH}} - V_c$ Scaling Relation with HI Rotation Curves

whether via thermal energy (Silk & Rees, 1998) or momentum (Ostriker et al., 2010), nor do we know the average efficiency of the feedback.

Therefore, empirical evidence that distinguishes the relative importance of different physical processes in establishing the scaling relations is key to constructing the coevolution history of black holes and galaxies. In this paper, we investigate the origin of BH-galaxy scaling relations by comparing the $M_{\text{BH}} - V_c$ relation to the $M_{\text{BH}} - \sigma_*$ relation. Circular velocity $V_c$ is a good indicator of dark matter halo mass, and velocity dispersion $\sigma_*$ serves as its counterpart on bulge scales. While some AGN feedback scenarios (e.g., Debuhr et al., 2010) suggest that BH mass will be most tightly linked to baryons (as opposed to dark matter), a pure merging scenario suggests that the $M_{\text{BH}} - M_{\text{DM}}$ (or $M_{\text{BH}} - V_c$) relation should be the cleanest and tightest relation, as it is free from the baryonic physics (e.g., star formation) that occurs during merging. Comparison of the two relations, especially their scatter, can help determine the mechanism that drives BH-galaxy coevolution (Ferrarese, 2002; Novak et al., 2006; Kormendy & Bender, 2011).

Ferrarese (2002) first proposed that BH mass may correlate with dark matter halo mass, based on the $M_{\text{BH}} - \sigma_*$ relation and the correlation between $\sigma_*$ and $V_c$. Later, a number of papers (Pizzella et al., 2005; Courteau et al., 2007; Ho, 2007) pointed out that the $\sigma_* - V_c$ relation depends on surface brightness, light concentration, and morphology, and suggested that the $M_{\text{BH}} - \sigma_*$ relation, not the $M_{\text{BH}} - V_c$ relation, is most fundamental. Kormendy & Bender (2011) compiled a sample of 25 galaxies with both dynamical BH mass measurements and $V_c$ from spatially resolved rotation curves. From this direct $M_{\text{BH}} - V_c$ correlation they concluded that the dark matter halo mass alone cannot determine the BH mass, given that the BH mass can range from $< 10^3 - 10^6 \, M_\odot$ at a circular velocity of 120 km s$^{-1}$ (for a different view see Volonteri et al., 2011). Beifiori et al. (2012) also found the scatter in the $M_{\text{BH}} - V_c$ relation to be about twice as large as that in the $M_{\text{BH}} - \sigma_*$ relation using a large sample of $M_{\text{BH}}$ upper limits from Hubble Space Telescope spectra (Beifiori et al., 2009) and $V_c$ from unresolved H I line-width measurements. For a comprehensive review, see Kormendy & Ho (2013).

In this work, we aim to refine the $M_{\text{BH}} - V_c$ statistics. We start with the most up-to-date galaxy sample with dynamically measured black hole masses, and study all of these that also have spatially resolved circular velocity measurements, predominantly disk galaxies observed with H I.
Chapter 2: Refining the $M_{\text{BH}} - V_c$ Scaling Relation with HI Rotation Curves

We present five new HI rotation curves measured with the Karl G. Jansky Very Large Array\(^1\) (VLA) during the Expanded Very Large Array (EVLA) construction period. Three of these galaxies have dynamical $M_{\text{BH}}$ measured from the kinematics of water megamasers in sub-pc disks (Reid et al., 2009; Greene et al., 2010; Kuo et al., 2011). With BH mass errors smaller than 11 percent, these megamaser measurements are especially useful in constraining the intrinsic scatter of the $M_{\text{BH}} - V_c$ relations. In total our sample contains thirty-three galaxies. We assign $V_c$ to all galaxies in a consistent way and investigate $V_c$ reliability as a function of the spatial extension of the rotation curve. Using only reliable $V_c$ measurements at large radius, we quantify the $M_{\text{BH}} - V_c$ correlation and compare it with the $M_{\text{BH}} - \sigma_*$ relation. We investigate whether $M_{\text{BH}}$ is correlated more tightly with $V_c$ or $\sigma_*$, to discriminate AGN feedback scenarios from those in which merging alone establishes the scaling relations.

2 HI Observations

We observed 5 spiral galaxies in HI with the VLA. The observations were taken in the L-band and the C configuration under project 10B–220 between October and December 2010 (for details see Table 2.1). The observations used dual circular polarizations and a single spectral window with 256 channels across the 4MHz (852 km s\(^{-1}\)) bandwidth, giving a channel width of 3.3 km s\(^{-1}\). Twenty-one edge channels on each side were flagged due to a higher noise level. Removing these channels did not affect our results since none of the sources had emission in these parts of the band. The full width at half power of the primary beam is 32', and the synthesized beam size ranges from 23'' to 52'' depending on the source declination and number of antennas used (Table 2.2).

The duration of each observation was 5 hours and the on-source time was $\sim 200$ minutes per source. During a track, the gain calibrator was observed for 3 – 6 minutes every 20 – 27 minutes, while the flux calibrator was observed once, for 15 – 23 minutes. The observations were carried out during the EVLA upgrade phase and some of the L-band receivers were not yet installed. For

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\(^1\)Operated by The National Radio Astronomy Observatory, a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.
the observations of NGC 1194, NGC 2748, and UGC 3789, four antennas were not in the array, three were missing during the NGC 7582 observations, and two during the NGC 2960 track. One additional antenna was flagged out of the data set for NGC 1194, NGC 2748, NGC 7582, and UGC 3789 for high noise levels. The total number of antennas used was between 22 and 25, as listed in Table 2.1. Radio Frequency Interference (RFI) was found in three observations, and the contaminated data were excluded, which accounts for only a few percent of the data.

Data calibration and image processing were carried out with the Common Astronomical Software Applications (CASA) package. Time averaging of 10 seconds and on-line flagging were applied before calibration. The amplitude loss due to time averaging is less than 1% according to the VLA Observational Status Summary. The antenna position correction, antenna-based delays, bandpass, phase gain, amplitude gain and flux scale calibrations were carried out consecutively. The minimum acceptable signal-to-noise ratio (SNR) for the bandpass and gain calibration tables were all set to 3. The bandpass solutions were solved for each channel, which gave stable solutions with amplitude variations $\lesssim 1\%$. The phase gain and amplitude gain were solved for each calibrator scan. Gain elevation curves were applied to correct for elevation-dependent amplitude gain due to antenna deformation. Data weighting was not used throughout the calibration process, since the VLA does not monitor system temperature. The two polarizations were calibrated separately and combined in the imaging process.

For the H I emission line analysis, the continuum was estimated from line-free channels with more than 20 channels on each side and subtracted in the $uv$ plane with the task $uvcontsub$. A constant continuum level was used for all galaxies but NGC 1194 and NGC 2960. In these two galaxies, an adapted linear spectrum was used in order to subtract a nearby bright source with an inclined spectrum. The nearby bright continuum sources were well-subtracted at this stage, and the contamination from their side-lobes was negligible.

For imaging we used the CASA task clean in velocity mode. This mode corrects for the doppler shift due to rotation of the Earth. In this process the channels were also regridded linearly into wider spectral bins - the image planes. The width of the image planes were chosen to be 10 km s$^{-1}$ for higher signal-to-noise (SNR) observations (NGC 2748 and NGC 7582), and 20 km s$^{-1}$ for lower SNR observations (NGC 1194, NGC 2960, and UGC 3789). The SNR ratios for
Chapter 2: Refining the $M_{BH} - V_c$ Scaling Relation with HI Rotation Curves

Table 2.1. VLA Observations

<table>
<thead>
<tr>
<th>Galaxy</th>
<th>Date (UTC)</th>
<th>Flux Cal.</th>
<th>Phase Cal.</th>
<th>$\Delta \theta$ (degrees)</th>
<th>$T_{total}$ (minutes)</th>
<th>$T_{scan}$ (minutes)</th>
<th>Antennas</th>
<th>RFI</th>
</tr>
</thead>
<tbody>
<tr>
<td>NGC 1194</td>
<td>2010 Oct 8</td>
<td>3C48</td>
<td>J0323+0534</td>
<td>8.3</td>
<td>212</td>
<td>26.6</td>
<td>22</td>
<td>Yes</td>
</tr>
<tr>
<td>NGC 2748</td>
<td>2010 Oct 10</td>
<td>3C147</td>
<td>J0841+7053</td>
<td>6.0</td>
<td>217</td>
<td>24.6</td>
<td>22</td>
<td>No</td>
</tr>
<tr>
<td>NGC 2960</td>
<td>2010 Nov 19</td>
<td>3C286</td>
<td>J0943−0819</td>
<td>11.9</td>
<td>210</td>
<td>26.3</td>
<td>25</td>
<td>Yes</td>
</tr>
<tr>
<td>NGC 7582</td>
<td>2010 Dec 4/5</td>
<td>3C48</td>
<td>J2326−4027</td>
<td>2.5</td>
<td>200</td>
<td>19.9</td>
<td>23</td>
<td>Yes</td>
</tr>
<tr>
<td>UGC 3789</td>
<td>2010 Oct 7</td>
<td>3C147</td>
<td>J0614+6046</td>
<td>8.2</td>
<td>198</td>
<td>22.0</td>
<td>22</td>
<td>No</td>
</tr>
</tbody>
</table>

Note. — Col. (1): Galaxy name. Col. (2): Observation date. Col. (3): The flux and bandpass calibrator. Col. (4): The phase calibrator. Col. (5): The angular separation between the source (galaxy) and the phase calibrator. Col. (6): Total on-source observation time. Col. (7): Average length of each source scan, which is the separation between two phase calibrator scans. Col. (8): Number of antennas used in the observation. Some antennas were not used because the L-band receiver was not yet installed or because the antenna had unstable or noisy data quality. Col. (9): Whether or not radio frequency interference (RFI) was found in the data. The RFI was visually inspected and flagged. After the flagging, there was negligible or minor contamination from RFI in the data cube. The most severe case was NGC 1194, where some faint elongated stripes parallel to the galaxy can be seen.

Each data cube, defined as the peak intensity per channel divided by the RMS noise, are listed in Table 2.2. For NGC 2748 and NGC 7582 we applied Briggs weighting with the parameter $robust$ set to 0.5, and natural weighting was applied for NGC 1194, NGC 2960, and UGC 3789. All images were cleaned to the $3 \sigma$ level. All velocities in this paper use the optical convention and the Local Standard of Rest Kinematic (LSRK) reference frame. Position angles (P.A.) in this paper are measured east of north.

3 Analysis

In this section we describe the procedures that we used to extract velocity fields from the HI data cubes and measure rotation curves and $V_c$. The HI properties of individual galaxies are discussed in Appendix 8.1.
Table 2.2. Image Quality

<table>
<thead>
<tr>
<th>Galaxy</th>
<th>Distance (Mpc)</th>
<th>Channel Width (km s(^{-1}))</th>
<th>Weighting</th>
<th>Noise (mJy beam(^{-1}))</th>
<th>Peak (mJy beam(^{-1}))</th>
<th>Beam FWHM (arcsec \times arcsec)</th>
<th>Beam P.A. (degrees)</th>
<th>SNR</th>
</tr>
</thead>
<tbody>
<tr>
<td>NGC 2748</td>
<td>24.9</td>
<td>10</td>
<td>Robust=0.5</td>
<td>0.58</td>
<td>21.98</td>
<td>19\times13</td>
<td>45</td>
<td>38</td>
</tr>
<tr>
<td>NGC 7582</td>
<td>22.3</td>
<td>10</td>
<td>Robust=0.5</td>
<td>0.81</td>
<td>18.99</td>
<td>52\times13</td>
<td>0</td>
<td>23</td>
</tr>
<tr>
<td>NGC 1194</td>
<td>55.5</td>
<td>20</td>
<td>Natural</td>
<td>0.41</td>
<td>5.80</td>
<td>23\times16</td>
<td>-2</td>
<td>14</td>
</tr>
<tr>
<td>NGC 2960</td>
<td>75.3</td>
<td>20</td>
<td>Natural</td>
<td>0.37</td>
<td>2.29</td>
<td>19\times18</td>
<td>-14</td>
<td>6</td>
</tr>
<tr>
<td>UGC 3789</td>
<td>48.4</td>
<td>20</td>
<td>Natural</td>
<td>0.58</td>
<td>3.42</td>
<td>25\times16</td>
<td>73</td>
<td>6</td>
</tr>
</tbody>
</table>

Note. — Col. (1): Galaxy name. Col. (2): Distance of the galaxy. For consistency, we adopt distances from McConnell & Ma (2013), which is used for \( M_{BH} \) measurements listed in Tab. 2.5. Col. (3): The binned channel (or image plane) width. The channel width of NGC 2748 and NGC 7582 are set to be smaller because of their higher signal-to-noise ratio. Col. (4): The imaging weighting method. Col. (5): The RMS noise level in each image plane measured in line-free channels. Col. (6): The peak intensity in the data cube. Col. (7): The clean beam full-width-half-maximum of the major and minor axes. Col. (8): The clean beam position angle. Col. (9): The signal-to-noise ratio, defined by the maximum intensity per channel divided by the RMS noise.
Chapter 2: Refining the $M_{\text{BH}} - V_c$ Scaling Relation with HI Rotation Curves

3.1 Non-parametric Moment-0 and Moment-1 Maps

Non-parametric integrated intensity moment-0 maps of the five galaxies are shown in the left columns of Figures 2.1 to 2.5. In order to improve the SNR, we used the CASA tool `image.moments`, which masked pixels with no signal in producing the moment maps. The masks were produced as follows: the data cube was first smoothed spatially over one beam and spectrally over two image planes (20 km s$^{-1}$ for NGC 2748 and NGC 7582; 40 km s$^{-1}$ for NGC 1194, NGC 2960, and UGC 3789). Then, pixels with smoothed intensity below a certain threshold were masked. The threshold was set to 3 $\sigma$ for NGC 2748, NGC 7582, and NGC 1194, and 2.5 $\sigma$ for NGC 2960 and UGC 3789, chosen to optimize the signal seen in the moment-0 maps.

Figure 2.1 Left: The NGC 2748 moment-0 map made by the CASA `image.moments` tool. The masking is described in §3.1. We mask out the pixels below 3 $\sigma$ in a map that is smoothed spatially and over two velocity channels (20 km s$^{-1}$). We then construct the moment-0 map from the original data using this mask. The ellipse in the bottom left corner represents the beam. Right: NGC 2748 Gaussian/Gauss-Hermite fitted velocity field. Velocity is in optical LSRK.
Figure 2.2 Left: The NGC 7582 moment-0 map. The masking is described in §3.1. We mask out the pixels below $3\sigma$ in a map that is smoothed spatially and over two velocity channels ($20\ \text{km s}^{-1}$). We then construct the moment-0 map from the original data using this mask. The ellipse in the bottom left corner represents the beam. Right: The NGC 7582 Gaussian/Gauss-Hermite fitted velocity field. The central region is masked because of the absorption feature.

Figure 2.3 Left: The NGC 1194 moment-0 map. The masking is described in §3.1. We mask out the pixels below $2.5\sigma$ in a map that is smoothed spatially and over two velocity channels ($40\ \text{km s}^{-1}$). We then construct the moment-0 map from the original data using this mask. The ellipse in the bottom left corner represents the beam size. Right: The NGC 1194 Gaussian/Gauss-Hermite fitted velocity field.
Chapter 2: Refining the $M_{BH} - V_c$ Scaling Relation with HI Rotation Curves

Figure 2.4 Left: The NGC 2960 moment-0 map. The masking is described in §3.1. We mask out the pixels below 2.5 $\sigma$ in a map that is smoothed spatially and over two velocity channels (40 km s$^{-1}$). We then construct the moment-0 map from the original data using this mask. The ellipse in the bottom left corner represents the beam. Right: The NGC 2960 Gaussian fitted velocity field.

Figure 2.5 Left: The UGC 3789 moment-0 map. The masking is described in §3.1. We mask out the pixels below 2.5 $\sigma$ in a map that is smoothed spatially and over two velocity channels (40 km s$^{-1}$). We then construct the moment-0 map from the original data using this mask. The ellipse in the bottom left corner represents the beam size. Right: The UGC 3789 Gaussian fitted velocity field.
3.2 Parametric Fitted Velocity Fields

To extract rotation curves from the HI data cube, it is conventional to fit a velocity-field model. The two-dimensional velocity-field model is parametrized by geometrical parameters and the rotation curve. Then, the model is fit to the two-dimensional velocity-field data derived from the 3-D data cube. To construct the velocity field, one assigns a representative velocity to each spectrum in the data cube. In the ideal case of a simple rotating disk with small random motions, the projected rotational velocity will correspond to the peak velocity in the spectrum. In practice, there are different ways to measure the velocity at each position, including the peak velocity, the intensity-weighted mean velocity, and parametrized fitting (e.g., Gaussian fitting, deBlok et al., 2008). We seek the velocity measure that can best recover the true projected rotation velocity in the case of finite resolution, sensitivity, disk warping and overlapping velocities along the line of sight.

Measuring the peak velocity is the most straightforward approach, but the measurement is sensitive to the noise. It may pick up a noise spike instead of the real signal when the SNR is low. Moreover, it is discretized to the velocity channel width, which is 10 or 20 km s$^{-1}$ in our case. The intensity-weighted mean (moment-1) velocity is less sensitive to the noise, but will be biased if the spectrum is not symmetric. For example, beam smearing will produce a wing towards the systemic velocity, causing the intensity-weighted mean velocity to be skewed towards lower values (see the left panel of Fig. 2.6).

Another alternative is parametrized fitting, such as with a Gaussian line profile. The Gaussian fit picks up the intensity peak if the line profile is symmetric, and it is not as sensitive to the noise as is the peak velocity, so Gaussian fitting is our preferred approach. However, at high SNR if the line shape is asymmetric, then the mean velocity of the best-fit Gaussian profile will be biased toward the wing (see the right panel of Figure 2.6). In this case, we can use a Gauss-Hermite expansion to capture the non-Gaussian line shape (van der Marel & Franx, 1993). For example,
the skewness asymmetry is taken into account using the third order Hermite polynomial $H_3(x)$

$$x : = \frac{v - \bar{v}}{\sigma},$$

$$f(x) = \frac{\gamma}{\sqrt{2\pi}\sigma} \exp\left[-\frac{1}{2} (x)^2 \right] [1 + h_3 H_3(x)],$$

$$H_3(x) = \frac{1}{\sqrt{6}} (2\sqrt{2}x^3 - 3\sqrt{2}x). \quad (2.1)$$

Here the skewness parameter $h_3$ quantifies the asymmetry of the line shape. The intensity-weighted mean velocity $v_{m,3}$ of this line shape $f(v)$ is calculated by van der Marel & Franx (1993) to be $v_{m,3} = \bar{v} + \sqrt{3}\sigma h_3$ to first order. Compared to a Gaussian, the mean velocity $v_{m,3}$ measured by Gauss-Hermite fitting is less biased towards the wing and closer to the peak, while compared to the peak velocity the Gauss-Hermite fit is also less sensitive to the noise. Differences in the velocity fields derived from these different methods and their effects on the resulting rotation curves are discussed in Appendix 8.2. We find that for high SNR data, the rotation curve derived from the moment-1 velocity field is systematically lower than from the Gaussian/Gauss-Hermite velocity field at the $\sim 15\%$ level, and that the peak-velocity produces noisy rotation curves for low SNR data.

Considering the advantages of Gaussian and Gauss-Hermite fitting, we utilized these two methods to construct the velocity field. In order to minimize contamination from noise, we applied the noise masking described in §3.1. We then performed a Markov Chain Monte Carlo (MCMC) fitting of a Gaussian line shape to the five H I data cubes. We assume the likelihood function of intensity is Gaussian, and the sigma of this Gaussian is a constant throughout the data cube. The sigma was measured from the RMS intensity of line-free channels in the cube.

For the three highest-SNR galaxies, i.e., NGC 2748, NGC 7582, and NGC 1194 (SNR > 14), there were regions along the major axis with high reduced-$\chi^2$ values, i.e., where the cumulative distribution function of $\chi^2$ is larger than 95 percent, indicating deviations of the line shape from a Gaussian, mostly because of the line asymmetry described above. To better capture the skewness of the line, we fitted these high $\chi^2$ spectra with a third-order Gauss-Hermite function. The final velocity fields of NGC 2748, NGC 7582, and NGC 1194 were constructed using a mixture of
Chapter 2: Refining the $M_{\text{BH}} - V_c$ Scaling Relation with HI Rotation Curves

Gaussian and Gauss-Hermite fitting. The lower SNR cubes of NGC 2960 and UGC 3789 (SNR $\sim$ 6) do not have enough SNR to show deviations from single Gaussians.

Higher-order deviations from the Gauss-Hermite line shape, such as the fourth-order kurtosis ($h_4$), still exist in smaller particular regions after using the third-order polynomial; along the major axis of the edge-on galaxy NGC 1194 the line-of-sight overlap is severe, and along the spiral arms in NGC 7582 the gas kinematics are complex. We did not apply higher-order fits as the inclusion of the $H_4$ polynomial would not change the mean velocity to the first order (van der Marel & Franx, 1993).

One advantage of the MCMC fitting is that the uncertainty in each fitted parameter can be estimated from the standard deviation of the probability distribution probed by the chain. The uncertainties in the velocities are especially useful. A large velocity uncertainty may indicate that the spectrum contains no emission line, only noise. We therefore performed a further masking to exclude pixels with velocity uncertainty larger than 80 km s$^{-1}$. The final velocity fields are shown in the right columns of Figures 2.1 to 2.5.

Figure 2.6 Comparison of different velocity assignments. The cyan vertical line is for peak velocity, green for moment-1 velocity, blue for the Gaussian fit, and red for the Gauss-Hermite fit. Dashed vertical lines are the fitting errors. Black horizontal lines show the zero and one sigma intensities. The spectrum on the left is from the NGC 7582 H I data cube, while the one on the right is from the NGC 1194 data cube.
Chapter 2: Refining the $M_{BH} - V_c$ Scaling Relation with HI Rotation Curves

3.3 Rotation Curves

Rotation curves are derived by fitting the velocity fields (§3.2) with a rotating disk model. This model consists of coplanar concentric rings, each with its own rotation velocity. The width of each ring is chosen to be $14''$, corresponding to the typical beam size. We do not use tilted-ring modeling, but we show in Appendix 8.2 that the rotation curves derived with a tilted ring analysis are consistent with those presented here.

The rotation-curve fitting was performed with the same MCMC method. We assume that the likelihood function of velocity is Gaussian, and use the velocity uncertainty estimated in §3.2, such that noisier pixels with larger velocity uncertainties are down-weighted naturally. We fit five geometrical parameters, the center $x_0, y_0$, the systemic velocity $v_{sys}$, the inclination $i$, and the position angle P.A., together with the rotation velocity, at each ring. These parameters describe the velocity-field model. For the megamaser galaxies (NGC 1194, NGC 2960, and UGC 3789) we fix the central positions $(x_0, y_0)$ to the VLBI maser positions, and we fit the kinematic center of NGC 2748 and NGC 7582 as free parameters. The $v_{sys}$, $i$, P.A., and rotation velocities are fitted as free parameters with the exceptions of the inclination in the case of NGC 2960 and UGC 3789, and the P.A. of UGC 3789, where these values cannot be constrained by the data. Therefore, we fix these three values to the HyperLeda values (Paturel et al., 2003), derived from the optical images. The best-fit geometrical parameters are listed in Table 2.3.

The best-fit rotation curves are plotted in Figure 2.7. Various error sources in the rotation curves are considered, including the fitting errors estimated by the standard deviation in the Markov chains, the RMS errors estimated by the RMS variation of the residuals in a ring, and the errors induced by uncertainties in inclination and P.A. It is commonly found that the formal fitting errors in the rotation curve fits are unrealistically small (e.g., deBlok et al., 2008), likely because the rotating disk model fails to capture features in the observed velocity field such that the residuals are non-Gaussian, causing the fitting errors to appear artificially small (5-20 times smaller than the RMS error). As shown in Appendix 8.2, the RMS error is larger than or comparable to the differences between various velocity assignment methods and different parameterized rotating disk models, and therefore provides a conservative estimate of the
Figure 2.7 Rotation curves of the five galaxies. Red error bars are the RMS errors, which dominate the error budget in all cases. Yellow is the MCMC fitting error. Green/blue is the error contribution from the inclination/position angle uncertainty. Black error bars are the total error, calculated by the quadratic sum of all the error sources. The circular velocity $V_c$ as measured from the outer-most radial bin is denoted with the black horizontal lines with the errors marked with the gray shaded region. This $V_c$ error includes the observational error and the rotation curve variation. The $R_{25}$ radii are marked as the solid black vertical lines and dashed black horizontal lines are the $R_{25}/2$. All of the five galaxies have rotation curves extending beyond $R_{25}/2$, and NGC 2748, and NGC 1194, and NGC 2960 are beyond $R_{25}$. For NGC 7582 and NGC 1194 the last two bins, linked by the dark gray lines, are noisy bins and thus not used for the $V_c$ measurements.

potential systematic uncertainties. For NGC 2960 and UGC 3789, we also include the uncertainties in the literature inclination and/or P.A. values. The uncertainties contributed by these values are estimated by recalculating the rotation velocities assuming an inclination and/or P.A. within $\pm 5^\circ$ of the HyperLeda value. The final error is the quadratic addition of the considered error sources.
Table 2.3. Fitted disk geometric parameters

<table>
<thead>
<tr>
<th>Galaxy</th>
<th>$x_0$ (R.A.)</th>
<th>$y_0$ (Dec)</th>
<th>$V_{sys}$ (km s$^{-1}$)</th>
<th>$i$ (degrees)</th>
<th>P.A. (degrees)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NGC 2748</td>
<td>09$^h$13$^m$43$^s$.33 + 76$^\circ$28'35.5&quot;</td>
<td>1482</td>
<td>72.6</td>
<td>35.5</td>
<td></td>
</tr>
<tr>
<td>NGC 7582</td>
<td>23$^h$18$^m$23$^s$.62 - 42$^\circ$22'14.0&quot;</td>
<td>1588</td>
<td>67.9</td>
<td>153.7</td>
<td></td>
</tr>
<tr>
<td>NGC 1194</td>
<td>03$^h$03$^m$49$^s$.14 - 01$^\circ$06'14.8&quot;</td>
<td>4075</td>
<td>69.1</td>
<td>142.8</td>
<td></td>
</tr>
<tr>
<td>NGC 2960</td>
<td>09$^h$40$^m$36$^s$.46 + 03$^\circ$34'36.6&quot;</td>
<td>4939</td>
<td>41.5*</td>
<td>49.5</td>
<td></td>
</tr>
<tr>
<td>UGC 3789</td>
<td>07$^h$19$^m$31$^s$.02 + 59$^\circ$21'17.9&quot;</td>
<td>3229</td>
<td>43.2*</td>
<td>164.7*</td>
<td></td>
</tr>
</tbody>
</table>

Note. — The rotating-disk model parameters as described in section 3.3. Col. (1): Galaxy name. Col. (2,3): Center position. For NGC 2748 and NGC 7582 the center position is the fitted H I kinematical center with fitting error ±0.2". For the megamaser galaxies (NGC 1194, NGC 2960, and UGC 3789) the center is fixed at the maser position (Kuo et al., 2011). Col. (4): Fitted systemic velocity. The random error from fitting is less than 0.1%, including determining the center for NGC 2748 and NGC 7582, which have no megamaser positions. Col. (5): Fitted inclination angle, except for NGC 2960 and UGC 3789, which are fixed at HyperLeda values (Paturel et al., 2003). Col. (6): Fitted position angle, except for UGC 3789, which is fixed at HyperLeda value (Paturel et al., 2003).

4 $M_{BH} - V_c$ Relation

4.1 The Sample

Our primary sample is an updated list of galaxies with both dynamical $M_{BH}$ and spatially resolved $V_c$ measurements, as tabulated in Table 2.4 and 2.5. There have been a number of compilations of $M_{BH}$ and $V_c$ (Kormendy & Bender, 2011; Beifiori et al., 2012); we introduce a few significant improvements over these. First, we update five maser and three stellar/gas dynamical $M_{BH}$ measurements. In addition to our five VLA H I rotation curve $V_c$ measurements, there are a few other $V_c$ measurements included in this sample from the literature that are not compiled in previous $M_{BH} - V_c$ studies. We also reexamine the literature $V_c$ values with a careful reliability analysis, to ensure that our measurements and the literature values are derived in a consistent manner. Thus, our $V_c$ values may differ from previous work. In addition to this primary sample, we also consider a secondary sample composed of galaxies with three spatially unresolved $V_c$ (single dish H I measurements) and fifteen black hole mass upper limits. This secondary sample is
Chapter 2: Refining the $M_{\text{BH}} - V_c$ Scaling Relation with HI Rotation Curves

Table 2.4 lists the $V_c$ values, sources, and rotation-curve properties of our primary sample. We examined each rotation curve from the original literature to assign a $V_c$ value. Because $V_c$ is used as a tracer of the dark matter halo potential in the outer parts of the galaxy, we assign $V_c$ as the rotation velocity at the largest observed radius $R_o$, which is consistent with the definition in Ferrarese (2002). If the inclination correction is applied in the original literature, we use this inclination-corrected rotational velocity, otherwise we apply a simple $1/\sin(i)$ inclination correction using the optically determined inclination from HyperLeda (Paturel et al., 2003). The uncertainty in $V_c$ that results from our inclination correction treatment is estimated to be less than $\pm10\%$ for a typical inclination error of $\pm5^\circ$ in the optically derived inclination (e.g., Dressler & Sandage, 1983) at an average inclination of $\sim 60^\circ$. This is comparable to or smaller than the $V_c$ measurement errors described below.

The observational error in $V_c$, listed first, is taken from the original literature. If it is not presented then we assume a 10% observational error, which is typical among our sample. The second error stands for the uncertainties due to rotation curve variation. In the ideal case where the rotation curve is flat at large radius, there is one uniquely defined $V_c$. However, if the rotation curve is not flat but keeps rising or starts to fall, then $V_c$ depends on where the outermost observed radius $R_o$ is located. To take this uncertainty into account, we assign a second error equivalent to the amplitude of variation in the rotation curve. While these error assignments may overestimate the real error between the observed $V_c$ and the true halo potential, we hope to avoid overestimating the intrinsic scatter $\epsilon_{\text{int}}$ in the $M_{\text{BH}} - V_c$ relation. The final error used in the $M_{\text{BH}} - V_c$ relation fit is taken as the larger of the observational and rotation curve variation error, as listed in Table 2.5.

There are two galaxies, NGC 3998 and NGC 5128 (Centaurus A) in our primary sample that have no rotation curve measurements but have spatially resolved HI data. For NGC 3998 we
adopt the \( V_c \) value and observational error estimated by the original literature (Knapp et al., 1985). For NGC 5128, we determine \( V_c \) using the published P-V diagram, and apply an inclination correction using the inclination from HyperLeda (Paturel et al., 2003). To reflect our lack of knowledge about the rotation curve trends, we assign conservative rotation curve variation errors of 20% in these two cases.

How faithfully \( V_c \) reflects the potential of the dark matter halo depends on whether the rotation curve is probing the halo-dominated part of the galaxy. Therefore we compare the outermost observed radius of the rotation curve \( R_o \) with the optically determined \( R_{25} \), which is the \( B = 25 \) mag arcsec\(^{-2} \) isophote from RC2 (de Vaucouleurs et al., 1995) shown in Column (6) of Table 2.4. It is worth noting that if \( R_o/R_{25} \) is small, as in the case of many optical rotation curves, then the rotation curve may be dominated by baryons rather than the dark matter halo, in turn biasing our measurement of intrinsic scatter in the \( M_{BH} - V_c \) relation. Thus, we divide galaxies into four groups according to the spatial extent and shape of their rotation curves. The first group has the largest spatial extent \( (R_o > R_{25}) \), followed by the second group \( (R_{25} > R_o > R_{25}/2) \). The third and fourth groups both have short rotation curves \( (R_o < R_{25}/2) \), but in the third group the rotation curves flatten while those ones in the fourth group are still rising until the last bin. We discuss the reliability of the \( V_c \) measurements for these groups in §4.3 and will conclude that only the first two groups \( (R_o > R_{25}/2) \) have reliable \( V_c \) for our \( M_{BH} - V_c \) analysis.

\[ \text{The } M_{BH} - V_c \text{ and } M_{BH} - \sigma_* \text{ Samples} \]

Table 2.5 lists \( V_c, M_{BH}, \sigma_* \) and other galaxy quantities. The black hole mass \( M_{BH} \), stellar velocity dispersion \( \sigma_* \), morphology, and distance are adopted from McConnell & Ma (2013), except for NGC 4526 (Davis et al., 2013). The method of \( M_{BH} \) measurement is also listed. We note potential caveats in the \( M_{BH} \) measurements of three galaxies as pointed out by McConnell & Ma (2013). Lodato & Bertin (2003) measured the black hole mass in NGC 1068 and found a non-Keplerian maser disk. For NGC 2748, Atkinson et al. (2005) cautions that the determination of the disk center may be affected by heavy extinction. Finally, the black hole mass in NGC 7457 as measured by Gebhardt et al. (2003) could be overestimated if the central bright source
excluded in their dynamical modeling is a nuclear cluster instead of an AGN. While we keep these three galaxies in our sample, we note these points of caution. The $\sigma_*$ that we adopt from McConnell & Ma (2013) is the light-weighted stellar velocity dispersion within one effective radius. However, for some galaxies the $\sigma_*$ is lower than in previous studies (e.g., Gültekin et al., 2009; Beifiori et al., 2012), as the BH sphere of influence is excluded in the velocity integration to avoid contamination. NGC 3998 and NGC 4594 in our primary sample, as well as NGC 1399 and NGC 4486 in our secondary sample, have $\sigma_*$ updated by McConnell & Ma (2013) with this correction. We also note that there is a new distance update from megamaser measurements for UGC 3789 (Reid et al., 2013), but we adopt the distance in McConnell & Ma (2013), which is consistent with Reid et al. (2013).
### Table 2.4: $V_c$ Sources for Primary Sample

<table>
<thead>
<tr>
<th>Galaxy</th>
<th>$V_c$ (km s$^{-1}$)</th>
<th>$V_c$ Method</th>
<th>$V_c$ Trend</th>
<th>Inc. (degrees)</th>
<th>$R_o/R_{25}$</th>
<th>$V_c$ Reference</th>
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<tbody>
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<td>flat</td>
<td>65</td>
<td>7.5</td>
<td>1</td>
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<tr>
<td>Milky Way</td>
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<td>oscillating</td>
<td>···</td>
<td>1.3</td>
<td>2</td>
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<tr>
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<td>77</td>
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<td>2</td>
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<tr>
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<td>69</td>
<td>1.8</td>
<td>···</td>
</tr>
<tr>
<td>NGC 1300</td>
<td>220±15±10</td>
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<td>35</td>
<td>1.6</td>
<td>3</td>
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<td>55</td>
<td>2.4</td>
<td>4</td>
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<tr>
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<td>···</td>
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<tr>
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<td>6</td>
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<td>9</td>
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</tr>
<tr>
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<td>···</td>
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<td>optical</td>
<td>flat</td>
<td>76</td>
<td>0.5</td>
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Continued on next page...
Table 2.4 – Continued

<table>
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<th>Galaxy</th>
<th>$V_c$ (km/s) ± Error</th>
<th>Method</th>
<th>Inclination</th>
<th>$R_{o}/R_{25}$</th>
<th>$\alpha$</th>
<th>Ref.</th>
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<tbody>
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<td>flat</td>
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(Group 4) Rising $R_{25}/2 > R_o$

<table>
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<tr>
<th>Galaxy</th>
<th>$V_c$ (km/s) ± Error</th>
<th>Method</th>
<th>Inclination</th>
<th>$R_{o}/R_{25}$</th>
<th>$\alpha$</th>
<th>Ref.</th>
</tr>
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<tr>
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<td>rising</td>
<td>62</td>
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<td>18</td>
</tr>
<tr>
<td>NGC 3998c</td>
<td>285±40±57</td>
<td>HI</td>
<td>unknown</td>
<td>70</td>
<td>0.5</td>
<td>19</td>
</tr>
<tr>
<td>NGC 4026</td>
<td>170±10±30</td>
<td>optical</td>
<td>rising</td>
<td>90</td>
<td>0.5</td>
<td>13</td>
</tr>
</tbody>
</table>

Table 2.4: Circular velocity $V_c$ for the primary sample with both dynamical $M_{BH}$ and rotation curve $V_c$. Galaxies are grouped according to their spatial extension and rotation curve variation as an indication of $V_c$ reliability. Only Groups (1) and (2) are used to constrain the $M_{BH} - V_c$ relation, while Groups (3) and (4) are excluded, as they may suffer from uncertainties due to short spatial extension. Col. (1): Galaxy name. Col. (2): Circular velocity $V_c$ of the galaxy with reference in Col. (7). The first error is the observational error. 10% observational error is assumed if it is not presented in the literature. The second one is the variation of the rotation curve or 20% if the variation is unknown. $V_c$ is evaluated at the outermost radius $R_o$. Col. (3): The observational method of rotation curve measurement. Col. (4): Radial trends in the rotation curve. Col. (5): Inclination angle adopted for the $V_c$ inclination correction. If the rotation curve is not inclination-corrected in the literature, the optical inclination from HyperLeda (Paturel et al., 2003) is applied. Col. (6): Ratio between the outermost radius $R_o$, at which $V_c$ is evaluated, and the galaxy radius at the $B = 25$ mag arcsec$^{-2}$ isophote $R_{25}$ from RC2 (de Vaucouleurs et al., 1995). Col. (7): References for $V_c$: (1) Jones et al. (1999); (2) Sofue et al. (1997); (3) Lindblad et al. (1997); (4) Noordermeer et al. (2007); (5) Shostak (1987); (6) deBlok et al. (2008); (7) Schiminovich et al. (1994); (8) Mundell et al. (1995); (9) Cherepashchuk et al. (2010); (10) Pellegrini et al. (1997); (11) Bajaja et al. (1984); (12) Kent (1990); (13) Dressler & Sandage (1983); (14) Bender et al. (1994); (15) Scorza & Bender (1995); (16) Guhathakurta et al. (1988); (17) Halliday et al. (2001); (18) Fisher (1997); (19) Knapp et al. (1985); ( ...) is from this paper. Notes on individual galaxies:

$a$ $V_c$ is estimated from H I velocity field as rotation curve is unavailable.

$b$ The inclination is estimated by the ratio of the minor/major axes ($\cos i = b/a$) from RC3 (de Vaucouleurs et al., 1991).

$c$ $V_c$ was estimated by Knapp et al. (1985) to be $285 \pm 40$ adopting an inclination larger than $70^\circ$, while rotation curve is not available.
### Table 2.5: $M_{BH} - V_c$

<table>
<thead>
<tr>
<th>Galaxy</th>
<th>Morphology</th>
<th>Distance (Mpc)</th>
<th>$M_{BH}$ ($M_\odot$)</th>
<th>$M_{BH}$ Method</th>
<th>$\sigma$ (km s$^{-1}$)</th>
<th>$V_c$ (km s$^{-1}$)</th>
<th>$V_c$ Method</th>
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</thead>
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<td>(Group 1)</td>
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<td></td>
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<td></td>
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</tr>
<tr>
<td>Circinus</td>
<td>S</td>
<td>4.0</td>
<td>$1.7^{+0.4}_{-0.3} \times 10^6$</td>
<td>masers</td>
<td>$158^{+18}_{-18}$</td>
<td>$155 \pm 10$</td>
<td>H I</td>
</tr>
<tr>
<td>Milky Way</td>
<td>S</td>
<td>0.008</td>
<td>$4.1^{+0.6}_{-0.6} \times 10^6$</td>
<td>stars</td>
<td>$103^{+20}_{-20}$</td>
<td>$200 \pm 30$</td>
<td>H I</td>
</tr>
<tr>
<td>NGC 0224</td>
<td>S</td>
<td>0.73</td>
<td>$1.4^{+0.8}_{-0.3} \times 10^8$</td>
<td>stars</td>
<td>$160^{+8}_{-8}$</td>
<td>$230 \pm 50$</td>
<td>H I</td>
</tr>
<tr>
<td>NGC 1194$^a$</td>
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<td>55.5</td>
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<td>masers</td>
<td>$148^{+26}_{-22}$</td>
<td>$217 \pm 28$</td>
<td>H I</td>
</tr>
<tr>
<td>NGC 1300</td>
<td>S</td>
<td>20.1</td>
<td>$7.1^{+1.4}_{-1.8} \times 10^7$</td>
<td>gas</td>
<td>$218^{+10}_{-10}$</td>
<td>$220 \pm 15$</td>
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<td>gas</td>
<td>$115^{+5}_{-5}$</td>
<td>$144 \pm 13$</td>
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</tr>
<tr>
<td>NGC 2787</td>
<td>S0</td>
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<td>$189^{+19}_{-9}$</td>
<td>$222 \pm 15$</td>
<td>H I</td>
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<tr>
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<td>H I</td>
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<td>$1.6^{+0.4}_{-0.4} \times 10^6$</td>
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<td>(Group 2)</td>
<td>$R_{25} &gt; R_o &gt; R_{25/2}$</td>
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<td>$247 \pm 10$</td>
<td>H I</td>
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<td>stars</td>
<td>$230^{+12}_{-12}$</td>
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<td>NGC 4596</td>
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<td>18.0</td>
<td>$8.4^{+3.6}_{-2.5} \times 10^7$</td>
<td>gas</td>
<td>$136^{+6}_{-6}$</td>
<td>$230 \pm 50$</td>
<td>optical</td>
</tr>
<tr>
<td>NGC 7457$^b$</td>
<td>S0</td>
<td>12.2</td>
<td>$8.7^{+5.2}_{-5.2} \times 10^6$</td>
<td>stars</td>
<td>$67^{+3}_{-3}$</td>
<td>$140 \pm 20$</td>
<td>optical</td>
</tr>
<tr>
<td>NGC 7582</td>
<td>S</td>
<td>22.3</td>
<td>$5.5^{+1.6}_{-1.1} \times 10^7$</td>
<td>gas</td>
<td>$156^{+19}_{-19}$</td>
<td>$187 \pm 21$</td>
<td>H I</td>
</tr>
<tr>
<td>UGC 3789$^a$</td>
<td>S</td>
<td>48.4</td>
<td>$1.08^{+0.06}_{-0.06} \times 10^7$</td>
<td>masers</td>
<td>$107^{+13}_{-12}$</td>
<td>$160 \pm 33$</td>
<td>H I</td>
</tr>
<tr>
<td>(Group 3)</td>
<td>Flat $R_o &lt; R_{25/2}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>NGC 1023</td>
<td>S0</td>
<td>10.5</td>
<td>$4.8^{+0.4}_{-0.4} \times 10^7$</td>
<td>stars</td>
<td>$205^{+10}_{-10}$</td>
<td>$256 \pm 30$</td>
<td>optical</td>
</tr>
<tr>
<td>NGC 1332</td>
<td>S0</td>
<td>22.7</td>
<td>$1.5^{+0.2}_{-0.2} \times 10^9$</td>
<td>stars</td>
<td>$328^{+16}_{-16}$</td>
<td>$229 \pm 20$</td>
<td>optical</td>
</tr>
</tbody>
</table>

Continued on next page...
Table 2.5: Black hole masses, stellar velocity dispersions and circular velocities of our primary sample. These quantities are plotted in Figure 2.8 with error bars symmetrized in log space. Col. (1): Galaxy Name. Col. (2): Morphology. Col. (3): Distance. Col. (4): Black hole mass measured by method in Col. (5). Col. (6): Stellar velocity dispersion. Col. (2-6) are taken from McConnell & Ma (2013), unless otherwise noted. Col. (7): Circular velocity with error taken as the larger one of observational or rotation curve variation error, for more detail see Table 2.4. Col. (8): Method of \( V_c \) observation. Notes on individual galaxies:

- **a** Black hole mass uncertainty of 6%, which is dominated by the error of the distance, is adopted as suggested in Kuo et al. (2011). Note that this error is different from what is listed in McConnell & Ma (2013).
- **b** These black hole mass measurements are noted in McConnell & Ma (2013) as complicated and are excluded in their paper. More discussion and the \( M_{BH} \) references can be found in Section 4.1.
- **c** The black hole mass is from Davis et al. (2013) using molecular gas dynamics.
- **d** Same as footnote \( a \) but black hole mass uncertainty of 11% is adopted.

<table>
<thead>
<tr>
<th>Galaxy</th>
<th>Morphology</th>
<th>Distance</th>
<th>( M_{BH} ) Method</th>
<th>Stellar Velocity Dispersion</th>
<th>Circular Velocity</th>
<th>Method of ( V_c ) Observation</th>
</tr>
</thead>
<tbody>
<tr>
<td>NGC 2549</td>
<td>S0</td>
<td>12.7</td>
<td>( 1.4^{+0.1}_{-0.4} \times 10^7 ) stars</td>
<td>( 145^{+7}_{-7} )</td>
<td>102 ± 13</td>
<td>optical</td>
</tr>
<tr>
<td>NGC 3115</td>
<td>S0</td>
<td>9.5</td>
<td>( 8.9^{+3.1}_{-2.7} \times 10^8 ) stars</td>
<td>( 230^{+11}_{-11} )</td>
<td>315 ± 10</td>
<td>optical</td>
</tr>
<tr>
<td>NGC 3585</td>
<td>S0</td>
<td>20.6</td>
<td>( 3.3^{+1.5}_{-0.6} \times 10^8 ) stars</td>
<td>( 213^{+10}_{-10} )</td>
<td>280 ± 20</td>
<td>optical</td>
</tr>
<tr>
<td>NGC 4388( ^d )</td>
<td>S</td>
<td>19.8</td>
<td>( 8.8^{+1.0}_{-1.0} \times 10^6 ) masers</td>
<td>( 107^{+8}_{-8} )</td>
<td>230 ± 23</td>
<td>H I</td>
</tr>
<tr>
<td>NGC 4564</td>
<td>S0</td>
<td>15.9</td>
<td>( 8.8^{+2.4}_{-2.4} \times 10^7 ) stars</td>
<td>( 162^{+8}_{-8} )</td>
<td>130 ± 25</td>
<td>optical</td>
</tr>
</tbody>
</table>

(Now Group 4) Rising \( R_o < R_{25/2} \)

<table>
<thead>
<tr>
<th>Galaxy</th>
<th>Morphology</th>
<th>Distance</th>
<th>( M_{BH} ) Method</th>
<th>Stellar Velocity Dispersion</th>
<th>Circular Velocity</th>
<th>Method of ( V_c ) Observation</th>
</tr>
</thead>
<tbody>
<tr>
<td>NGC 1068( ^b )</td>
<td>S</td>
<td>15.4</td>
<td>( 8.6^{+0.3}_{-0.3} \times 10^6 ) masers</td>
<td>( 151^{+7}_{-7} )</td>
<td>283 ± 60</td>
<td>optical</td>
</tr>
<tr>
<td>NGC 3384</td>
<td>E</td>
<td>11.5</td>
<td>( 1.1^{+0.5}_{-0.5} \times 10^7 ) stars</td>
<td>( 143^{+7}_{-7} )</td>
<td>156 ± 50</td>
<td>optical</td>
</tr>
<tr>
<td>NGC 3998</td>
<td>S0</td>
<td>14.3</td>
<td>( 8.3^{+0.7}_{-0.7} \times 10^8 ) stars</td>
<td>( 272^{+14}_{-14} )</td>
<td>285 ± 57</td>
<td>H I</td>
</tr>
<tr>
<td>NGC 4026</td>
<td>S0</td>
<td>13.4</td>
<td>( 1.8^{+0.6}_{-0.6} \times 10^8 ) stars</td>
<td>( 180^{+9}_{-9} )</td>
<td>170 ± 30</td>
<td>optical</td>
</tr>
</tbody>
</table>
Chapter 2: Refining the $M_{BH} - V_c$ Scaling Relation with HI Rotation Curves

4.2 Fitting Method

To quantitatively analyze the $M_{BH} - V_c$ and $M_{BH} - \sigma_*$ relations, we fit each scaling relation with a power-law functional form

\[
\log \left( \frac{M_{BH}}{M_\odot} \right) = \alpha + \beta \log \left( \frac{V_c}{200 \text{ km s}^{-1}} \right),
\]

(2.2)

\[
\log \left( \frac{M_{BH}}{M_\odot} \right) = \alpha + \beta \log \left( \sqrt{2} \sigma_* / 200 \text{ km s}^{-1} \right).
\]

(2.3)

Here $\alpha$ is the intercept and $\beta$ is the logarithmic slope of the relation. We use $\sqrt{2} \sigma_*$ to compare with $V_c$, motivated by the widely used singular isothermal sphere model where $V_c = \sqrt{2} \sigma_*$ (Binney & Tremaine, 2008). Observationally Ferrarese (2002) also found an almost linear relation between $V_c$ and $\sigma$ with a ratio close to $\sqrt{2}$.

We use a maximum-likelihood fitting method similar to Gültekin et al. (2009) that takes intrinsic (or cosmic) scatter $\epsilon_{int}$ into account, with modifications regarding the $V_c$ error treatment. For simplicity we assume that the probability distribution of both the observational errors and intrinsic scatter are normal in log space, and all the observational errors are symmetrized in log space before fitting. Here we denote

\[
\mu_i = \log \left( \frac{M_{BH,i}}{M_\odot} \right),
\]

(2.4)

\[
\nu_i = \log \left( \frac{V_{c,i}}{200 \text{ km s}^{-1}} \right)
\]

(2.5)

or \( \log \left( \sqrt{2} \sigma_*,i / 200 \text{ km s}^{-1} \right) \),

(2.6)

and the normalized Gaussian error distribution to be $G_\epsilon(x)$ with mean zero and standard deviation $\epsilon$.

To take the error in the independent variable ($V_c$ and $\sigma_*$ in this case) into account, we have an error term $\sigma_\nu$ in the likelihood function. We write the likelihood for observing one galaxy ($\mu_i$, $\nu_i$) given an intrinsic scaling relation $\mu = \alpha + \beta \nu$ with intrinsic scatter $\epsilon_{int}$ to be

\[
l_i = G_\epsilon \sqrt{\sigma_\mu^2 + \beta^2 \sigma_\nu^2 + \epsilon_{int}^2} (\mu_i - \alpha - \beta \nu_i).
\]

(2.7)
This treatment of the errors in the independent variable is less computationally expensive than the Monte Carlo method used in Gültekin et al. (2009). We then maximize the total likelihood

$$L = \prod_i l_i$$

(2.8)

to get the best-fit scaling relation parameters, the intercept $\alpha$, the slope $\beta$, and the intrinsic scatter $\epsilon_{\text{int}}$. This maximum-likelihood method is similar to the minimum $\chi^2$-square method described in Tremaine et al. (2002), except for the $1/\epsilon\sqrt{2\pi}$ normalization factor of the Gaussian function. We adopt the $\Delta\chi^2 = 1$ confidence limit as an error estimate for the fitted parameters $\alpha$, $\beta$, and $\epsilon_{\text{int}}$.

### 4.3 Fitting Results

We find that $M_{\text{BH}}$ is correlated with both $V_c$ and $\sigma_*$, with Spearman rank correlations of $\rho = 0.62$ ($p$-value $2 \times 10^{-3}$) and $\rho = 0.67$ ($6 \times 10^{-4}$) respectively, for the reliable sample of 22 $R_o > R_{25}/2$ galaxies discussed below, meaning that a correlation exists for both of the relations. Using this sample, the best-fit $M_{\text{BH}} - V_c$ relation is $\alpha = 7.43^{+0.13}_{-0.13}$, $\beta = 3.68^{+1.23}_{-1.20}$, and $\epsilon_{\text{int}} = 0.51^{+0.11}_{-0.09}$, and is plotted as blue lines in Figure 2.8. There is no significant correlation between the residuals in the $M_{\text{BH}} - V_c$ relation and $\sigma_*$ (Spearman $\rho = 0.33$, $p$-value= 0.13). The parameters of different $M_{\text{BH}} - V_c$ samples as well as the comparison with the $M_{\text{BH}} - \sigma_*$ relation are shown in Table 2.6.

To determine a reliable sample and investigate how the spatial extension of the rotation curves affect the reliability of the $V_c$ measurements, we derive the scaling relations using sample with different $R_o$ criteria. The first group of fourteen galaxies ($R_o > R_{25}$) should be the most reliable sample with rotation curves that probe the outer, halo-dominated, region of the galaxy. The second sample of eight galaxies ($R_{25} > R_o > R_{25}/2$) also gives the same intrinsic scatter as the first group, showing that the $V_c$ measurements with $R_{25} > R_o > R_{25}/2$ are as reliable as the first group for our purpose. When we include groups three and four, the eleven shorter rotation curves with $R_o < R_{25}/2$, which are predominantly measured in the optical, the intrinsic scatter increases significantly. It is a sign that for these short rotation curves the halo potential is not represented
by the observed $V_c$, and the intrinsic scatter will be inflated artificially if they are included in the analysis. We therefore rely only on the $R_o > R_{25}/2$ sample of twenty-two galaxies from the first two groups for our main scientific discussion.

Using this $R_o > R_{25}/2$ sample, the $M_{BH} - V_c$ relation has an intercept consistent with the $M_{BH} - \sigma_*$ relation, if $V_c$ corresponds to $\sqrt{2} \sigma_*$. While the slopes of the $M_{BH} - V_c$ and $M_{BH} - \sigma_*$ relations are consistent within our sample, our $M_{BH} - V_c$ relation slope falls on the lower end of reported slopes from studies of the $M_{BH} - \sigma_*$ relation using larger samples, (e.g., Gültekin et al., 2009; McConnell & Ma, 2013), possibly due to our limited dynamic range. The intrinsic scatter in the $M_{BH} - V_c$ relation of $\epsilon_{int} = 0.51^{+0.11}_{-0.06}$ is similar to that in the $M_{BH} - \sigma_*$ relation of $\epsilon_{int} = 0.48^{+0.10}_{-0.08}$ when using matched $R_o > R_{25}/2$ samples, but is larger than the $M_{BH} - \sigma_*$ relation scatter $\epsilon_{int} = 0.38$ for the entire sample in McConnell & Ma (2013), which includes both early and late-type galaxies. The implications of our fits are discussed in §6.

Some elliptical galaxies also have $V_c$ measured from dynamical modeling. Although these measurements may involve different systematics than the rotation-curve-derived $V_c$ for disk galaxies, we plot six such ellipticals from Beifiori et al. (2012) in Fig. 2.8 as an attempt to probe the $M_{BH} - V_c$ trend at the high mass end. NGC 1399, NGC 3379, NGC 4374, NGC 4472, and NGC 4486 (M87) have $V_c$ measured by Kronawitter et al. (2000) using stellar kinematics, while NGC 3608 is measured by Coccato et al. (2009). Note that for NGC 4486 (M87), Kronawitter et al. (2000) measured $V_c = 508 \pm 38$ km s$^{-1}$, while Murphy et al. (2011) measured a much larger $V_c = 800^{+75}_{-25}$ km s$^{-1}$, highlighting the challenges in this method. All the black hole masses are from McConnell & Ma (2013). When these ellipticals are added, the slopes of the $M_{BH} - V_c$ relation and $M_{BH} - \sigma_*$ relation increase significantly (by $\sim 1 \sigma$ to $\beta = 5.03^{+0.69}_{-0.75}$ and $\beta = 4.77^{+0.57}_{0.58}$ respectively). McConnell & Ma (2013) found a similar steepening in the $M_{BH} - \sigma_*$ relation when considering both early and late-type galaxies. On the other hand, the intrinsic scatter decreases slightly by about $0.5 \sigma$ to $\epsilon_{int} = 0.46^{+0.10}_{-0.09}$ and $\epsilon_{int} = 0.45^{+0.08}_{-0.07}$ for the $M_{BH} - V_c$ and $M_{BH} - \sigma_*$ relations respectively. These results will not be used in our scientific discussion, as their interpretation awaits better understanding of the correspondence between the $V_c$ from the dynamical modeling and from H I rotation curves.
Table 2.6. Fitted scaling relations

<table>
<thead>
<tr>
<th>$x$</th>
<th>Sample Criteria</th>
<th>n</th>
<th>$\alpha$</th>
<th>$\beta$</th>
<th>$\epsilon_{int}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$(1)$</td>
<td>$(2)$</td>
<td>$(3)$</td>
<td>$(4)$</td>
<td>$(5)$</td>
<td>$(6)$</td>
</tr>
<tr>
<td>$V_c$</td>
<td>Group 1, 2</td>
<td>$R_o &gt; R_{25}/2$</td>
<td>22</td>
<td>$7.43^{\pm0.13}_{-0.13}$</td>
<td>$3.68^{+1.23}_{-1.20}$</td>
</tr>
<tr>
<td></td>
<td>Group 1, 2</td>
<td>$R_o &gt; R_{25}/2$</td>
<td>22</td>
<td>$7.48^{+0.11}_{-0.11}$</td>
<td>$3.73^{+0.87}_{-0.89}$</td>
</tr>
<tr>
<td>$\sqrt{2}\sigma$</td>
<td>Group 1, 2</td>
<td>$R_o &gt; R_{25}/2$</td>
<td>22</td>
<td>$7.59^{+0.12}_{-0.12}$</td>
<td>$3.01^{+1.02}_{-0.97}$</td>
</tr>
<tr>
<td>$V_c$</td>
<td>Group 1</td>
<td></td>
<td>14</td>
<td>$7.30^{+0.16}_{-0.15}$</td>
<td>$2.39^{+1.79}_{-1.49}$</td>
</tr>
<tr>
<td>$V_c$</td>
<td>Group 1, 2, 3</td>
<td></td>
<td>29</td>
<td>$7.61^{+0.12}_{-0.12}$</td>
<td>$2.86^{+0.99}_{-0.94}$</td>
</tr>
<tr>
<td>$V_c$</td>
<td>Group 1, 2, 3, 4</td>
<td>all Primary Sample</td>
<td>33</td>
<td>$7.61^{+0.12}_{-0.12}$</td>
<td>$2.86^{+0.99}_{-0.94}$</td>
</tr>
</tbody>
</table>

Note. — Best-fit $M_{BH} - V_c$ and $M_{BH} - \sigma_*$ scaling relations with model log($M_{BH}/M_\odot$) = $\alpha + \beta \log(x/200 \text{ kms}^{-1})$ of different samples. The first two rows include only galaxies with measured rotation curves extending beyond $R_o > R_{25}/2$ and are used for our $M_{BH} - V_c$ to $M_{BH} - \sigma_*$ comparison. Col. (1): The $x$ axis of the relation. Col. (2-3): The sample and the sample criteria used in fitting, see Table 2.4. Col. (4): Number of galaxies in the sample. Col. (5): Best-fit intercept $\alpha$. Col. (6): Slope $\beta$. Col. (7): Intrinsic scatter $\epsilon_{int}$.

4.4 Comparison with the Literature

Volonteri et al. (2011) re-analyze the 25 galaxies in Kormendy & Bender (2011), which have dynamical $M_{BH}$ measurements and $V_c$ from spatially resolved H I or stellar kinematics, using the methods of Gültekin et al. (2009). They constrain the $M_{BH} - V_c$ relation to have $\alpha = 7.39 \pm 0.14$, $\beta = 4.33 \pm 0.93$, and $\epsilon_{int} = 0.53 \pm 0.10$, consistent with our results.

Beifiori et al. (2012) study the $M_{BH} - V_c$ relation using 28 galaxies with $M_{BH}$ compiled by Gültekin et al. (2009), and $V_c$ from resolved H I kinematics, unresolved H I line width, or dynamical models of stellar kinematics in early type galaxies. Their $M_{BH} - V_c$ relation parameters are $\alpha = 7.82 \pm 0.15$, $\beta = 3.29 \pm 0.61$, and intrinsic scatter $\epsilon_{int} = 0.51 \pm 0.09$. Their intercept $\alpha$ is different from our result, possibly because more elliptical galaxies are included in their sample. Their fit for the slope has a larger dynamic range because they include more elliptical galaxies, but is still consistent with ours, as is their intrinsic scatter measurement.
Chapter 2: Refining the $M_{\text{BH}} - V_c$ Scaling Relation with HI Rotation Curves

Figure 2.8 The $M_{\text{BH}} - V_c$ (left) and $M_{\text{BH}} - \sigma_*$ (right) relations. The data is described in §4 and listed in Table 2.5. Our primary sample with dynamical $M_{\text{BH}}$ and spatially resolved $V_c$ measurements is plotted in blue or green depending on the rotation curve extent. The blue circles ($R_o > R_{25}$) and blue squares ($R_{25} > R_o > R_{25}/2$) have long rotation curves and are used for constraining the two relations. The green circles/squares have short rotation curves ($R_o < R_{25}$) with flat/rising trends. They are not used to constrain the two relations because of their lower reliability reflected by the larger scatter in the $M_{\text{BH}} - V_c$ relation. Also plotted is our secondary sample described in Appendix 8.3 and listed in Table 2.9. The gray diamonds and triangles represent the single-dish $V_c$ measurements and $M_{\text{BH}}$ upper limits respectively. The red circles are the elliptical galaxies with $V_c$ measured by dynamical modeling and $M_{\text{BH}}$ from McConnell & Ma (2013) as discussed in §4.3. Our five observed H I galaxies are marked by magenta dots labeled as A (NGC 2748), B (NGC 7582), C (NGC 1194), D (NGC 2960), and E (UGC 3789). The fitted $M_{\text{BH}} - V_c$ and $M_{\text{BH}} - \sigma_*$ scaling relations using the $R_o > R_{25}/2$ primary sample, plotted in blue, is shown by the thick blue line with the intrinsic scatter plotted by the two thin lines. We use $\sqrt{2}\sigma_*$ for the abscissa of the $M_{\text{BH}} - \sigma_*$ relation as a direct comparison to $V_c$.

5 Possible Systemic Uncertainties

Intrinsic scatter in the scaling relations provides an important discriminant between different BH scaling relation scenarios. Various observational errors in $V_c$ have been taken into account in §4 to avoid contaminating the intrinsic scatter measurement, including the inclination correction, the observational error, rotation curve variations, and the uncertainties due to short rotation curves.

Here we discuss whether other systematic uncertainties, such as sample bias, may affect the interpretation of, and the comparison between, the $M_{\text{BH}} - V_c$ and $M_{\text{BH}} - \sigma_*$ relations. Also, in order to interpret the $M_{\text{BH}} - M_{\text{DM}}$ relation from the observed $M_{\text{BH}} - V_c$ relation, we discuss the scatter that may be introduced in the $V_c - M_{\text{DM}}$ conversion. We conclude first that the
comparison between the $M_{\text{BH}} - V_c$ and the $M_{\text{BH}} - \sigma_*$ relations should be fair even in the face of selection effects, and second, that the scatter introduced by the $V_c - M_{\text{DM}}$ conversion or halo triaxiality is not important compared to other sources of uncertainty.

5.1 Selection Effects

If our sample is subject to selection effects, it may not represent the true distribution of objects. Selection effects may exist for both BH and circular velocity measurements. First, it has been argued that analysis excluding $M_{\text{BH}}$ upper limits might be biased toward more massive BHs at a given velocity dispersion, especially for late-type galaxies, since only massive BHs have a sphere of influence large enough to be spatially resolved (Gültekin et al., 2011). Beifiori et al. (2012) includes a large number of $M_{\text{BH}}$ upper limits in their fits to the $M_{\text{BH}} - V_c$ and $M_{\text{BH}} - \sigma_*$ relations, which should be closer to the true distribution. They find a slope $\beta$ for the $M_{\text{BH}} - V_c$ relation consistent with ours, but cannot derive a reliable intrinsic scatter. While concerns over $M_{\text{BH}}$ selection biases cannot be excluded definitively, we use the same sample for both $M_{\text{BH}} - \sigma_*$ and $M_{\text{BH}} - V_c$ relations, such that if $M_{\text{BH}}$ biases exist, they have the same effect on the two relations.

In addition to selecting against low-mass BHs, we also select against galaxies that have no $V_c$ from HI rotation curves, which includes massive elliptical (gas-poor) galaxies, and disk galaxies that either have only optical (mostly covering a limited radial distance) or no rotation-curve measurements. With no stellar dynamical $V_c$ measurements for ellipticals, our dynamic range is limited compared to the $M_{\text{BH}} - \sigma_*$ relation in other studies, (e.g., Gültekin et al., 2009; McConnell & Ma, 2013). While selection biases in $V_c$ measurements also exist, at least there is no obvious bias on the intrinsic scatter inherent with these selections.

5.2 Uncertainties in Translating $V_c$ to $M_{\text{DM}}$

If we wish to interpret the $M_{\text{BH}} - V_c$ relation as a reflection of the underlying $M_{\text{BH}} - M_{\text{DM}}$ relation, then scatter may be introduced in the conversion from $V_c$ to $M_{\text{DM}}$. To estimate the magnitude of this scatter, we take the Navarro-Frenk-White (NFW; Navarro et al., 1996) model as an example. This model is a mass profile that is parametrized by the inner density $\rho_s$ and the
Chapter 2: Refining the $M_{\text{BH}} - V_c$ Scaling Relation with HI Rotation Curves

characteristic inner radius $r_s$, or equivalently the virial mass $M_{\text{vir}}$ and the concentration $c_{\text{vir}} \equiv R_{\text{vir}}/r_s$. The virial radius $R_{\text{vir}}$ is defined as the radius within which the averaged halo density exceeds the background density by a certain factor, the virial mass $M_{\text{vir}}$ is the mass enclosed within $R_{\text{vir}}$, and the virial velocity $V_{\text{vir}}$ is the rotation velocity at $R_{\text{vir}}$. Because there is a one-to-one correspondence between $M_{\text{vir}}$ and $V_{\text{vir}}$, the main uncertainty actually comes from the conversion between $V_{\text{vir}}$ at the virial radius (typically a few hundred kpc) and $V_c$ at the observed radius (typically 10-20 kpc, Ferrarese, 2002). The observed $V_c$ is close to the maximum velocity $V_{\text{max}}$ occurring at radius $r_{\text{max}} \sim 2.16\ r_s$, which is a few to a few tens of kpc. The ratio $V_{\text{max}}/V_{\text{vir}}$ depends on $c_{\text{vir}}$

$$\frac{V_{\text{max}}}{V_{\text{vir}}} = 0.46 \sqrt{\frac{c_{\text{vir}}}{\ln(1+c_{\text{vir}}) - c_{\text{vir}}/(1+c_{\text{vir}})}}.$$  

(2.9)

The scatter in concentration is estimated by Bullock et al. (2001) and corrected by Wechsler et al. (2002) to be $\Delta \log_{10} c_{\text{vir}} = 0.14$ dex, which translates to an error of 0.035 dex in $V_{\text{max}}$ or 0.14 dex in $M_{\text{BH}}$ for a slope of $\beta = 4$ in the $M_{\text{BH}} - V_c$ relation. There is also a weak dependence of concentration on the virial mass, which affects the slope of the $M_{\text{BH}} - V_c$ relation in principle.

Additionally, if the halo is not spherically symmetric, as assumed by the NFW profile, but is prolate or triaxial, there will be extra uncertainty in the $V_c - M_{\text{DM}}$ conversion. Franx & de Zeeuw (1992) estimate that the low observed scatter in the Tully-Fisher relation constrains the ellipticity of the halo potential in the disk plane to be $\leq 0.1$. Triaxiality can at most contribute a scatter of 0.026 dex in $V_c$ or 0.1 dex in $M_{\text{BH}}$ in the $M_{\text{BH}} - V_c$ relation.

Removing these additional sources of uncertainty in quadrature, assuming that they are uncorrelated, changes the final intrinsic scatter very little (0.48 rather than 0.51). Thus we conclude that those sources of scatter are small compared to outstanding measurement uncertainty.

6 Discussion

We will now consider the implications of our new fits for the evolution of BHs and galaxies. In §6.1, we hope to gain new insight into whether AGN feedback is required to explain the BH-bulge
Chapter 2: Refining the $M_{\text{BH}} - V_c$ Scaling Relation with HI Rotation Curves

scaling relations (e.g., Silk & Rees, 1998; Hopkins et al., 2006), or whether galaxy merging alone may lead to tight BH-bulge correlations in massive galaxies (e.g., Peng, 2007; Jahnke & Macciò, 2011). In §6.2 we discuss the implications of $M_{\text{BH}}$ upper limits as outliers in the $M_{\text{BH}} - V_c$ relation.

6.1 Is It Feedback or Merging That Sets the Scaling Relations?

We address the relative importance of feedback and merging empirically by asking which can account for features in the observed $M_{\text{BH}} - V_c$ and $M_{\text{BH}} - \sigma_*$ relations. We start by reviewing the expected slope, outlier behavior, and intrinsic scatter of the scaling relations in the context of each scenario. We will find that while more theoretical guidance and a larger sample size are needed to make inferences from the outliers and slope measurements, the intrinsic scatter is already an available and useful discriminant between the two scenarios.

In the galaxy merging scenario (Peng, 2007; Hirschmann et al., 2010b; Jahnke & Macciò, 2011), the correlations between $M_{\text{BH}}$ and galactic quantities (e.g., $M_*$, $M_{\text{bulge}}$, $M_{\text{DM}}$) emerge from a large number of mergers simply by the central limit theorem, even without a physical mechanism linking the two. In the context of this scenario, we expect the following features of the scaling relations. First, as the number of mergers increases and the galaxies grow larger, the scatter between $M_{\text{BH}}$ and galaxy properties will decrease and the distribution will converge to a tighter correlation. Therefore, it is expected that the intrinsic scatter $\epsilon_{\text{int}}$ will decrease as the number of mergers increases towards larger $V_c$ and $\sigma_*$. Outliers, with BH masses deviating from a power-law scaling relation, become increasingly unlikely towards higher masses. Second, the logarithmic slope $\beta$ of the correlation between two linear quantities, e.g., $M_{\text{BH}}$ and $M_{\text{DM}}$, should be close to unity if the impact of growth via accretion for any component is small. In other words, the average ratio $\langle M_{\text{BH}}/M_{\text{DM}} \rangle$ should be similar across all masses. If we translate this slope to the $M_{\text{BH}} - V_c$ relation, assuming $M_{\text{DM}} \propto V_c^{3 - 3.32}$ (Ferrarese, 2002), we should find the slope of the $M_{\text{BH}} - V_c$ relation, $\beta$, to be close to $3 - 3.32$, somewhat smaller than, but allowed by, our observations. Lastly, the $M_{\text{BH}} - M_{\text{DM}}$ relation should be tighter than other scaling relations, e.g., the $M_{\text{BH}} - M_*$ or $M_{\text{BH}} - M_{\text{bulge}}$ relations, because $M_{\text{DM}}$ simply adds during merging and does
not depend on the baryonic physics that $M_*$ and $M_{\text{bulge}}$ are subject to. For example, during merging, extra factors of star formation and disk to bulge conversion have to be considered for the evolution of $M_{\text{bulge}}$, and this will make the scatter in the $M_{\text{BH}} - M_{\text{bulge}}$ relation larger than that in the $M_{\text{BH}} - M_{\text{DM}}$ relation, if the baryonic regulation mechanism is not present. However, we note that diffuse DM accretion in principle may also enhance the scatter in $M_{\text{DM}}$.

Feedback, on the other hand, provides a physical mechanism that couples BH mass directly with the galaxy potential well (e.g., Silk & Rees, 1998). If the BH is massive enough, its energy or momentum output can expel gas from its vicinity and quench the further growth of both the BH and the galaxy. This feedback loop sets an upper limit on the BH mass for a given potential well depth, measured by the stellar velocity dispersion $\sigma_*$ of the bulge or $V_c$ of the dark matter halo. However, it is unclear whether this self-regulation process takes place on the scale of the BH sphere of influence, the bulge (Debuhr et al., 2010), or the dark matter halo (Di Matteo et al., 2003; Booth & Schaye, 2010b). Some predictions of the feedback scenario are as follows. First, the scaling relations form an upper boundary for $M_{\text{BH}}$. The BH cannot grow above the relation via accretion (although over-massive BHs could already be in place from massive seeds Volonteri & Natarajan (2009)). Second, the slope of the $M_{\text{BH}} - \sigma_*$ or the $M_{\text{BH}} - V_c$ relation is predicted to be five for energy feedback (Silk & Rees, 1998) and four for momentum feedback (Murray et al., 2005). Third, the correlation between BH mass and the potential indicator ($\sigma_*$ or $V_c$) on the feedback scale should be tighter than on other scales.

We here compare the statistics of our $V_c$ sample with the predictions discussed above regarding the outlier properties, slope, and the intrinsic scatter, respectively. There are no obvious outliers above the $M_{\text{BH}} - V_c$ relation in our sample, possibly due to limited sample size. However, there are bulgeless galaxies with $M_{\text{BH}}$ upper-limits that are low compared to their $V_c$, which will be further discussed in §6.2. Regarding the measured slopes, with such limited dynamic range our data are still inadequate to discriminate the two scenarios. Both scenarios are consistent with the wide range of allowed $M_{\text{BH}} - V_c$ slopes ($\beta = 2.48 - 4.91$).

However, the comparison of intrinsic scatter between the two relations can provide useful constraints on the origin of the scaling relations. Our measurements show that the scatter in the $M_{\text{BH}} - V_c$ relation is similar to that in the $M_{\text{BH}} - \sigma_*$ relation, within the errors. It is worth
noticing that the intrinsic scatter in $M_{\text{BH}} - V_c$, $\epsilon_{\text{int}} = 0.51^{+0.11}_{-0.09}$ dex, is a conservatively low estimate, as we have assigned large errors to the $V_c$ measurements to account for various observational uncertainties, including inclination uncertainties and rotation curve variations. Even so, we still find a value that is consistent with our measured $M_{\text{BH}} - \sigma_*$ scatter, $\epsilon_{\text{int}} = 0.48^{+0.10}_{-0.08}$ dex, and that is not smaller than the $M_{\text{BH}} - \sigma_*$ intrinsic scatter $\epsilon_{\text{int}} = 0.46$ for late-type galaxies constrained by McConnell & Ma (2013) or $\epsilon_{\text{int}} = 0.38$ for the entire sample in McConnell & Ma (2013).

We find no evidence that the $M_{\text{BH}} - V_c$ (or $M_{\text{BH}} - M_{\text{DM}}$) relation is significantly tighter than the $M_{\text{BH}} - \sigma_*$ relation, in contradiction with naive expectations from the pure merging scenario. Therefore, our result disfavors merging as the only mechanism that ties together BHs and galaxies. Note that we use $\sigma_*$ to trace the baryonic mass in the bulge, while Jahnke & Macciò (2011) looked at the $M_{\text{BH}} - M_{\text{bulge}}$ relation instead. Unfortunately, observations of $M_{\text{bulge}}$ for lower-mass galaxies with dynamical $M_{\text{BH}}$ are scarce, so a direct comparison between $M_{\text{BH}} - M_{\text{DM}}$ and $M_{\text{BH}} - M_{\text{bulge}}$ is not yet possible. If the real scatter in the $M_{\text{BH}} - M_{\text{bulge}}$ relation is even smaller than in $M_{\text{BH}} - \sigma_*$, our conclusion is stronger. Even if the scatter in the $M_{\text{BH}} - M_{\text{bulge}}$ relation turns out to be larger than in the $M_{\text{BH}} - \sigma_*$ relation, the fact that the scatter in the $M_{\text{BH}} - V_c$ relation is no smaller than that in the $M_{\text{BH}} - \sigma_*$ relation still requires (baryonic) mechanisms beyond the pure merging scenario.

On the other hand, if AGN feedback is important in regulating BH growth, and it acts primarily on the bulge scale (Debuhr et al., 2010), the smaller intrinsic scatter in the $M_{\text{BH}} - \sigma_*$ relation could be explained. We speculate that on top of the correlations formed by merging, feedback further regulates the BH mass according to the bulge potential $\sigma_*$, tightens the $M_{\text{BH}} - \sigma_*$ relation (not the $M_{\text{BH}} - V_c$ relation), and decreases the intrinsic scatter in a relative sense. Alternatively, other baryonic mechanisms that connect the BH to the bulge, e.g., via feeding of bulge stars onto the accretion disk (Miralda-Escudé & Kollmeier, 2005), or star formation-regulated BH growth (Burkert & Silk, 2001), could also contribute to the tighter $M_{\text{BH}} - \sigma_*$ relation.
Chapter 2: Refining the $M_{BH} - V_c$ Scaling Relation with HI Rotation Curves

6.2 $M_{BH}$ Upper Limits in the Two Scaling Relations

$M_{BH}$ upper limits in bulgeless galaxies have also been used to differentiate the dependence of black hole mass on galaxy halos or bulges. Kormendy & Bender (2011) found that $M_{BH}$ cannot be uniquely determined by $V_c$. Bulgeless galaxies have low (or zero) $M_{BH}$ and low $\sigma_*$ but relatively high $V_c$. Therefore, $\sigma_*$ is a better predictor of $M_{BH}$ than is $V_c$ for these galaxies.

We expand the sample of bulgeless galaxies with $M_{BH}$ upper limits by including the measurements from Neumayer & Walcher (2012) in our secondary sample. This sample is described in Appendix 8.4 and listed in Tables 2.8 and 2.9. As can be seen from Figure 2.8, there are a few upper limits lying below the $M_{BH} - V_c$ relation but not the $M_{BH} - \sigma_*$ relation. With a larger number of galaxies, we confirm Kormendy’s statement that the halo mass alone does not determine the black hole mass.

However, it is also possible that these bulgeless galaxies do not host a massive black hole at all. The presence or absence of a BH seed may involve different physical mechanisms than those that couple BHs to galaxies (e.g., Volonteri et al., 2011). In any case, the upper limits strengthen our conclusion that bulge scales matter, likely both in seeding and in BH growth with cosmic time.

7 Summary

We refine the measured $M_{BH} - V_c$ relation and compare it to the $M_{BH} - \sigma_*$ relation to gain insight into the mechanisms that drive BH scaling relations. We perform VLA observations to measure the circular velocities $V_c$ for five galaxies with dynamical $M_{BH}$. Together with a thorough literature search, we increase the sample size of galaxies with both $M_{BH}$ and $V_c$ measurements to thirty-three. Twenty-two of these have $V_c$ evaluated at large enough radius ($> R_{25/2}$) to be reliable for our scientific purpose.

With this sample, we constrain the power-law $M_{BH} - V_c$ relation to have an intercept $\alpha = 7.43^{+0.13}_{-0.13}$, slope $\beta = 3.68^{+1.23}_{-1.20}$, and intrinsic scatter $\epsilon_{int} = 0.51^{+0.11}_{-0.09}$. The intrinsic scatter in the $M_{BH} - V_c$ relation is not significantly smaller than that in the $M_{BH} - \sigma_*$ relation, showing that $M_{BH}$ does not correlate better with dark matter halo mass than with bulge properties. This
contradicts naive expectations from pure merging scenarios. Furthermore, we consider a number of $M_{\text{BH}}$ upper limits in bulgeless galaxies that lie significantly below the $M_{\text{BH}} - V_c$ relation, suggesting that BH masses are better predicted by the bulge, not the halo, either via its seeding or accreting mechanism. We thus suggest that pure merging is not likely to be the only mechanism that drives the scaling relations. AGN feedback may also be an essential ingredient to tighten the correlation between BH mass and bulge properties.

We highlight possible future improvements to this work. First, modeling of the dark matter halo mass distribution, to separate the halo mass from the baryons using both rotation curves and light distributions, can improve the halo mass estimation and better constrain the $M_{\text{BH}} - M_{\text{DM}}$ relation. Second, $V_c$ measured by stellar dynamical modeling for elliptical galaxies, if proven to be comparable to those from H I rotation curves, can improve the dynamic range and better constrain the slope of the relation. Third, quantitative theoretical predictions for the scaling relations, especially the intrinsic scatter, from both feedback and pure merging scenarios, will enable more direct comparisons with the empirical relations. Ultimately, a large sample unbiased with respect to $M_{\text{BH}}$ and $V_c$, which awaits next-generation telescopes, would be the most ideal data set for this study.

8 Appendix

8.1 H I Properties of Individual Galaxies

In addition to the rotation curves kinematics, there is also rich information about the H I gas properties in our VLA data cubes. We discuss the H I fluxes and masses and the H I properties of each individual galaxy in this section. H I moment maps of these galaxies are shown in Figures 2.1 to 2.5 and the integrated spectra of lower SNR galaxies are shown in Figure 2.9.

H I Flux and Mass

The H I fluxes and mass are tabulated in Table 2.7. We measured the H I flux by integrating the data cube over the spatial regions as shown in the moment-0 maps. To avoid contamination, for
Figure 2.9 The spectrum of the NGC 7582 central H I absorption feature and the integrated H I emission spectra of the three lower SNR galaxies (NGC 1194, NGC 2960, and UGC 3789).
NGC 1194, we excluded the north-western cloud, which is detached from the main galaxy as seen from the moment-0 map. We also removed the central absorption region in NGC 7582. As an estimate of the H I flux error, we also measured the flux from the masked moment-0 maps, which exclude the noise-dominated channels and therefore can underestimate the total flux. We take the difference between the two as the systematic flux error. The H I masses are calculated using the equation

$$M_{\text{HI}} = 2.343 \times 10^5 M_\odot (1 + z) \left( \frac{D_L}{\text{Mpc}} \right)^2 \left( \frac{\int F_\nu \, dv}{\text{Jy km s}^{-1}} \right)$$

from Draine (2011). For consistency, we adopt the same distances as those used for the $M_{\text{BH}}$ measurements in §4.1 and Table 2.2. Distance uncertainties of 10% are assumed, and the uncertainties in $M_{\text{HI}}$ are propagated from the uncertainties in flux and distance. It is common in the literature to compare the H I mass to the total stellar mass, to understand the gas fractions and available fuel for future star formation. Here we use the B-band luminosity ($L_B$) as a proxy for the stellar mass and calculate the H I mass-to-light ratio ($M_{\text{HI}}/L_B$) as a proxy for the H I-to-stellar mass ratio. Using the B-band luminosity from HyperLeda (Paturel et al., 2003), the $M_{\text{HI}}/L_B$ ratios of our galaxies range from 3% to 22% (Table 2.7). This is similar to the range of typical Sa galaxies, which have an average value $\sim 10\%$ with a factor of $\sim 3$ dispersion (Roberts & Haynes, 1994), as well as AGN hosts which also have $M_{\text{HI}}/L_B \sim 10\%$ (Fabello et al., 2011; Ho et al., 2008). Therefore, our sample galaxies have roughly similar H I-to-stellar mass ratios as typical disk galaxies and AGN hosts.

**NGC 2748**

NGC 2748 is an SAbc galaxy (de Vaucouleurs et al., 1991) at a distance of 21.6 ± 1.4 Mpc. The H I observation of this galaxy has the highest SNR among our five galaxies, with an H I-based inclination of 72.6°, compared to 68.1° from optical data in HyperLeda (Paturel et al., 2003). The fitted H I systemic velocity is 1482 km s$^{-1}$. The kinematics show the typical signature of a rotating disk (Fig. 2.1). The asymmetric velocity field suggests that slight disk warping may
Table 2.7. HI and Optical Properties

<table>
<thead>
<tr>
<th>Galaxy</th>
<th>$F_{\text{HI}}$ (Jy km s$^{-1}$)</th>
<th>$M_{\text{HI}}$ ($10^9 M_\odot$)</th>
<th>$M_B$ (mag)</th>
<th>$M_{\text{HI}}/L_B$ ($M_\odot L_\odot^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NGC 2748</td>
<td>37.4 ± 5.4</td>
<td>5.47 ± 1.35</td>
<td>-20.33</td>
<td>0.26</td>
</tr>
<tr>
<td>NGC 7582</td>
<td>19.6 ± 2.8</td>
<td>2.30 ± 0.57</td>
<td>-20.70</td>
<td>0.08</td>
</tr>
<tr>
<td>NGC 1194</td>
<td>7.14 ± 1.07</td>
<td>5.19 ± 1.30</td>
<td>-20.36</td>
<td>0.24</td>
</tr>
<tr>
<td>NGC 2960</td>
<td>2.18 ± 0.28</td>
<td>2.92 ± 0.69</td>
<td>-20.76</td>
<td>0.09</td>
</tr>
<tr>
<td>UGC 3789</td>
<td>1.26 ± 0.38</td>
<td>0.70 ± 0.25</td>
<td>-20.50</td>
<td>0.03</td>
</tr>
</tbody>
</table>


exist. The angular diameter along the major axis at the 3 $\sigma$ level, i.e., where H I is detected above the 3 $\sigma$ level, is 3'8. The H I flux is measured to be $37 \pm 5$ Jy km s$^{-1}$, which corresponds to an H I mass of $4.2 \pm 0.9 \times 10^9 M_\odot$.

NGC 7582

NGC 7582 is an SB(s)ab galaxy (de Vaucouleurs et al., 1991) at a distance of $20.6 \pm 2.4$ Mpc. Our observation of this galaxy also has high SNR. The inclination derived from the H I kinematics is 67.9°, compared with 68.2° from HyperLeda (Paturel et al., 2003). The systemic velocity is 1588 km s$^{-1}$ as fit by H I. Its velocity field shows the clear signature of rotation and is asymmetric (Fig. 2.2), suggesting a warped disk. The velocity discontinuity at the edge of the warp coincides with the location of the spiral arms. Its angular diameter is 3'7 at the 3 $\sigma$ level. The H I flux is $20 \pm 3$ Jy km s$^{-1}$, which corresponds to an H I mass of $2.0 \pm 0.5 \times 10^9 M_\odot$.

NGC 7582 shows H I absorption features against the central continuum source. The continuum-subtracted spectrum averaged over the central beam is shown in Figure 2.9. There is
Figure 2.10 Left: The NGC 7582 moment-0 map on larger scale. The masking is the same as in Figure 2.2. We mask out the pixels below 3 $\sigma$ in a map that is smoothed spatially and over two velocity channels (20 km s$^{-1}$). We then construct the moment-0 map from the original data using this mask. Two companions, NGC 7590 and NGC 7599, and an elongated tidal stream can be seen. Right: The moment-1 map of the same field.

an emission peak at a velocity of 1500 km s$^{-1}$ coinciding in velocity with the emission in nearby regions. Therefore, we suspect that we are observing the superposition of a wide absorption feature with narrow emission. The wide absorption feature has a FWHM of $\sim$ 400 km s$^{-1}$ centered at 1580 km s$^{-1}$, close to the systemic velocity. Because of contamination from H I emission, we can only estimate a lower limit on the absorbed flux. Using the line width and depth, that flux limit is $> 0.94$ Jy km s$^{-1}$. The lower limit on the H I absorption optical depth is estimated to be $> 0.027$.

Finally, there are two H I companions of NGC 7582 observed in the same velocity range and sitting 9$'$ and 12$'$ to the north-east respectively. These are the companion galaxies NGC 7590 and NGC 7599. There is faint diffuse H I emission $\sim$ 13$'$ long that extends from NGC 7590 to the west of NGC 7582 with a closest distance to NGC 7582 of 5.5$'$. This is possibly tidally stripped gas due to interactions between these galaxies. Larger scale moment-0 and moment-1 maps showing these structures are plotted in Figure 2.10.
NGC 1194

NGC 1194 is an SA0 galaxy (de Vaucouleurs et al., 1991) at a distance of 53.2 ± 3.7 Mpc. It is one of our water megamaser galaxies (Kuo et al., 2011). The H I SNR is sufficiently high to determine an inclination of 69.1°, compared to 71.1° from HyperLeda (Paturel et al., 2003). The systemic velocity as measured from the H I map is 4075 km s⁻¹. The H I moment-0 map shows an elongated morphology with angular diameter 2'8 at the 3 σ level, showing that the H I gas is organized within the galaxy disk. The velocity field shows a clear velocity gradient due to rotation (Fig. 2.3). The integrated spectrum (Fig. 2.9) also has a clear double peaked rotation signature with the width consistent with our \( V_c \) measurement. The H I flux is measured to be 7 ± 1 Jy km s⁻¹, corresponding to a mass of 5 ± 1 \( \times 10^9 \) \( M_\odot \). There is one H I cloud to the north-west side of the galaxy that is detached from the main galaxy body (see Fig. 2.3). This cloud has a mass of 5 ± 2 \( \times 10^8 \) \( M_\odot \).

NGC 2960

NGC 2960, also called Mrk 1419, is an Sa (de Vaucouleurs et al., 1991) galaxy at 72.2 ± 5.1 Mpc and also a water megamaser galaxy from Kuo et al. (2011). The systemic velocity from H I is 4939 km s⁻¹. Our map of NGC 2960 has lower SNR (SNR = 6). Although H I emission is only seen in discrete patches of the galaxy, an overall velocity gradient is observed (Fig 2.4). The detected diameter is 2'5 at the 1 σ level from the moment-0 map. The inclination cannot be constrained by the H I data alone, and we derive the rotation curve by adopting the optical inclination from HyperLeda (Paturel et al., 2003) of 41.5°. The integrated spectrum (Fig. 2.9) shows a double peaked rotation signature and a width that is consistent with our \( V_c \) measurement. The H I flux is measured to be 2.2 ± 0.3 Jy km s⁻¹, corresponding to a mass of 2.7 ± 0.5 \( \times 10^9 \) \( M_\odot \). Previous D-array VLA observations (Kuo et al., 2008) are consistent with the spatial extent and velocity from our data, but their H I flux of 1.7 ± 0.3 Jy km s⁻¹ is lower than ours. This is understandable as their flux was calculated from the moment-0 map and should be lower than from the data cube.
Our H I data also provides images of the radio continuum at 20 cm. We find that the radio continuum of NGC 2960 is slightly extended, suggesting that there is a radio jet launched from the central black hole (Fig. 2.11). The continuum image is made from line-free channels on both sides of the H I line with a total velocity range of 300 km s$^{-1}$, and is cleaned to the 5 $\sigma$ level using $\text{robust} = 0.5$ weighting. We measure the size and position angle of the jet using two different methods. First, we fit a central point source (15$''$) and subtract it. We detect residual emission to the south-east. Taking into account the positional uncertainty due to the finite beamsize, this extended emission is $20 \pm 3''$ away from the center at a position angle of $125^\circ$. The flux in the extended emission is $1.6 \pm 0.2$ mJy. To estimate the size and P.A. error we also try a second method to quantify the elongated structure. We fit the whole continuum image with a two-dimensional Gaussian while allowing the semi-major and semi-minor axis, central position, and P.A. to vary, without deconvolution of the beam. The fitted Gaussian has a major axis of $22 \pm 4''$, and a minor axis of $18 \pm 4''$ with P.A. $119 \pm 7^\circ$, consistent with the first method. Therefore we conclude that the jet size is $20 \pm 5''$ at a P.A. of $125 \pm 10^\circ$. As in all megamaser galaxies studied to date, the jet axis is coincident with the rotation axis of the maser disk (Greene et al., 2013).

**UGC 3789**

UGC 3789 also hosts a water maser disk, is an SA(r)ab galaxy (de Vaucouleurs et al., 1991), and is at a distance of $49.9 \pm 7.0$ Mpc (Braatz et al., 2010). The H I systemic velocity is 3229 km s$^{-1}$. The H I observation also has low SNR = 6 and shows a ring-like structure with a diameter of 1.3 at the 1 $\sigma$ level on the moment-0 map (Fig. 2.5). There is a clear velocity gradient. Neither inclination nor position angle can be constrained from the H I data alone. The optical inclination $i = 43.2^\circ$ and position angle P.A. = 164.7$^\circ$ (Paturel et al., 2003) are adopted to derive the rotation curve. The measured H I flux is $1.3 \pm 0.4$ Jy km s$^{-1}$, corresponding to a mass of $0.7 \pm 0.3 \times 10^9 M_\odot$. Companion UGC 3797, which is 5$'$ away to the east, is detected in H I at the same angular distance but we do not detect any H I tidal tails.
Chapter 2: Refining the $M_{\text{BH}} - V_c$ Scaling Relation with HI Rotation Curves

Figure 2.11 The 20 cm continuum image of NGC 2960. There is extended emission on the south-west side of the central point source at the water maser position, suggesting that there is a jet launched from the galaxy nucleus (§8.1)

8.2 Details of Rotation Curves Estimation

In this section we investigate two complications that may affect rotation curve estimation. First, we consider differences in rotation curves arising from different methods of assigning velocity. Second, we look at tilted ring modeling, which captures warps in the rotation disk, to see if our circular velocities are changed.

As discussed in §3.2, there are various methods to assign velocity to a spectrum, e.g., the peak velocity, the intensity-weighted mean (moment-1), or Gaussian/Gauss-Hermite velocities. The first two methods have some drawbacks. The peak velocity is sensitive to the noise in the data, and is discretized to the channel width of the data cube, and the moment-1 velocity is biased towards the wing if the spectral line is asymmetric. Our preferred method is therefore the Gaussian/Gauss-Hermite fit. The averaged difference between the Gaussian/Gauss-Hermite and the peak velocity (moment-1) velocity field is 17 (18) km s$^{-1}$ for the high SNR galaxies (NGC 2748, NGC 7582, and NGC 1194) and 37 (33) km s$^{-1}$ for low SNR galaxies (NGC 2960 and UGC 3789).
We now propagate these different velocity assignments to investigate the differences in our inferred rotation curves. We focus on two representative galaxies, NGC 7582 (high SNR = 23) and NGC 2960 (low SNR = 6). We use the same MCMC procedure as discussed in §3.3, assuming a homogeneous error in the velocity field of 20 km s\(^{-1}\) for NGC 7582 and 40 km s\(^{-1}\) for NGC 2960, and applying the same masking as in the Gaussian/Gauss-Hermite velocity field to mask out noisy pixels. The fitted rotation curves are shown in Fig. 2.12. The average differences between Gaussian/Gauss-Hermite and the peak velocity (moment-1) rotation curves are 11 (23) km s\(^{-1}\) for NGC 7582 and 67 (39) km s\(^{-1}\) for NGC 2960. Compared to the RMS errors of the Gaussian/Gauss-Hermite rotation curves, which are 24 km s\(^{-1}\) for NGC 7582 and 37 km s\(^{-1}\) for NGC 2960, we found that: First, the peak velocity rotation curve of NGC 7582 is consistent with the Gaussian/Gauss-Hermite rotation curve within the error. However, the peak velocity rotation curve deviates from the Gaussian significantly for the lower SNR galaxy NGC 2960.

These tests confirm our concern that the peak velocity is highly sensitive to noise and is not suitable for estimating the rotation curves for low SNR data. Also, NGC 7582 has a moment-1–derived rotation curve that is systematically lower than the Gaussian/Gauss-Hermite one, with a deviation comparable to the RMS error. This is consistent with our expectation that the moment-1 velocity is biased by the wing of the spectral line. Moment-1 velocities usually underestimate the rotation velocity for high SNR data, due to beam smearing and higher intensity at the inner part of the galaxy. This bias was also demonstrated in the left panel of Fig. 2.6. NGC 2690 has a moment-1 rotation curve that differs from the Gaussian rotation curve at a level that is comparable to the RMS errors as well. In this case we see no systematic bias, possibly because the SNR is not high enough to manifest an asymmetric line shape. Considering these effects, we find that the Gaussian/Gauss-Hermite method is relatively reliable in the face of asymmetric line shapes and noisy data.

In §3.3 we adopt a coplanar disk model for rotation curve fitting. However, this model does not capture the asymmetry in the velocity field that arises from warping of the disk, as seen in NGC 2748 and NGC 7582. Here we assess whether these asymmetries have an effect on our \(V_c\) estimates. We take our most asymmetric galaxy NGC 7582 as an example, and use the \textit{Kinemetry} method (Krajnovi´c et al., 2006) to fit a tilted-ring model. In this model, the position
Figure 2.12 Comparing the rotation curves derived from different velocity fields - Gaussian/Gauss-Hermite (blue), moment-1 (green), and peak velocity (red). The left is NGC 7582 with high SNR = 23, and the right is NGC 2960 with lower SNR = 6. The thick error bars represent the fitted error and the thin error bars are the RMS error. NGC 7582 has $V_c$, the rotation velocity at large radius, from the three velocity fields consistent with each other. However, NGC 2960 has peak-velocity $V_c$ significantly differs from the other two methods. Therefore, the peak velocity may incur large errors in the rotation curves for low SNR data.

angle and the inclination of each ring are allowed to vary. Furthermore, second and third order harmonic terms, e.g., $\sin(2\psi)$ and $\sin(3\psi)$, are included to capture higher frequency variations along each ring. The best-fit models are plotted in Fig. 2.13 with their residuals, and the fitted rotation curves are plotted in Fig. 2.14. The tilted-ring model better captures warps in the disk and reduces the residuals, but the best-fit rotation velocities stay unchanged within the uncertainties. The difference at the outer-most bin is less than 5% of the RMS error. This demonstrates the robustness of the rotation curve fitting against warps and higher order variations of the velocity field, and shows that the RMS error is a conservative estimate of the potential systematics in the rotation curve fitting.

8.3 $V_c$ from Single Dish Measurements

In our secondary sample we have three galaxies (NGC 3368, NGC 3393, NGC 3489) with dynamical $M_{BH}$ but no available rotation curves. However, $V_c$ can also be inferred from the line
Chapter 2: Refining the $M_{\text{BH}} - V_c$ Scaling Relation with HI Rotation Curves

Figure 2.13 Comparing coplanar (top) and tilted-ring (bottom) models for the velocity field of NGC 7582. From left to right we show the data (Gauss-Hermite velocity field), the best-fit model, and the residuals. The coplanar model is described in §3.3 and the tilted-ring model in Appendix 8.2. The color bar represents the color scheme of the residuals. While the tilted-ring model captures the warping feature in the velocity field, we show in Fig. 2.14 that there is very little impact on the inferred rotation curve.

width of integrated H I spectra taken with single dish radio observations ($V_{c,\text{SD}}$), and the single dish $V_c$ for these three galaxies from HyperLeda (Paturel et al., 2003) are listed in Table 2.8.

Since single-dish measurements are more readily available for large samples, they have been used in previous scaling-relation studies (Pizzella et al., 2005; Courteau et al., 2007; Ho, 2007; Beifiori et al., 2012). Roberts (1978) and Ho (2007) find that $V_{c,\text{SD}}$ is a robust substitute for $V_{c,\text{RC}}$. On the other hand, without spatial information, single-dish circular velocities may contain large uncertainties due to the distribution of atomic gas, irregular rotation-curve shape, or contamination from companion galaxies. In general, the values may skew towards lower values, since single-dish measurements are biased to the inner part of the rotation curve.

To understand how much $V_{c,\text{SD}}$ can deviate from $V_{c,\text{RC}}$, we compare the two numbers for all galaxies in our sample that have both measurements (Figure 2.15). For most of the galaxies, $V_{c,\text{SD}}$ is consistent with $V_{c,\text{RC}}$. However for a few of them the two numbers can deviate by up to a factor
Figure 2.14 The rotation curves (top), inclinations (middle), and position angles (bottom) of the coplanar (blue) and Kinemetry tilted-ring (green) models for NGC 7582, for details see Appendix 8.2 and Figure 2.13 above. The error bars in the rotation curve measurements represent the RMS variation in the residual map. The rotation curves of the two models are consistent with each other within the RMS errors, even when the inclination and P.A. of the tilted ring model fluctuates about the coplanar value. The RMS errors in the tilted-ring models are smaller than in the coplanar model by 40% between 60 and 130', meaning that some of the variations are accounted for by the higher-order terms and the tilted-rings of Kinemetry.

of two. These are preferentially S0 galaxies, suggesting that in these cases low gas fractions are skewing the \( V_c, SD \) values low. On the other hand, there are only three galaxies in our sample that only have single-dish H I measurements. In practice, including or excluding these three galaxies from our fitting does not change the result. We decide not to include them in our primary sample.

### 8.4 \( M_{BH} \) Upper Limits

For completeness, dynamically constrained \( M_{BH} \) upper limits for bulgeless galaxies, mostly from Neumayer & Walcher (2012), are listed in the second section of Table 2.8 and 2.9. The \( V_c \) values are assigned as described in §4.1, except for the single-dish \( V_c \), which are from HyperLeda (Paturel et al., 2003). These upper limits are also plotted in Figure 2.8 as gray triangles in both of the scaling relations. Some of them are outliers in the \( M_{BH} - V_c \) relation (see discussion in §6.2).
Figure 2.15 Single dish circular velocity versus rotation curve circular velocity for all galaxies in our sample with both. The solid green line represents $V_{c,SD} = V_{c,RC}$. 
### Table 2.8. $V_c$ Sources for Secondary Sample

<table>
<thead>
<tr>
<th>Galaxy</th>
<th>$V_c$ (km s$^{-1}$)</th>
<th>$V_c$ Method</th>
<th>$V_c$ Trend</th>
<th>Inc. (degrees)</th>
<th>$R_o/R_{25}$</th>
<th>$V_c$ Reference</th>
</tr>
</thead>
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<td>(3)</td>
<td>(4)</td>
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<td>(6)</td>
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<td>...</td>
<td>49</td>
<td>...</td>
<td>2</td>
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<tr>
<td>NGC 3393</td>
<td>157±8</td>
<td>SD</td>
<td>...</td>
<td>31</td>
<td>...</td>
<td>1</td>
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<td>NGC 3489</td>
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**Dynamical $M_{BH}$ with Single dish $V_c$**

<table>
<thead>
<tr>
<th>Galaxy</th>
<th>$V_c$ (km s$^{-1}$)</th>
<th>$V_c$ Method</th>
<th>$V_c$ Trend</th>
<th>Inc. (degrees)</th>
<th>$R_o/R_{25}$</th>
<th>$V_c$ Reference</th>
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</thead>
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<td>190±15±</td>
<td>RC</td>
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<td>25</td>
<td>1.6</td>
<td>3</td>
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<tr>
<td>NGC 0205$^a$</td>
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<td>V-field</td>
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<td>0.2</td>
<td>4</td>
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<tr>
<td>NGC 0300</td>
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<td>2</td>
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<tr>
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<td>oscillating</td>
<td>48</td>
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<td>5</td>
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<td>6</td>
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<tr>
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<td>3</td>
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<tr>
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<td>8</td>
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<td>...</td>
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<td>2</td>
</tr>
<tr>
<td>NGC 7424</td>
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<td>...</td>
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<td>2</td>
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<tr>
<td>NGC 7793</td>
<td>102±5±26</td>
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**Upper-limit $M_{BH}$**

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<th>Galaxy</th>
<th>$V_c$ (km s$^{-1}$)</th>
<th>$V_c$ Method</th>
<th>$V_c$ Trend</th>
<th>Inc. (degrees)</th>
<th>$R_o/R_{25}$</th>
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<td>1.6</td>
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<td>90</td>
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<td>oscillating</td>
<td>48</td>
<td>1.3</td>
<td>5</td>
</tr>
<tr>
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<td>RC</td>
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<td>50</td>
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<td>6</td>
</tr>
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<td>SD</td>
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<td>RC</td>
<td>slightly declining</td>
<td>42</td>
<td>1.3</td>
<td>7</td>
</tr>
</tbody>
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Note. — $V_c$ reliability for the secondary sample. Col. (1): Galaxy name. Col. (2): Circular velocity $V_c$ of the galaxy with reference in col. (7). The first error is the observational error. For rotation curve $V_c$ the second error is the variation in the rotation curve or 20% if the variation is unknown. For rotation curves, $V_c$ is evaluated at the outermost radius $R_o$. Col. (3): The observational method used to derive $V_c$. RC stands for spatially resolved rotation curve, and SD for H I single dish observation. Col. (4): Radial trend in the rotation curve. Col. (5): Inclination used for $V_c$ inclination correction. Col. (6): Ratio between the outermost radius $R_o$ and the galaxy radius at B = 25 mag arcsec$^{-2}$ isophote $R_{25}$ from RC2 (de Vaucouleurs et al., 1995). Col. (7): References for $V_c$: (1) HyperLeda (Paturel et al., 2003); (2) Ho (2007); (3) Sofue et al. (1997); (4) Young & Lo (1997); (5) Cherepashchuk et al. (2010); (6) Corbelli & Salucci (2000); (7) deBlok et al. (2008); (8) Begeman et al. (1991). Notes on individual galaxies: $^a$ $V_c$ is estimated from the H I velocity field as a rotation curve is unavailable.
Table 2.9: $M_{\text{BH}} - V_c$ Secondary Sample

<table>
<thead>
<tr>
<th>Galaxy</th>
<th>Morphology</th>
<th>Distance (Mpc)</th>
<th>$M_{\text{BH}}$ ($M_\odot$)</th>
<th>$M_{\text{BH}}$ Method</th>
<th>$M_{\text{BH}}$ Ref.</th>
<th>$\sigma$ (km s$^{-1}$)</th>
<th>$V_c$ (km s$^{-1}$)</th>
<th>$V_c$ Method</th>
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<td>NGC 3368</td>
<td>S</td>
<td>10.6</td>
<td>$7.6_{-1.5}^{+1.6} \times 10^6$</td>
<td>stars</td>
<td>1</td>
<td>$122^{+28}_{-24}$</td>
<td>203 ± 6</td>
<td>SD</td>
</tr>
<tr>
<td>NGC 3393</td>
<td>S</td>
<td>53.6</td>
<td>$3.3_{-0.2}^{+0.3} \times 10^7$</td>
<td>masers</td>
<td>1</td>
<td>$148_{-10}^{+10}$</td>
<td>157 ± 8</td>
<td>SD</td>
</tr>
<tr>
<td>NGC 3489</td>
<td>S0</td>
<td>12.0</td>
<td>$6.0_{-0.9}^{+0.8} \times 10^6$</td>
<td>stars</td>
<td>1</td>
<td>$100_{-11}^{+15}$</td>
<td>144 ± 14</td>
<td>SD</td>
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Upper-limit $M_{\text{BH}}$

<table>
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<th>Galaxy</th>
<th>Morphology</th>
<th>Distance (Mpc)</th>
<th>$M_{\text{BH}}$ ($M_\odot$)</th>
<th>$M_{\text{BH}}$ Method</th>
<th>$M_{\text{BH}}$ Ref.</th>
<th>$\sigma$ (km s$^{-1}$)</th>
<th>$V_c$ (km s$^{-1}$)</th>
<th>$V_c$ Method</th>
</tr>
</thead>
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<tr>
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<td>S</td>
<td>1.8</td>
<td>$&lt; 5 \times 10^5$</td>
<td>stars</td>
<td>2</td>
<td>33 ± 3</td>
<td>190 ± 15</td>
<td>RC</td>
</tr>
<tr>
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<td>E (dwarf)</td>
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<td>stars</td>
<td>3</td>
<td>39 ± 6</td>
<td>26 ± 5</td>
<td>V-field</td>
</tr>
<tr>
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<td>S</td>
<td>2.2</td>
<td>$&lt; 1 \times 10^5$</td>
<td>stars</td>
<td>4</td>
<td>13 ± 2</td>
<td>80 ± 3</td>
<td>SD</td>
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<td>stars</td>
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<td>24 ± 4</td>
<td>180 ± 50</td>
<td>optical</td>
</tr>
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<td>stars</td>
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<td>32 ± 5</td>
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<td>4</td>
<td>25 ± 4</td>
<td>102 ± 26</td>
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Continued on next page...
Table 2.9: Black hole masses, stellar velocity dispersions, and circular velocities of our secondary sample for either H I single dish $V_c$ or upper-limits for $M_{BH}$. These quantities are plotted in Figure 2.8 in gray with error bars symmetrized in log space. Col. (1): Galaxy Name. Col. (2): Morphology. Col. (3): Distance. Col. (4): Black hole mass measured by method col. (5): from reference col. (6). Col. (7): Stellar velocity dispersion. For the first section (single-dish $V_c$) Col. (2-7) are taken from McConnell & Ma (2013) and original references can be found therein. For the second section ($M_{BH}$ upper-limits) Col. (2-3) are from McConnell & Ma (2013) and Col. (4, 5, 7) are from the $M_{BH}$ references listed in Col. (6). Col. (8): Circular velocity with error taken as the larger one of observational or RC variation error (see Table 2.8). Col. (9): The observational method of $V_c$. SD stands for spatially unresolved single dish $V_c$, RC for H I rotation curve $V_c$, H I V-field for spatially resolved data but unavailable rotation curves, and optical for optical rotation curves.

References: (1) McConnell & Ma (2013); (2) Böker et al. (1999); (3) Valluri et al. (2005); (4) Neumayer & Walcher (2012); (5) Gebhardt et al. (2001); (6) Barth et al. (2009); (7) Kormendy et al. (2010)
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Chapter 3

ALMA Observations of a Candidate Molecular Outflow in an Obscured Quasar

abstract

We present Atacama Large Millimeter/Submillimeter Array (ALMA) CO (1-0) and CO (3-2) observations of SDSS J135646.10+102609.0, an obscured quasar and ultra-luminous infrared galaxy (ULIRG) with two merging nuclei and a known 20-kpc-scale ionized outflow. The total molecular gas mass is $M_{\text{mol}} \approx 9^{+19}_{-6} \times 10^8 \, M_\odot$, mostly distributed in a compact rotating disk at the primary nucleus ($M_{\text{mol}} \approx 3 \times 10^8 \, M_\odot$) and an extended tidal arm ($M_{\text{mol}} \approx 5 \times 10^8 \, M_\odot$). The tidal arm is one of the most massive molecular tidal features known; we suggest that it is due to the lower chance of shock dissociation in this elliptical/disk galaxy merger. In the spatially resolved CO (3-2) data, we find a compact ($r \approx 0.3 \, \text{kpc}$) high velocity ($v \approx 500 \, \text{km s}^{-1}$) red-shifted feature in addition to the rotation at the N nucleus. We propose a molecular outflow as the most likely explanation for the high velocity gas. The outflowing mass of $M_{\text{mol}} \approx 7 \times 10^7 \, M_\odot$ and the short dynamical time of $t_{\text{dyn}} \approx 0.6 \, \text{Myr}$ yield a very high outflow rate of $\dot{M}_{\text{mol}} \approx 350 \, M_\odot \, \text{yr}^{-1}$ and can deplete the gas in a million years. We find a low star formation rate ($< 16 \, M_\odot \, \text{yr}^{-1}$ from the molecular content and $< 21 \, M_\odot \, \text{yr}^{-1}$ from the far-infrared spectral energy distribution decomposition) that is inadequate to supply the kinetic luminosity of the outflow ($\dot{E} \approx 3 \times 10^{43} \, \text{ergs s}^{-1}$). Therefore, the active galactic nucleus, with a bolometric luminosity of $10^{46} \, \text{ergs s}^{-1}$, likely powers the outflow. The momentum boost rate of the outflow ($\dot{p}/(L_{\text{bol}}/c) \approx 3$) is lower than typical molecular outflows associated with AGN, which may be
related to its compactness. The molecular and ionized outflows are likely two distinct bursts induced by episodic AGN activity that varies on a time scale of $10^7$ yr.

1 Introduction

In the past decade, supermassive black holes (BHs) have been found to be a common constituent of galaxy centers (e.g., Kormendy & Ho, 2013). At the same time, we have come to appreciate that supermassive BHs may play an active role in shaping galaxy evolution through feedback in the active galactic nucleus (AGN) phase (e.g., Fabian, 2012). The steep high-mass cut-off in the galaxy luminosity function (e.g., Bower et al., 2006) and the over-production of massive blue galaxies in cosmological simulations (e.g., Croton et al., 2006) requires a mechanism to quench star formation at the high-mass end. The enormous amount of energy released by black hole accretion provides a way to heat up or expel gas on galaxy-wide scales (e.g., Ciotti & Ostriker, 2001; Faucher-Giguère & Quataert, 2012). This kind of AGN feedback may regulate star formation (e.g., Page et al., 2012) and/or BH growth (e.g., Booth & Schaye, 2010) in a way that links the evolution of the BH and the galaxy and results in the local BH scaling relations (e.g., McConnell & Ma, 2013; Kormendy & Ho, 2013; Sun et al., 2013).

The actual mechanisms that link the AGN with galaxy-scale gas remain unknown. There have been many studies searching for outflows in different gas phases, including X-ray emitting hot gas (e.g., Wang et al., 2009, 2011; Greene et al., 2014), warm ionized (e.g., Stockton & MacKenty, 1987; Whittle, 1992; Nesvadba et al., 2006; Fu & Stockton, 2008; Greene et al., 2011; Villar-Martín et al., 2011; Rupke & Veilleux, 2013; Yuma et al., 2013; Liu et al., 2013a; Hainline et al., 2013; Villar-Martín et al., 2014; Zakamska & Greene, 2014), neutral (e.g., Rupke et al., 2005; Teng et al., 2013), and cold molecular gas (e.g., Walter et al., 2002; Feruglio et al., 2010; Alatalo et al., 2011; Sturm et al., 2011; Aalto et al., 2012; Flower & Pineau des Forêts, 2013; Feruglio et al., 2012; Veilleux et al., 2013; Cicone et al., 2014). As has been shown by these studies, AGN-driven outflow is a complex phenomenon involving gas at a wide range of temperatures, densities, and distributions. Identifying the driving mechanism of the outflow, e.g. star formation or AGN, is challenging in many cases, in particular because of ambiguities between
star formation and AGN activity indicators. Therefore, multi-wavelength observations are essential to put together a comprehensive picture of AGN feedback.

Only recently have we come to appreciate the ubiquity of molecular outflows. They are commonly seen in Herschel OH spectroscopy (e.g., Sturm et al., 2011; Veilleux et al., 2013). Also, exciting evidence from interferometric observations suggest that these molecular outflows are massive, with a high mass loss rate that can deplete the cold gas in the galaxy in $10^6 - 10^8$ yr (e.g., Feruglio et al., 2010; Alatalo et al., 2011; Cicone et al., 2014). As molecular gas is the fuel for star formation, monitoring the molecular content in the host galaxy is key to determining whether or not the AGN can quench star formation and shape galaxy evolution.

In this paper, we inspect the molecular properties of the obscured quasar SDSS J1356+1026 with the Atacama Large Millimeter/Submillimeter Array (ALMA), looking for traces of the impact of the AGN on the cold gas component in the galaxy. SDSS J1356+1026 is an example of feedback in action; an extended and energetic outflow is detected in ionized gas that is most likely AGN-driven (Greene et al., 2012). The spatially resolved ALMA CO (1-0) and CO (3-2) observations presented here allow us to constrain the morphology, kinematics, and mass of the molecular gas and to investigate the relation between the molecular gas and the ionized outflow.

Throughout, we assume $h = H_0/100$ km s$^{-1}$ Mpc$^{-1} = 0.7$, $\Omega_m = 0.3$, and $\Omega_\Lambda = 0.7$. At the redshift of the object ($z=0.1231$), 1″ corresponds to 2.2 kpc, and the luminosity distance is 580 Mpc. All velocities used in this paper are in the heliocentric frame using the optical velocity convention. Wavelengths are expressed in vacuum.

### 1.1 SDSS J1356+1026

SDSS J1356+1026 is a merging system at $z=0.123$ classified as a luminous obscured (Type 2) quasar with a bolometric luminosity $L_{\text{bol}} \approx 10^{46}$ ergs s$^{-1}$ inferred from the [O III] luminosity, $L_{[\text{OIII}]} = 10^{42.77}$ ergs s$^{-1}$ (Greene et al., 2009; Liu et al., 2009). It is also an ultra-luminous infrared galaxy (ULIRG; $L_{\text{FIR}} = 2.68 \pm 0.53 \times 10^{45}$ ergs s$^{-1}$). The radio continuum is unresolved with a luminosity density of $\nu L_\nu = 3.4 \times 10^{40}$ ergs s$^{-1}$ from the VLA FIRST survey at 1.4 GHz.
Figure 3.1 Integrated line intensity (moment-0) maps for SDSS J1356+1026 in CO (1-0) (left) and CO (3-2) (right) are shown in color. These moment-0 maps are integrated over a velocity range of $-300$ to $+300$ km s$^{-1}$. $1\sigma$ noise level is 0.15 Jy beam$^{-1}$ km s$^{-1}$ and 0.16 Jy beam$^{-1}$ km s$^{-1}$ for CO (1-0) and CO (3-2) respectively. The beam ellipse is shown in the lower left corner. Contours show intensity of optical emission as seen in the HST/WFC3 F814W $I$-band images and are spaced by a factor of two in intensity. The CO emission is most prominent at the N nucleus and the W arm $2''$ to the west of the N nucleus. Emission at the S nucleus is also detected in CO (1-0) in certain channels, see Fig. 3.3. The red clump at the bottom of the CO (1-0) map is noise at $3\sigma$ level. The green region marks the ionized outflow, and the magenta region is its base. There is no detection of a CO counterpart to the extended (10 kpc) ionized [O III] outflow. The red line across the N nucleus on the right panel indicates the pv-diagram cut (Fig. 3.7).
Chapter 3: ALMA Observations of a Candidate Molecular Outflow in an Obscured Quasar

(1.6 GHz rest frame), indicating that it is a radio-quiet quasar (Greene et al., 2012). The coordinate of SDSS J1356+1026 is (13:56:46.10, +10:26:09.09).

The two merging galaxies, which we refer to as the northern (N) and southern (S) nuclei, are separated by 2.5 kpc (17′1). The N nucleus is detected at 2-10 keV and is the primary AGN host in the system (Greene et al. 2014). Both the total molecular mass (Section 3.3) and the r-band light (Greene et al., 2009) are dominated by the northern nucleus, with a ratio of ∼4 : 1 (N:S).

The progenitor of the northern galaxy is likely a moderately massive early-type galaxy, with a stellar spectrum that is dominated by an old stellar population and a stellar velocity dispersion \( \sigma_* = 206 \pm 36 \text{ km s}^{-1} \) (Greene et al., 2009), corresponding to a stellar mass \( M_* \approx 10^{11} M_\odot \) (Hyde & Bernardi, 2009), and the black hole mass is estimated to be \( M_{BH} \approx 3 \times 10^8 M_\odot \) \((\pm0.38 \text{ dex, McConnell & Ma, 2013})\). The corresponding Eddington luminosity is \( L_{\text{Edd}} = 3.1 \times 10^{46} \text{ ergs s}^{-1} \) \((\pm0.38 \text{ dex})\), which yields an Eddington ratio range of 0.1-1, energetic enough to drive a hot wind (e.g., Veilleux et al., 2005).

The most spectacular feature of this system is an [O III]-emitting bubble extending ∼10 kpc to the south of the nuclei (green region in Fig. 3.1), with a weaker symmetric counterpart to the north. Long-slit spectroscopy along the outflow reveals the distinctive double-peaked spectrum of an expanding shell. A simple geometric model yields a deprojected velocity \( v \approx 1000 \text{ km s}^{-1} \), a dynamical time \( t_{\text{dyn}} \approx 10^7 \text{ yr} \), and a kinetic luminosity \( \dot{E} \approx 10^{44-45} \text{ ergs s}^{-1} \) (Greene et al., 2012). As the radio emission is compact and faint (Sec. 3.1, 5.2), and the star formation rate is low (Sec. 3.3, 3.4), this ionized outflow provides a strong case for a quasar-driven wind (Greene et al., 2014).

2 Observations

2.1 ALMA CO (1-0) and CO (3-2) Observations

The ALMA CO (1-0) and CO (3-2) observations were conducted during Cycle 0 and Cycle 1 under project codes 2011.0.00652.S and 2012.1.00797.S respectively. The CO (1-0), at sky frequency 102.6 GHz, was observed in band 3 in two blocks on May 9 and July 30, 2012, using 16 and 23 12-m antennae for 68 and 63 minutes respectively (27 and 24 minutes on-source). The CO
(3-2) at 307.9 GHz was observed in band 7 on July 6, 2013 with twenty-seven 12-m antennae in 24 minutes (19 minutes on-source). In the following, CO (1-0) properties are followed by CO (3-2) in parenthesis. Both lines use a single pointing covering the whole system with a field of view of 62″ (21″), and dual polarizations. They use the same spectral set-up with a total bandwidth of 2 GHz divided into 128 channels, each 15.625 MHz wide, corresponding to a channel width of 46 km s\(^{-1}\) (15 km s\(^{-1}\)). The CO (1-0) data has an additional spectral window at 93 GHz. The channels are Hanning-smoothed within the correlator. QSO 3C279 (J1516+0015), Mars (Titan), and J1415+133 (J1347+1217) were used for the bandpass, flux, and phase calibrators respectively. The phase calibrator is observed for 30 (90) seconds every 11 (9) minutes. The absolute flux calibration accuracy is 5% for CO (1-0) (Band 3) and 10% for CO (3-2) (Band 7).

The data calibration was carried out by the ALMA team using CASA version 3.3.0 for CO (1-0) and 4.1.0 for CO (3-2). We further used CASA version 4.1.0 to apply continuum subtraction [CO (1-0) only], heliocentric correction, imaging, and cleaning. For CO (1-0), the continuum level was estimated from line free channels (36/43 channels on the blue/red side) and subtracted in the \(uv\)-plane. Continuum subtraction was not applied to the CO (3-2) data cube as there are not enough line-free channels to determine the continuum level. However, we extrapolate from the 100 GHz and 1.4 GHz continuum flux densities (spectral index \(\alpha = -0.86\), Sec. 3.4) to estimate a 300 GHz flux density of 0.58 mJy. This extrapolated continuum level is lower than the noise level in each CO (3-2) channel and is less than 10% of the emission line flux density at the N nucleus. The CO (3-2) channel is further binned by two to increase the SNR in each channel, giving a final channel width of 30 km s\(^{-1}\), while the CO (1-0) channel width is unchanged (46 km s\(^{-1}\)).

The imaging processing was carried out with the CASA task \textit{clean}. We used the \textit{Briggs} visibility weighting with a \textit{robustness} parameter of 0.5 (Briggs, 1995), which is a compromise between maximum resolution and maximum sensitivity. The beam size is \(\theta_{\text{beam}} = 1″.9 \times 1″.3 \ (0″.35 \times 0″.29)\) with a PA=−62° (−60°), and the maximum resolvable scale is \(\theta_{\text{MRS}} = 29″ \ (10″)\). All images are cleaned to the 3 \(\sigma\) level in each channel. The resulting RMS noise level in each channel is 0.37 mJy beam\(^{-1}\) (0.77 mJy beam\(^{-1}\)).
<table>
<thead>
<tr>
<th>Name</th>
<th>Δν (km s⁻¹)</th>
<th>SνΔν (Jy km s⁻¹)</th>
<th>L (10³ L⊙)</th>
<th>L' (10⁹ K km s⁻¹ pc²)</th>
<th>SνΔν (Jy km s⁻¹)</th>
<th>L (10³ L⊙)</th>
<th>L' (10⁹ K km s⁻¹ pc²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>N Nucleus</td>
<td>-300 : 500</td>
<td>0.46 ± 0.27</td>
<td>16.6 ± 9.6</td>
<td>0.34 ± 0.19</td>
<td>4.90 ± 0.22</td>
<td>528 ± 24</td>
<td>0.40 ± 0.02</td>
</tr>
<tr>
<td>N Outflow</td>
<td>300 : 500</td>
<td>0.06 ± 0.08</td>
<td>2.2 ± 2.7</td>
<td>0.04 ± 0.06</td>
<td>0.99 ± 0.10</td>
<td>107 ± 11</td>
<td>0.08 ± 0.01</td>
</tr>
<tr>
<td>S Nucleus</td>
<td>-80 : 50</td>
<td>0.13 ± 0.06</td>
<td>4.5 ± 2.2</td>
<td>0.09 ± 0.04</td>
<td>0.11 ± 0.07</td>
<td>12 ± 7</td>
<td>0.01 ± 0.01</td>
</tr>
<tr>
<td>W Arm</td>
<td>-300 : 500</td>
<td>0.82 ± 0.34</td>
<td>29.3 ± 12.2</td>
<td>0.60 ± 0.25</td>
<td>2.55 ± 0.40</td>
<td>275 ± 44</td>
<td>0.21 ± 0.03</td>
</tr>
<tr>
<td>Sum</td>
<td>-300 : 500</td>
<td>1.40 ± 0.44</td>
<td>50.4 ± 15.7</td>
<td>1.03 ± 0.32</td>
<td>7.57 ± 0.46</td>
<td>815 ± 50</td>
<td>0.62 ± 0.04</td>
</tr>
</tbody>
</table>

Note. — The CO (1-0) and CO (3-2) fluxes and derived properties of the main components (Sec. 3.2). Columns 3 to 5 pertain to CO (1-0) and columns 6 to 8 pertain to CO (3-2). The last row is a sum of the three components: the N/S nuclei and the W arm. The listed errors correspond to the RMS noise in the data. In addition, there is a 5% and 10% flux calibration error for CO (1-0) and CO (3-2) respectively. The CO (1-0) flux errors of the N nucleus and W arm also include errors due to source decomposition. Column 1: component. Column 2: the velocity range over which the flux is integrated. Column 3: integrated CO (1-0) flux. Column 4: the CO (1-0) line luminosity, adopting a luminosity distance of 580 Mpc. Column 5: the emitting area and velocity integrated CO (1-0) source brightness temperature. Column 6: integrated CO (3-2) flux. Column 7: the CO (3-2) line luminosity, adopting a luminosity distance of 580 Mpc. Column 8: the emitting area and velocity integrated CO (3-2) source brightness temperature.
2.2 Matching ALMA with Optical Data

In order to compare the molecular and stellar components of the galaxies, we match the ALMA data cube to the SDSS spectrum in velocity and the Hubble Space Telescope HST/WFC3 F814W (I-band) image in position (Comerford et al. in prep.). We use the SDSS DR7 spectrum (Abazajian et al., 2009), which was taken in a 3′′ aperture with a spectral resolution of FWHM ≈ 150 km s$^{-1}$ centered on the N nucleus. The HST/WFC3 F814W image was observed on May 19 2012 with an integration time of 900 seconds and resolution of 0.′′07.

To perform positional alignment, we identify another galaxy SDSS J135646.50+102553.6 that appears in the ALMA, SDSS, and HST images, and two other fainter galaxies in both SDSS and HST. We found that while the ALMA and SDSS positions are well-matched, there is a 0.′′6 offset from the HST position. After applying this offset to the HST image, the ALMA (continuum) and HST coordinates of the northern nucleus are aligned well within 0.′′04, much smaller than the ALMA CO (3-2) beam size (0.′′35 × 0.′′29). Rotation and stretching of the HST image with respect to the SDSS coordinates are also constrained to be within 0.4° rotation and 0.5% stretching.

The velocities in this paper are with respect to the rest frame of the stellar absorption features of N galaxy. We define the systemic velocity to be the best-fit redshift (z = 0.1231) from the SDSS spectrum, which is dominated by the light of the N nucleus, as the N nucleus is brighter and the fiber is centered on it. Both the stellar absorption and AGN emission lines are fitted by the SDSS template. A redshift warning flag “many outliers” is raised, indicating that the template cannot capture the multi-component emission lines, but this is not a major concern for redshift accuracy. As a sanity check, we refit the stellar continuum using Bruzual & Charlot (2003) stellar population synthesis templates and the best-fit redshift differs from that of the SDSS by −30 km s$^{-1}$. We therefore adopt a redshift error of δz = ±0.0001 (± 30 km s$^{-1}$). This stellar continuum fitting also reveals that the light in the N nucleus is dominated by old stellar populations, as discussed in Greene et al. (2009).
Figure 3.2 SDSS J1356+1026 CO (1-0) (left) and CO (3-2) (right) channel maps in color. Each of the channel maps is 100 km s$^{-1}$ wide in velocity. The 1-σ noise level of the image is 0.31 mJy beam$^{-1}$ km s$^{-1}$ and 0.32 mJy beam$^{-1}$ km s$^{-1}$ for CO (1-0) and CO (3-2) respectively. The beam ellipse is shown in the lower left corner. Contours show intensity of optical emission as seen in the HST/WFC3 F814W $I$–band images and are spaced by a factor of two in intensity. The N nucleus is prominent with a wide velocity range between $-300$ to $500$ km s$^{-1}$ especially in the CO (3-2) maps. The W arm is strong in two channels $-200$ and $-100$ km s$^{-1}$, and the S nucleus can be seen at 0 km s$^{-1}$ in the CO (1-0) maps.
Figure 3.3 CO (1-0) (left) and CO (3-2) (right) spectra of the N/S nucleus and the W arm. The N nucleus has wide line width in both CO (1-0) and CO (3-2), and the peak at $-100$ km s$^{-1}$ in the CO (1-0) spectrum is contamination from the W arm. The W arm has relatively narrow line width, reflecting its coherent kinematics structure across the arm. The S nucleus is fainter and is detected only in CO (1-0). The dashed horizontal lines indicate the $1\sigma$ noise level. To avoid contamination between sources, the CO (1-0) spectra are integrated only over one beam size, and therefore do not include all the flux in the sources. The CO (3-2) spectra are integrated over regions at least twice as large as the beam, and therefore contains $\sim 95\%$ of the flux in the N nucleus.

3 Analysis

In this section, we describe our procedures to estimate the 100 GHz continuum flux density, CO (1-0) and CO (3-2) line fluxes, molecular gas masses, the star formation rate, and the AGN bolometric luminosity. The measurements are summarized in Tables 3.1 and 3.2, and will be discussed in Section 4.

We first introduce the three major components in the CO data: the N nucleus, the S nucleus, and the Western arm (W). All three are spatially coincident with optical features. The N nucleus has strong emission from both CO (1-0) and CO (3-2), as seen in the integrated line intensity maps (moment-0, Fig. 3.1) and the channel maps (Fig. 3.2) with a very broad spectrum (Fig. 3.3). The S nucleus is not detected in CO (3-2), but is seen in CO (1-0) (Fig. 3.3). To the west of the N nucleus is another strong blue-shifted and extended emission feature in both transitions, which we call the W arm. This feature overlaps with an extended stellar plume in the HST images, and has blue-shifted but narrow CO lines. Other than these three main components, no
Figure 3.4 100 GHz radio continuum image (color) overlaid with the HST/F814W image (contour). The contours of the HST image are in log scale; each contour differs by a factor of 2. The radio image is made from line-free channels at the two spectral windows of 93/103 GHz (rest-frame 104/115 GHz), each 2 GHz wide. There is one unresolved radio continuum source associated with the N nucleus, likely from the AGN (see Fig. 3.5).

prominent CO emission is detected. There is no large-scale molecular gas associated with the [O III] outflow discovered by Greene et al. (2012), but there is a low significance (3 σ) double-peaked CO (3-2) emission component at the base of the [O III] expanding bubble (Sec. 4.4).

3.1 100 GHz Continuum

The radio 100 GHz continuum is measured from the line-free channels in two spectral windows at 93/103 GHz (rest-frame 104/115 GHz) in the CO (1-0) data. The moment-0 map (Fig. 3.4) shows an unresolved point source with a beam size of 1″9 × 1″3 (4.2 × 2.9 kpc) at the N nucleus with a flux density of 1.51 ± 0.07 ± 0.07 mJy. The first error is from the RMS noise, and the
second is the 5% calibration error. The spectral energy distribution of SDSS J1356+1026 including this 100 GHz flux density is discussed in Section 3.4.

3.2 CO Flux Measurements

We extract the CO(1-0)/(3-2) spectra (flux densities $F_\nu$, Fig. 3.3), and fluxes ($F = F_\nu \Delta v$, Table 3.1) for the three components (the N/S nuclei and the W arm) from the cleaned data. In addition to the RMS noise errors presented in Fig. 3.3 and Table 3.1, there is a 5 % and 10 % flux calibration error for the CO (1-0) and CO (3-2) data respectively. We start with the CO (3-2) data as it has higher resolution to spatially separate the components. We use simple aperture photometry with apertures at least twice as large as the beam in order to enclose $\geq 95\%$ of the flux. As the N and W apertures are adjacent to each other, we expect flux contamination between these two components at a level of 10% or less for CO (3-2). The S aperture is well-separated from the other two sources and does not overlap with side-lobes of the N nucleus.

Assuming Gaussian noise correlated on the scale of the beam, we estimate the errors in the spectra $F_\nu$ based on the image noise level $\text{rms}(I_\nu)$, taken from large emission-free regions, the beam $B(r)$, a 2D Gaussian with peak value 1, and the aperture $T(r) = 1$ inside the aperture and zero everywhere else, adopting the following equation:

$$\text{rms}(F_\nu) = \text{rms}(I_\nu) \sqrt{\int \int B(r_2 - r_1) T(r_1) T(r_2) d^2 r_1 d^2 r_2. \quad (3.1)}$$

To obtain the fluxes $F$, we integrate the spectra $F_\nu$ over a velocity range of $-300 \text{ km s}^{-1} < v < 500 \text{ km s}^{-1}$ for the N nucleus and W arm, which is chosen as the velocity width where the CO (3-2) flux density is detected with greater than 2 $\sigma$ significance from the N nucleus. A velocity range of $300 \text{ km s}^{-1} < v < 500 \text{ km s}^{-1}$ is used for the high velocity component of the N nucleus. For the S nucleus, although there is no CO (3-2) detection, we use the velocity range $-80 < v < 50\text{ km s}^{-1}$ which covers the $> 1 \sigma$ CO (1-0) emission. While estimating the errors in the fluxes, we take into account the correlation between adjacent channels, which has a Pearson
correlation coefficient of $r = 0.375$, due to Hanning smoothing during the observation and 2:1 binning in the image processing.

Estimating the CO (1-0) fluxes is more complicated, as the sources, especially the N nucleus and the W arm, are spatially blended. The CO (1-0) spectrum of the N nucleus clearly shows the narrow peak of the W arm at $-100$ km s$^{-1}$ (Fig. 3.3). However, we can still extract the uncontaminated N nucleus fluxes making use of their distinct spectral shape. We first estimate the N nucleus flux in the 100 to 500 km s$^{-1}$ channels that are free from W arm emission by fitting a model of the beam to the stacked moment-0 map of these channels. This point-source assumption should be valid as the CO (1-0) beam is much larger than the CO (3-2) N nucleus size. We then recover the total N nucleus CO (1-0) flux in the entire velocity range ($-300$ to 500 km s$^{-1}$) assuming that the CO (1-0) spectrum has a similar spectral shape to the CO (3-2) spectrum.

The W arm CO (1-0) flux is then estimated as the difference between the total flux including both sources and the decomposed N nucleus flux. The CO (1-0) flux in the high velocity component of the N nucleus is estimated by the same point source fitting procedure over the velocity range of 300 to 500 km s$^{-1}$, as is the S nucleus over a velocity range of $-80$ to 50 km s$^{-1}$, where the emission is seen. Correlations between adjacent channels are determined from emission-free regions and are taken into account for the flux error estimation. Using the estimated fluxes of the components in both lines, we express the line ratio as $L'_{\text{CO}(3-2)}/L'_{\text{CO}(1-0)}$ in Table 3.2, where $L'$ is in units of K km s$^{-1}$ pc$^2$, proportional to the brightness temperature.

### 3.3 Molecular Gas Mass and Star Formation Rate

From the measured CO (1-0) luminosity we can estimate the molecular gas mass (e.g., Bolatto et al., 2013). The masses are listed in Table 3.2. The CO-to-H$_2$ conversion factor $X_{\text{CO}}$ is defined as

$$X_{\text{CO}} = N_{\text{mol}}/W(\text{CO}(1-0)), \quad (3.2)$$
Table 3.2. Molecular Gas Properties

<table>
<thead>
<tr>
<th>Name</th>
<th>$M_{\text{mol}} (M_\odot)$</th>
<th>$L'<em>{\text{CO}(3-2)}/L'</em>{\text{CO}(1-0)}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>N Nucleus</td>
<td>$3^{+6}_{-2} \times 10^8$</td>
<td>$1.18 \pm 0.73$</td>
</tr>
<tr>
<td>N Outflow</td>
<td>$7^{+15}_{-5} \times 10^7$ a</td>
<td>$&gt; 0.45$ b</td>
</tr>
<tr>
<td>S Nucleus</td>
<td>$&lt; 3.8 \times 10^8$ c</td>
<td>$0.10 \pm 0.11$</td>
</tr>
<tr>
<td>W Arm</td>
<td>$5^{+11}_{-3} \times 10^8$</td>
<td>$0.35 \pm 0.20$</td>
</tr>
<tr>
<td>Sum</td>
<td>$9^{+19}_{-6} \times 10^8$</td>
<td>$0.60 \pm 0.22$</td>
</tr>
</tbody>
</table>

Note. — The molecular gas properties. Column 1: component. Column 2: the molecular gas mass (Sec. 3.3). The errors are dominated by the 0.5 dex error in the $X_{\text{CO}}$ factor. Column 3: the CO (3-2) to CO (1-0) ratio (Sec. 3.2), where $L'$ is in unit of K km s$^{-1}$ pc$^2$. The errors are inferred from the RMS noise.

a The molecular outflow mass is estimated from the CO (3-2) flux assuming $L'_{\text{CO}(3-2)}/L'_{\text{CO}(1-0)} = 1$.

b 3 $\sigma$ lower-limit.

c This is a conservative upper-limit inferred from the CO (1-0) 3 $\sigma$ detection limit and the $X_{\text{CO}}$ uncertainty is taken into account.
Figure 3.5 Rest-frame spectral energy distribution of SDSS J1356+1026 (Sec. 3.4, Table 3.3). The black points are taken from the SED summarized by Greene et al. (2012). In addition, we include the WISE (blue), Herschel (red), and ALMA 100 GHz (green, Sec. 3.1) photometry. The solid black line shows the best-fit two-temperature modified black-body model fitted to the 22 µm WISE, 60 µm IRAS, and 70-350 µm Herschel data. The warm component (blue solid line) has a best-fit temperature of 81 K, while the temperature of the cold component (red solid line) is fixed at 35 K. The grey dashed line on the right panel links the ALMA 100 GHz and FIRST 1.4 GHz (from Greene et al., 2012) points with a spectral index of $\alpha = -0.86$ ($F_\nu \propto \nu^\alpha$).

where $N_{\text{mol}}$ is the molecular column density in units of cm$^{-2}$, and $W(\text{CO}(1-0))$ is the CO (1-0) brightness in units of K km s$^{-1}$. Although $X_{\text{CO}}$ is roughly constant in normal Galactic molecular clouds (Solomon et al., 1987), it is found to be lower in ULIRG/starburst galaxies by a factor of 2-5 with large scatter (Downes & Solomon, 1998). Likely because the molecular clouds blend together due to tidal forces in the dense environment of the ULIRG nucleus, the CO emission emerges from a diffuse volume-filling medium rather than discrete self-gravitating molecular clouds.

SDSS J1356+1026 is identified as a ULIRG and has disturbed gas dynamics, so we adopt an $X_{\text{CO}}$ value for ULIRGs $X_{\text{CO}} = 0.4 \times 10^{20}$ cm$^{-2}$ (K km s$^{-1}$)$^{-1}$ with an error of 0.5 dex (Downes & Solomon, 1998; Bolatto et al., 2013). This corresponds to $\alpha_{\text{CO}} = 0.86$ $M_\odot$ (K kms pc$^2$)$^{-1}$, matching the value used in other ULIRG/AGN CO studies (e.g., Cicone et al., 2014). This factor of three uncertainty in the $X_{\text{CO}}$ factor dominates the errors in the mass estimates. We find a total molecular mass of $9^{+19}_{-6} \times 10^8$ $M_\odot$. Half of the molecular mass is in the extended W arm ($5^{+11}_{-3} \times 10^8$ $M_\odot$), while the N nucleus shares a third ($3^{+6}_{-2} \times 10^8$ $M_\odot$). As CO (1-0) is only
marginally detected at the S nucleus, a conservative mass limit of $< 3.8 \times 10^8 M_\odot$ is estimated from the 3 $\sigma$ detection limit and the uncertainty in $X_{\text{CO}}$.

Since molecular gas is the fuel for star formation, we can estimate the star formation that can be supported by the molecular content in SDSS J1356+1026. Using the Schmidt-Kennicutt law (Kennicutt, 1998), we find the star formation rate at the N nucleus to be $\text{SFR}=1.2 \ M_\odot \ yr^{-1}$ ($\pm$ 0.5 dex) assuming that all of the molecular gas at the N nucleus is distributed in a disk with a radius of 300 pc, half of the beam deconvolved source FWHM in CO (3-2). As the morphology of the molecular gas in the W arm and the S nucleus are uncertain, their SFR is poorly constrained. A conservatively high estimate of the entire system can be calculated by putting all the molecular gas, including that in the diffuse W arm, in a disk with a radius of 300 pc, which gives 5 $M_\odot \ yr^{-1}$. Taking the factor of three $X_{\text{CO}}$ uncertainty into account, an absolute upper-limit is placed at 16 $M_\odot \ yr^{-1}$. However, the star formation rate inferred from the CO luminosity is indirect. Whether the assumed $X_{\text{CO}}$ factor and/or the Schmidt-Kennicutt law apply in this environment is uncertain. In the following section, we constrain the star formation rate directly from the infrared spectral energy distribution (SED) decomposition.

### 3.4 SED, Star Formation Rate and AGN Bolometric Luminosity

We use the infrared spectral energy distribution (SED) decomposition to constrain the star formation rate (Fig. 3.5, Table 3.3). It is usually thought that the dust close to the AGN is heated to much higher temperature than the diffuse dust heated by starlight. The difference in the dust temperatures is at the core of the SED-fitting method to distinguish between AGN-dominated and star formation-dominated sources. Greene et al. (2012) compiled a UV to radio spectral energy distribution (SED) of SDSS J1356+1026 making use of the 2MASS (Skrutskie et al., 2006), IRAS (Neugebauer et al., 1984), FIRST (Becker et al., 1995), and NVSS (Condon et al., 1998) data. We further include data from the Wide-field Infrared Survey Explorer WISE (Wright et al., 2010) and the Herschel Space Observatory (Pilbratt et al., 2010) PACS (Poglitsch et al., 2010) and SPIRE (Griffin et al., 2010) data from Petric et al. in prep., which extends to 500 $\mu$m to cover the Rayleigh-Jeans tail of the dust emission.
Following the decomposition procedures of Kirkpatrick et al. (2012) we fit a two-temperature modified blackbody to the seven-point SED. This SED of 22 µm WISE, 60 µm IRAS, and 70-350 µm Herschel is sensitive to the temperature of the dust emission. There are three free parameters in the model: the temperature \( T_{\text{warm}} \) and luminosity \( L_{\text{warm}} \) of the warm component and the luminosity of the cold component \( L_{\text{cold}} \). The temperature of the cold dust is fixed at \( T_{\text{cold}} = 35 \) K, as found in a wide range of systems by Kirkpatrick et al. (2012). Even if we fit the temperature of the cold component we recover \( T_{\text{cold}} = 35 \) K. The emissivity of the dust is assumed to be a power-law function of frequency with index \( \beta = 1.5 \). All photometry errors are assumed to be 10\%, which is representative of the systematic errors. The best-fit model (black line, Fig. 3.5) matches the data well with a reduced \( \chi^2 \) of 1. The best-fit temperature of the warm component is high \( T_{\text{warm}} = 81 \) K, and the luminosity is \( L_{\text{warm}} = 2.6 \times 10^{45} \) ergs s\(^{-1}\), much higher than that of the cold component \( L_{\text{cold}} = 4.3 \times 10^{44} \) ergs s\(^{-1}\).

The luminosity-weighted temperature \( T_{\text{eff}} = 75 \) K is higher than that seen in Kirkpatrick et al. (2012) even in those of their objects that have an AGN dominated SED (\( T_{\text{eff}} = 65 \) K). Therefore, as the warm component is consistent with being AGN-heated, the AGN is the major heating source for the bulk of the dust-emission. However, star-formation cannot be ruled out as the heating source for the 35 K cold component. We therefore use the luminosity of this 35 K component as an upper limit on the luminosity of dust emission associated with star formation, and use calibrations from Bell (2003) to calculate an upper limit on the star formation rate of 21 \( M_\odot \) yr\(^{-1}\). If the SFR were much higher, at the same \( T_{\text{cold}} \), the dust emission would exceed the measured 250 µm to 350 µm flux. This SFR upper-limit is insensitive to the temperature and luminosity of the warm component because the 250 µm and 350 µm luminosities are dominated by the cold component. Harrison et al. (2014) estimated a higher star formation rate of \( 63^{+7}_{-17} \) \( M_\odot \) yr\(^{-1}\), inconsistent with our limit. This high SFR is inferred from the WISE and IRAS data alone covering 4.6 µm to 100 µm. In this case, the Herschel photometry at 250 µm and 350 µm are critical for the SED decomposition and SFR estimation.

We plot our measured 100 GHz flux (Sec. 3.1) in the SED (right panel of Fig. 3.5). The flux at 100 GHz is much higher than the extrapolated Rayleigh-Jeans tail of the dust emission, and thus must have a different origin. We find a spectral slope of \( \alpha = -0.86 \) (\( F_\nu \propto \nu^\alpha \)) between the
100 GHz and the 1.4 GHz fluxes, similar to the typical spectral indices $\alpha \approx -0.7$ seen from synchrotron emission for radio-loud AGN (Zakamska et al., 2004).

Mid-infrared (5-25 $\mu$m) luminosity has also been used as a bolometric indicator for the AGN. We use the WISE photometry to infer $L_{\text{bol}}$ following similar procedures as Liu et al. (2013b). As pointed out by Liu et al. (2013b), type 2 quasars have significantly redder mid-infrared colors than type 1 unobscured quasars, possibly due to dust reddening. This red color is also seen in SDSS J1356+1026. Therefore, to avoid attenuation from the dust, we choose the reddest WISE band at 22 $\mu$m (19.5 $\mu$m rest-frame) to apply the bolometric correction of $L_{\text{bol}} = \nu L_{\nu} \times (11 \pm 5)$ from Richards et al. (2006), which gives $L_{\text{bol}} \approx 1.1 \pm 0.5 \times 10^{46}$ ergs s$^{-1}$. However, this $L_{\text{bol}}$ might still be underestimated due to the strong extinction. We further use the 30 $\mu$m luminosity density extrapolated from the 3.4, 4.6, 12, and 22 $\mu$m data assuming a power-law spectral shape to set a conservative upper-limit of $L_{\text{bol}} < 2.3 \times 10^{46}$ ergs s$^{-1}$ with a bolometric correction factor of 13 (Liu et al., 2013b). The $L_{\text{bol}}$ estimate from the mid-infrared data is similar to that inferred from the [O III] luminosity, $L_{\text{bol}} \approx 10^{46}$ ergs s$^{-1}$ (Greene et al., 2012), using a $L_{\text{bol}}-L_{\text{[OIII]}}$ relation (Liu et al., 2009) calibrated with type 1 AGN.

4 Results

4.1 The N nucleus

There is strong CO (1-0) and CO (3-2) emission at the N nucleus with a wide velocity distribution from $-300$ km s$^{-1}$ to 500 km s$^{-1}$ (Fig. 3.3). From the CO (1-0) flux, the molecular gas mass is estimated to be $3^{+6}_{-2} \times 10^{8} M_{\odot}$, which can fuel star formation at an approximate rate of $\sim 1 M_{\odot}$ yr$^{-1}$, if the molecular gas is in a disk of radius 300 pc. The N nucleus has a CO line ratio $L'_{\text{CO}(3-2)}/L'_{\text{CO}(1-0)} = 1.18 \pm 0.73$. As various factors affect the line ratio, including the gas temperature and density, we are unable to infer the physical conditions of the gas from this one ratio. Instead, we empirically compare our measured line ratio to other objects using the compilation in Carilli & Walter (2013), including quasars ($L'_{\text{CO}(3-2)}/L'_{\text{CO}(1-0)} \approx 1.0$), sub-millimeter galaxies ($\sim 0.7$), normal star-forming galaxies ($\sim 0.4-0.6$, Bauermeister et al.,...
### Table 3.3. Spectral Energy Distribution

<table>
<thead>
<tr>
<th>Band</th>
<th>$\lambda_{\text{rest}}$ (µm)</th>
<th>$\nu_{\text{rest}}$ (Hz)</th>
<th>$\nu L_{\nu}$ ($10^{44}$ ergs s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>WISE</strong> W1 3.4 µm</td>
<td>3.0</td>
<td>$9.9 \times 10^{13}$</td>
<td>0.80</td>
</tr>
<tr>
<td><strong>WISE</strong> W2 4.6 µm</td>
<td>4.1</td>
<td>$7.3 \times 10^{13}$</td>
<td>1.21</td>
</tr>
<tr>
<td><strong>WISE</strong> W3 12 µm</td>
<td>11</td>
<td>$2.8 \times 10^{13}$</td>
<td>2.72</td>
</tr>
<tr>
<td><strong>WISE</strong> W4 22 µm$^a$</td>
<td>20</td>
<td>$1.5 \times 10^{13}$</td>
<td>10.5</td>
</tr>
<tr>
<td><strong>IRAS</strong> 60 µm$^a$</td>
<td>53</td>
<td>$5.6 \times 10^{12}$</td>
<td>16.1</td>
</tr>
<tr>
<td><strong>Herschel</strong> PACS 70 µm$^a$</td>
<td>62</td>
<td>$4.8 \times 10^{12}$</td>
<td>13.5</td>
</tr>
<tr>
<td><strong>Herschel</strong> PACS 100 µm$^a$</td>
<td>89</td>
<td>$3.4 \times 10^{12}$</td>
<td>7.50</td>
</tr>
<tr>
<td><strong>Herschel</strong> PACS 160 µm$^a$</td>
<td>142</td>
<td>$2.1 \times 10^{12}$</td>
<td>2.18</td>
</tr>
<tr>
<td><strong>Herschel</strong> SPIRE 250 µm$^a$</td>
<td>223</td>
<td>$1.3 \times 10^{12}$</td>
<td>0.59</td>
</tr>
<tr>
<td><strong>Herschel</strong> SPIRE 350 µm$^a$</td>
<td>312</td>
<td>$9.6 \times 10^{11}$</td>
<td>0.16</td>
</tr>
<tr>
<td><strong>Herschel</strong> SPIRE 500 µm</td>
<td>445</td>
<td>$6.7 \times 10^{11}$</td>
<td>$&lt;0.08$</td>
</tr>
<tr>
<td><strong>ALMA</strong> 100 GHz</td>
<td>$2.67 \times 10^3$</td>
<td>$1.1 \times 10^{11}$</td>
<td>$6.10 \times 10^{-4}$</td>
</tr>
</tbody>
</table>

Note. — The rest-frame mid-to-far infrared spectral energy distribution of SDSS J1356 +1026 (Sec. 3.4, Fig. 3.5). Column 1: the telescope and band. Column 2: the rest frame wavelength. Column 3: the rest frame frequency. Column 4: the frequency times the luminosity density in the rest frame. The errors in the infrared data (**WISE**, **IRAS**, and **Herschel**) are assumed to be 10%.

$^a$ The seven data points from the **WISE** 22µm to **Herschel** SPIRE 350 µm are used for the FIR SED decomposition fitting.
Figure 3.6 CO (3-2) channel maps of the N nucleus. Each map is 1'' wide in size and 30 km s\(^{-1}\) wide in velocity. The 1-\(\sigma\) noise level of the image is 0.77 mJy beam\(^{-1}\) km s\(^{-1}\). The beam ellipse is shown in the lower left corner. The black cross marks the best-fit centroid, while the line shows the direction of the velocity gradient in the low velocity component (\(|v| < 300\) km s\(^{-1}\)). While the low velocity emission is well aligned from channel to channel, the high velocity emission (\(v > 300\) km s\(^{-1}\), last row) systematically deviates in position from this black line.
2013a), and the Milky Way (∼0.3). The N nucleus has a relatively high line ratio similar to that of a quasar.

The CO (3-2) emission is marginally resolved (FWHM = 0′′.45 > Beam = 0′′.35) with a decomposed FWHM of 0.6 ± 0.1 kpc. This spatial resolution allows us to analyze the molecular kinematics at the N nucleus. The channel maps (Fig. 3.6) show that the emission moves toward the south-east as the velocity increases until about 300 km s\(^{-1}\). Above 300 km s\(^{-1}\), there is high velocity emission extending to 500 km s\(^{-1}\), but the position does not align with the low velocity gas.

In each channel we fit the emission with a 2-D Gaussian profile, and derive the best fit x and y positions (Fig. 3.6). We fit a linear model \(x = av + b\) to the best fit positions in the velocity range of ±300 km s\(^{-1}\) to yield a PA = 127°. We then extract a position-velocity diagram (hereafter \(pv\)-diagram, Fig. 3.7) along this PA. The \(pv\)-diagram is extracted over a width of 0′′.5, which encloses > 95% of the flux. It can be seen in the \(pv\)-diagram that the emission within ±300 km s\(^{-1}\) roughly follows a linear position-velocity relation that is symmetric about the systemic velocity and has a best-fit gradient of 1077 km s\(^{-1}\) kpc\(^{-1}\). The stellar velocity dispersion at the N nucleus (within a 1″ aperture) is \(\sigma_* = 206 \pm 36\) km s\(^{-1}\) (Greene et al., 2009), which would correspond to a circular velocity of \(V_c = \sqrt{2}\sigma_* = 291 \pm 50\) km s\(^{-1}\) for an isothermal sphere. Therefore, the linear velocity gradient within ±300 km s\(^{-1}\) is consistent with a rotating disk. This velocity gradient corresponds to a constant dynamical mass density of \(\rho_{\text{dyn}} \approx 63 M_\odot\) pc\(^{-3}\), which gives a dynamical mass within a radius of 0.25 kpc (0.3 kpc) of \(M_{\text{dyn}} \approx 4 \times 10^9 M_\odot\) (7 × 10\(^9\) M\(_\odot\)).

The molecular gas mass of \(M_{\text{mol}} = 3^{+6}_{-2} \times 10^8 M_\odot\) inferred from the CO emission accounts for 1 – 20% of the dynamical mass in the N nucleus.

Beyond this rotating component, the red-shifted high velocity feature (300 < \(v\) < 500 km s\(^{-1}\)) deviates from the linear velocity gradient and has a velocity too high to be explained by rotation alone. The bottom of Figure 3.6 and the left panel of Figure 3.7 show that the position of this feature has a slight offset (0′′.02) to the north-east from the disk plane. There is no counterpart on the blue-shifted side. The CO (3-2) emission is detected with 9 \(\sigma\) significance (0.99 ± 0.10 Jy km s\(^{-1}\)), while there is only a marginal detection 0.06 ± 0.08 Jy km s\(^{-1}\) for CO (1-0). Therefore,
the line ratio $L'_{\text{CO}(3-2)}/L'_{\text{CO}(1-0)} = 1.8 \pm 2.5$ is poorly constrained, but hints at a high excitation level. The 3 $\sigma$ detection limit of CO (1-0) places a lower limit on the line ratio $L'_{\text{CO}(3-2)}/L'_{\text{CO}(1-0)} > 0.45$. We use the CO (3-2) flux to infer a molecular mass $M_{\text{mol}} = 7^{+15}_{-5} \times 10^7 M_\odot$, assuming a line ratio of $L'_{\text{CO}(3-2)}/L'_{\text{CO}(1-0)} = 1$ as observed in the bulk of the N nucleus as well as in other AGN. This high velocity component accounts for a significant fraction ($\sim 20\%$) of the molecular mass in the N nucleus, under the assumption of constant line ratio and $X_{\text{CO}}$ factor. We discuss the interpretation of this component in Section 5.2.

### 4.2 The W arm

The extended emission to the west of the N nucleus is $2''$ (4 kpc) long, and has a blue-shifted narrow line at $-150 \text{ km s}^{-1}$ with a FWHM of 200 km s$^{-1}$ (Fig. 3.3). The CO (1-0) flux is $0.82 \pm 0.34 \text{ Jy km s}^{-1}$ once the overlap with the N nucleus is accounted for, and the CO (3-2) flux is $2.55 \pm 0.40 \text{ Jy km s}^{-1}$. Adopting a ULIRG $X_{\text{CO}}$ ratio, the W arm contains $5^{+11}_{-3} \times 10^8 M_\odot$ of molecular gas, about half of the total mass in the system. The actual mass could be even higher, up to $2.5 \times 10^9 M_\odot$, if the molecular gas is in self-gravitating clouds and the higher Milky Way $X_{\text{CO}}$ ratio applies. It has a moderate line ratio of $L'_{\text{CO}(3-2)}/L'_{\text{CO}(1-0)} = 0.35 \pm 0.20$, which is lower than the N nucleus and is similar to star forming galaxies (0.4-0.6, Bauermeister et al., 2013a; Carilli & Walter, 2013).

The W arm is likely a tidal feature (Sec. 5.1). It is only slightly offset from the position of an extended stellar plume to the north west of the N nucleus (see the CO (1-0) map in Figure 3.1). Decoupling between stellar and gas components in merging systems is not only predicted by simulations (e.g., Barnes & Hernquist, 1996) but also commonly seen in observations of tidal tails (e.g., Hibbard et al., 2000), as the gas is subject to dissipational processes that can affect its trajectory. Furthermore, the cool and coherent kinematics of the W arm, as seen from its narrow line width (Fig. 3.3), across its full length of 4 kpc, makes it hard to explain by either outflow or inflow.
4.3 The S nucleus

At the location of the southern nucleus identified from the *HST* images, there is only a $\sim 2\sigma$ CO (1-0) detection of $0.13 \pm 0.06$ Jy km s$^{-1}$, and no detection for CO (3-2). The $3\sigma$ detection limit of CO (1-0) translates into a molecular gas mass of $1.2 \times 10^8 M_\odot$, about 10% of the total molecular gas mass in the system. Taking the uncertainty in the $X_{\text{CO}}$ factor into account, we can place an upper-limit of $M_{\text{mol}} < 3.8 \times 10^8 M_\odot$. Therefore, the S nucleus is not a major reservoir of molecules in SDSS J1356+1026. Although the sensitivity is not adequate to constrain the detailed line profiles, the CO (1-0) marginal detection suggests a narrow blue-shifted line centered on $-30$ km s$^{-1}$ (Fig. 3.3). The much narrower CO (1-0) line width compared to the N nucleus can result from the shallower gravitational potential or the absence of gas outflow/inflow in the S galaxy.

The $L'_{\text{CO(3-2)}/L'_{\text{CO(1-0)}}}$ line ratio is constrained to be $0.10 \pm 0.11$, much lower than the N nucleus and the W arm.

4.4 Molecular Counterpart to the Ionized Bubble

As we describe in Section 1.1, SDSS J1356+1026 contains an extended ionized outflow discovered by Greene et al. (2012). However, there is no detection of molecular gas at the corresponding location. We identify the region of ionized line emission from the elongated luminous structure in the *HST* F814W image (green region in Fig. 3.1). The integrated CO (1-0) flux of $-32 \pm 102$ mJy km s$^{-1}$ places a molecular gas mass upper-limit (95% c.l.) of $M_{\text{mol}} < 8.6 \times 10^7 M_\odot$, while Greene et al. (2012) give a lower-limit on the ionized gas mass $M_{\text{ion}} > 5 \times 10^7 M_\odot$. Therefore, the molecular gas does not dominate the mass of the extended ionized outflow.

Despite the non-detection of CO in the ionized outflow, we note a tentative detection of a double-peaked CO (3-2) emission line at an optically bright spot in the *HST* F814W image about 4″ south of the N nucleus where the [O III] expanding-shell signature starts to emerge (the “bubble base” shown in magenta in Fig. 3.1). The two CO (3-2) peaks, each having 3 to 4 $\sigma$ significance, are at $-600$ and $+400$ km s$^{-1}$ respectively. Despite the intriguing location and velocity of this component, its confirmation requires further observations.
Figure 3.7 Left: CO (3-2) N nucleus moment-0 map of the low velocity component $|v| < 300$ km s$^{-1}$ (blue contours) and the high velocity component $v > 300$ km s$^{-1}$ (red contours). The contours have a step size of 3 $\sigma$ (0.48 and 0.22 Jy beam$^{-1}$ km s$^{-1}$, respectively) between each level. The crosses show the best-fit Gaussian centroids of the two components. The beam ellipse is shown in the lower left corner. The direction of the velocity gradient of the low velocity component (P.A. $= 127^\circ$) is indicated by the blue line. We extract a $pv$-diagram along this blue line and show it on the right panel. It is over a width of $0^\prime.55$, such that it contains $\sim 95\%$ of the flux. The offset on the horizontal axis is with respect to the best-fit Gaussian centroid of the low velocity component (blue cross on the left panel). The black points represents the centroid position at each velocity channel, fitted by Gaussian intensity profile. The black line shows the best-fit linear velocity gradient (1077 km s$^{-1}$ kpc$^{-1}$) of the low velocity component ($|v| < 300$ km s$^{-1}$, black circles) that is consistent with a rotating disk, and the grey line is fitted to all the velocity channels ($-300 < v < 500$ km s$^{-1}$). The high velocity points (black squares, $v > 300$ km s$^{-1}$) systematically deviate from this velocity gradient, and have velocities too high to be consistent with rotation.
5 Discussion

5.1 Origin of the Molecular Gas

We first discuss the origin and evolution of the molecular gas in the system. A significant amount of molecular gas is detected in the N nucleus and the W arm with a total mass of $9^{+19}_{-6} \times 10^8 \, M_\odot$ (Section 3). However, the stellar absorption spectrum of the N nucleus is dominated by an old stellar population (Greene et al., 2009), and based on the velocity dispersion we suspect that the galaxy started as an early-type with little cold gas. For local elliptical/S0 galaxies like SDSS J1356+1026 with $\sigma_* > 200 \, \text{km} \, \text{s}^{-1}$, Young et al. (2011) find that only one out of thirty galaxies has a molecular gas mass as high as $8 \times 10^8 \, M_\odot$, while most of the ellipticals are below the CO detection limit of $M_{\text{mol}} < 10^8 \, M_\odot$. Therefore, the exceptionally high molecular content in the N galaxy was likely accreted externally, perhaps from the S galaxy. The current optical spectroscopy is not adequate to identify the stellar population of the S galaxy. But if it was a late-type galaxy, with a stellar mass of about $M_* \approx 3 \times 10^{10} \, M_\odot$, it could bring in plenty of molecular gas, as the typical molecular to stellar mass ratio is about 5% for local spirals (Leroy et al., 2009; Bauermeister et al., 2013b). Gas transfer from disk companions to elliptical galaxies has been observed (Schweizer, 1987). Furthermore, some early-type galaxies have cold gas components that are kinematically decoupled from the stellar components, suggesting an external origin of the cold gas (Knapp, 1987; Davis et al., 2013). Therefore, a primary elliptical/satellite disk galaxy merger is a likely scenario to explain the molecular gas content in SDSS J1356+1026.

In simulations, when the gas collides during a merger, its orbital energy and angular momentum are dissipated, and thus the gas tunnels into the center to form a nuclear disk and triggers AGN or star formation activity (e.g., Hernquist, 1989; Barnes, 2002). In particular, if it is a primary elliptical and satellite disk galaxy merger, in some cases the gas in the disk galaxy is disrupted and sinks into the center of the primary elliptical (Weil & Hernquist, 1993). These nuclear gas disks, growing from infalling tidal tails, usually contain about half of the cool gas in the system and have peculiar kinematics relative to the stars. While these simulations do not treat the molecular gas phase explicitly, we expect the nuclear disks to have a large molecular fraction because of the dense environment. Observationally, molecular nuclear gas disks and rings
are indeed common in infrared luminous mergers (Downes & Solomon, 1998). These compact nuclear disks have radii \( \sim 0.5 \text{ kpc} \), as opposed to \( \sim 1 \text{ kpc} \) in normal ellipticals (Davis et al., 2013), and can be as massive as \( 10^9 M_\odot \), similar to the compact nuclear disk of SDSS J1356+1026. The energetic nuclear activity of SDSS J1356+1026 could be a direct result of the nuclear inflow induced by the interaction between the two merging galaxies (Barnes & Hernquist, 1996).

Observationally, although extended molecular tails can survive after being stripped from the galaxies (e.g., through ram pressure stripping, Dasyra et al., 2012; Jachym et al., 2014), it is not common to find a significant amount of molecular gas in tidal tails. Aalto et al. (2001) found 4\% (\( M_{\text{mol}} \approx 8 \times 10^7 M_\odot \)) of the molecular gas along a 10 kpc long optical tidal tail in NGC 4194, a elliptical/disk merger remnant. The ULIRG merger Mrk 273 also shows a 5 kpc extended CO streamer with mass \( M_{\text{mol}} \approx 1 \times 10^8 M_\odot \), accounting for a few percent of the CO flux (Downes & Solomon, 1998). One of the nuclei of Mrk 273 has no molecular gas, so it was possibly a gas poor galaxy or the gas was depleted by transfer (Yun & Scoville, 1995). However, none of these examples contain as much molecular gas as in the W arm of SDSS J1356+1026 (\( 5 \times 10^8 M_\odot \), half of the total molecular mass).

Both SDSS J1356+1026 and NGC 4194 are probably elliptical/disk minor mergers. We suspect that the formation of molecular tidal features may require particular progenitor properties and orbital configurations. For example, in the primary elliptical/satellite disk merger, the elliptical with its concentrated potential may disrupt the molecular disk in the satellite galaxy. At the same time, the absence of gas in the elliptical can reduce the shock dissociation of molecular gas during the encounter and thus preserve gas in the molecular phase in tidal features.

### 5.2 High Velocity Molecular Gas at the N Nucleus

In Section 4.1, we find a high velocity CO (3-2) feature at the N nucleus with a radius of \( \sim 300 \) pc. This feature ranges in velocity from 300 to 500 km s\(^{-1}\), which is too high to be part of the rotating disk. Its mass is estimated to be \( M \approx 7 \times 10^7 M_\odot \), a quarter of the mass at the N nucleus. Also, it has complex kinematics that deviate from rotation and has a slight offset with respect to the disk plane (Fig. 3.6, 3.7). There are various possible interpretations for this high
velocity component. It could be inflowing or outflowing, or could result from tidal forces or feedback mechanisms. We discuss two of the most plausible scenarios.

First, the high velocity feature may represent material accreting onto the disk from an external source, perhaps the W tidal arm. The projected angular momentum of the two features are parallel to each other, although they lie on opposite sides of the disk. Furthermore, the angular momentum of the high velocity gas is smaller than the W arm, as expected for gas that is accreting onto a nuclear disk.

The second possibility is a molecular outflow. Herschel OH line observations have found molecular outflow to be a common phenomenon in ULIRG/AGN like SDSS J1356+1026 (Veilleux et al., 2013). The high velocity feature seen in SDSS J1356+1026 meets one of the outflow criterion used by the CO interferometry study by Cicone et al. (2014), in that it has a velocity above 300 km s$^{-1}$ and deviates from the rotation pattern, making it a likely outflow candidate. However, CO confirmed molecular outflows in luminous ULIRG/AGN are typically more massive and larger in size. The six molecular outflows in luminous ULIRG/AGN ($L_{bol} > 10^{44.5}$) discussed by Cicone et al. (2014), including IRAS F08572+3915, IRAS F10565+2448, IRAS 23365+3604, Mrk 273, Mrk 231, and NGC6240, have molecular outflow masses $M \approx 3 \times 10^8$, sizes $r = 0.6-1.2$ kpc, and velocities $v = 400-1200$ km s$^{-1}$. This discrepancy in size could be partly due to the high angular resolution of the ALMA observations. Structures of size 300 pc may not have been resolved by previous CO studies. The fact that this compact size is measured by CO (3-2), a denser tracer than CO (1-0), may also contribute to the discrepancy. In fact, very compact molecular outflows on the scale of $\sim 100$ pc have been discovered by OH observations combined with radiative-transfer modeling (Sturm et al., 2011; González-Alfonso et al., 2013).

With the current observations we are unable to completely confirm or rule out either scenario. Given the ubiquity of nuclear outflows observed with Herschel on similar scales, in what follows we elaborate further on the outflow scenario and discuss the implications of the possible compact molecular outflow in this source.
Properties of the Molecular Outflow

We adopt a size of $r = 0.3$ kpc, velocity $v = 500$ km s$^{-1}$, and mass $M \approx 7 \times 10^7$ $M_\odot$ for the molecular outflow. These quantities are only order of magnitude estimates. In addition to measurement error, the size and velocity are subject to projection effects. There are also potential systematics in the mass estimate. First, the $X_{\text{CO}}$ factor in the context of an outflow is uncertain. The lower ULIRG $X_{\text{CO}}$ factor should already account for (at least part of) the fact that the molecular gas in outflows is not in self-gravitating clouds, but little is known about whether the violent kinematics in the outflow would further enhance the CO luminosity and thus reduce the $X_{\text{CO}}$. In principal, if CO (1-0) became optically thin due to very turbulent velocity structure, the $X_{\text{CO}}$ could further decrease by a factor of 2-3 (Bolatto et al., 2013). Second, we assume a typical quasar line ratio of $L'_{\text{CO}(3-2)}/L'_{\text{CO}(1-0)} = 1$, but we have only a loose constraint from the observations. Potentially, the shocks in the outflow could induce a different temperature profile and thus affect the line ratio, although this effect is not seen in Mrk 231, where the excitation ratios of the molecular outflow and the bulk of the molecular gas are similar (Cicone et al., 2012).

We estimate the time scale, outflow rate, momentum, and energetics of the outflow. The dynamical time is very short, $t_{\text{dyn}} = r/v \approx 0.6$ Myr, reflecting the compact size. The mass outflow rate depends on the geometry of the outflow, which cannot be constrained with the current data. We consider two limiting cases. If the outflow is a single burst and the material is distributed in a shell (or clump) with a distance $r$ from the center, then the mass outflow rate is

$$\dot{M} = M v / r \approx 116 \ M_\odot \ \text{yr}^{-1}.$$

If the outflow is continuous and volume filling inside a sphere or cone with a constant velocity, the mass outflow rate is $\dot{M} = 3M v / r \approx 350 \ M_\odot \ \text{yr}^{-1}$, a factor of three higher due to the ratio between the surface area and the volume of a sphere. In the following we assume a volume-filling continuous outflow, as in Maiolino et al. (2012) and Cicone et al. (2014). The time it takes to deplete the molecular gas in the N nucleus ($\sim 3 \times 10^8$ $M_\odot$) with a constant mass outflow rate is $t_{\text{dep}} \approx 1$ Myr. The kinetic energy and kinetic luminosity of the outflow are $E_{\text{kin}} \approx 2 \times 10^{56}$ ergs and $\dot{E}_{\text{kin}} \approx 3 \times 10^{43}$ ergs s$^{-1}$, and the momentum and momentum rate are $p \approx 7 \times 10^{48}$ g cm s$^{-1}$ and $\dot{p} \approx 1 \times 10^{36}$ dyne.
Chapter 3: ALMA Observations of a Candidate Molecular Outflow in an Obscured Quasar

AGN or Star Formation Driven Outflow?

We now discuss the possible driving mechanism of this compact molecular outflow. To examine whether star formation can power the molecular outflow, we adopt a star formation feedback efficiency of $\dot{E}_*/SFR = 7 \times 10^{41}$ ergs s$^{-1}$ ($M_\odot$ yr$^{-1})^{-1}$ calculated by Leitherer et al. (1999) using the stellar evolution code Starburst99 (see also Veilleux et al., 2005). The energy injection rate is dominated by supernovae that occur 40 Myr after the starburst; at earlier times the rate is lower. Therefore, to power an outflow with a kinetic luminosity of $\dot{E} \approx 3 \times 10^{43}$ ergs s$^{-1}$, we need a star formation rate of at least $SFR > 43 M_\odot$ yr$^{-1}$, much higher than the star formation rate that can be sustained by the molecular gas in the N nucleus ($SFR \approx 1.2 M_\odot$ yr$^{-1}$), assuming the Schmidt-Kennicutt law. It is also higher than our conservative upper-limits inferred from either the total molecular gas content ($SFR < 16 M_\odot$ yr$^{-1}$ Sec. 3.3) or the far-infrared SED fitting ($SFR < 21 M_\odot$ yr$^{-1}$ Sec. 3.4). To fuel a SFR of 43 $M_\odot$ yr$^{-1}$ in a disk of radius 300 pc requires a molecular mass of $4 \times 10^9 M_\odot$ (Kennicutt, 1998), which is an order of magnitude higher than the molecular mass in the N nucleus and is equal to its dynamical mass. Therefore, we conclude that there is not enough star formation activity to drive the compact molecular outflow.

A jet is another possible way to drive the outflow. As discussed in Greene et al. (2012), SDSS J1356+1026 is classified as a radio-quiet quasar, and its radio emission is not resolved by the FIRST survey (beam size $5''.4$, Becker et al., 1995), which puts a constraint on the size $r < 2''$ (4 kpc). The agreement of flux between FIRST and NVSS, which has a larger beam size of 45'', observations suggests that there is no extended radio emission beyond the 2'' scale. This rules out a jet as the driver for the extended (20 kpc) ionized outflow. Our 100 GHz measurement (Sec. 3.1) further constrains the size of the high frequency radio emission to be no larger than $1''9 \times 1''3$ (4.2 x 2.9 kpc). However, as the high frequency emission may trace only the base of the radio jet, we cannot rule out a compact jet $< 2''$. Further observations are required to confirm or rule out a jet as the driving mechanism of the compact molecular outflow.

A radiative driven wind from the obscured quasar at the N nucleus (Murray et al., 1995; Proga et al., 2000) could also be responsible for driving the molecular outflow. Hydrodynamics simulations of AGN wind typically adopt a wind kinetic luminosity of a few percent of $L_{bol}$ in
order to reproduce the observed black hole mass - stellar velocity dispersion \((M_{\text{BH}} - \sigma)\) and the X-ray luminosity - stellar velocity dispersion \((L_X - \sigma)\) relations (e.g., DeBuhr et al., 2011; Choi et al., 2014). The AGN bolometric luminosity \(L_{\text{bol}} \approx 10^{46}\) ergs s\(^{-1}\), indirectly inferred from the [O III] and mid-infrared luminosities (Sec. 3.4), is much higher than the kinetic luminosity of the molecular outflow \((\dot{E} \approx 3 \times 10^{43}\) ergs s\(^{-1}\)) with a ratio of only \(\dot{E}/L_{\text{bol}} \sim 0.3\%\). The ionized outflow \((\dot{E} \approx 10^{44} - 45\) ergs s\(^{-1}\), Greene et al. 2012\) has a kinetic luminosity \(1 - 10\%\) of \(L_{\text{bol}}\). Therefore, the AGN wind is a feasible scenario in terms of energetics to drive the molecular and ionized outflows.

We find that the momentum rate \(\dot{p} \approx 1 \times 10^{36}\) dyne\) of the molecular outflow is similar to the radiation momentum rate from the AGN \((L_{\text{bol}}/c \approx 3 \times 10^{35}\) dyne\) with a momentum boost of \(\dot{p}/(L_{\text{bol}}/c) \approx 3\). This value is somewhat lower than what is inferred for the luminous ULIRG/AGN that have CO outflows confirmed by Cicone et al. (2014), which typically have a momentum boost of \(\dot{M}v/(L_{\text{bol}}/c) \gtrsim 20\). This discrepancy may partly be due to the higher sensitivity of ALMA, which allows us to identify features of lower molecular gas mass. The lower momentum boost of the outflow in SDSS J1356+1026 indicates that it is more consistent with being momentum-driven than those found by Cicone et al. (2014). King (2003) and Zubovas & King (2012) argue that outflows on small scales tend to be momentum-conserving, because the hot wind of a luminous AGN is efficiently Compton-cooled at the vicinity of the AGN \((r \lesssim 1\) kpc\). Outflows at larger radius, in contrast, are energy-conserving. Given that the molecular outflow in SDSS J1356+1026 is more compact than other ULIRG/AGN outflows and shows a lower momentum boost, we are possibly starting to approach the momentum-driven regime of AGN outflows.

**Comparison with the Ionized Outflow**

SDSS J1356+1026 hosts an extended ionized outflow, previously discovered by Greene et al. (2012). In this section, we examine the relationship between these two outflows with their very different sizes, time scales, and molecular contents by tying them together into an integrated picture of an AGN wind interacting with galactic gas.

It is intriguing that the molecular outflow is much smaller \((r \approx 0.3\) kpc\) and is characterized by shorter time scales \((t_{\text{dyn}} \approx 0.6\) Myr, and \(t_{\text{dep}} \approx 1\) Myr\) than the extended ionized outflow, which
Chapter 3: ALMA Observations of a Candidate Molecular Outflow in an Obscured Quasar

has $r^{\text{ion}} \approx 10$ kpc, $v^{\text{ion}} \approx 1000$ km s$^{-1}$, and $t^{\text{ion}}_{\text{dyn}} \approx 10$ Myr (Greene et al., 2012). The two outflows are different in morphology - the ionized outflow is symmetrically bipolar in the north-south direction while the compact molecular outflow has only one component which is redshifted and extends to the S-E direction. Furthermore, they have different physical conditions, as the molecular gas dominates the small scale outflow, but is ruled out as the dominant component of the extended outflow (Sec. 4.4). But the biggest puzzle is the short time scale characteristic of the molecular outflow, which raises concerns about its duty cycle: if the molecular outflow is indeed a transient phenomenon, how did we capture this rare event at this exact moment?

There are two scenarios, continuous and discrete outflows, that could account for the fact that we see outflows on very different scales. First, it could be that the quasar has been active and driving winds for more than $10^7$ years, and the extended ionized and compact molecular outflows are two segments of a continuous wind-driven outflow stream. They are constituted by gas of different phases possibly due to the differences in the environments, such as density. However, sustaining an outflow with a constant outflow rate of $\dot{M} = 350$ $M_\odot$ yr$^{-1}$ for $10^7$ yr would require a gas mass of $\sim 10^{9.5}$ $M_\odot$. Unless we happened to catch the outflow in the last 10% of its life time, we would expect to find a comparable quantity of gas reservoir in the system, which we do not see. There is only $\sim 3 \times 10^8$ $M_\odot$ of molecular gas at the N nucleus, which can fuel the outflow for only $\sim 1$ Myr. Even if the molecular gas in the W arm also fuels the outflow, this outflow would only last for $\sim 3$ Myr. There is no other gas reservoir to replenish the N nucleus; the S nucleus contains little molecular gas, and the extended outflow is unlikely to return once it travels with a velocity of 1000 km s$^{-1}$ to 10 kpc, where the escape velocity is 760 km s$^{-1}$, assuming a singular isothermal density profile with $\sigma_* = 206$ km s$^{-1}$ (eq. 2 of Greene et al. 2011).

Furthermore, we do not find $\sim 10^{9.5}$ $M_\odot$ of gas in the outflow, although it could be present in a hotter phase. Only $\sim 10^7$ $M_\odot$ of outflowing ionized gas is observed, although this number is only a lower limit due to the unknown gas density (Greene et al., 2011).

Discrete outflow is the second possibility. If the AGN activity is episodic (e.g., Schirmer et al., 2013; Hickox et al., 2014), the two outflows may be driven by two separate bursts of the AGN, possibly associated with multiple passages of the companion (S) galaxy. The S galaxy has an orbital period of $\sim 5 \times 10^7$ yr, assuming a circular orbit with a radius of 2.5 kpc or free falling...
from a distance of 2.5 kpc. In this case, the compact molecular outflow would reflect the most recent ($\sim 10^6$ yr) burst while the extended ionized outflow is the relic of previous activity ($\sim 10^7$ yr ago). This scenario has several advantages over the continuous outflow scenario. First, we can naturally connect the time scales of the outflow to the AGN cycle, which is in the end controlled by the gas supply. Every $\sim 10^7$ yr, the passage of the S nucleus triggers a new burst of nuclear activity, which in turn drives a nuclear outburst that depletes the nucleus in $\sim 10^6$ yr, thus shutting down further activity. It is therefore not surprising to see the compact molecular outflow with both a dynamical time and a depletion time of $\sim 10^6$ yr. Also, it is not a coincidence that we catch this transient molecular outflow at the right time. Given that we select this object based on its bright quasar luminosity, its feedback is presumably most active. Furthermore, it could explain why we see a comparable amount of gas ($10^7$–$10^8 M_\odot$) in the compact and ionized outflow, if each burst releases roughly the same amount of energy and expels the same amounts of gas. An outflow driven by episodic AGN activity seems to be a reasonable possibility that is consistent with the various measured time and mass scales.

6 Summary

The sub-millimeter observations of CO (1-0) and CO (3-2) with ALMA of the luminous obscured quasar SDSS J1356+1026 provide insights into molecular gas dynamics during a merger, AGN feedback on molecular gas, and episodic AGN activity on 10 Myr time scales. We summarize the highlights of our study below.

SDSS J1356+1026 contains two merging nuclei, with the primary galaxy likely of early type. Given the high molecular content we find in the system ($M_{\text{mol}} \approx 9^{+19}_{-6} \times 10^8 M_\odot$), we speculate that the secondary galaxy was a disk galaxy which brought in the majority of the gas. In this scenario, the cold gas from the secondary was disrupted during the encounter. Roughly a third of the gas sank into the primary nucleus and formed a compact disk (N nucleus, $r \approx 300$ pc, $M_{\text{mol}} \approx 3^{+6}_{-2} \times 10^8 M_\odot$), while half of the gas is now in an extended tidal tail (W arm, $r \approx 5$ kpc, $M_{\text{mol}} \approx 5^{+11}_{-3} \times 10^8 M_\odot$), which is one of the most massive molecular tidal features known.
In addition to a compact disk, we find a red-shifted high-velocity component deviating from rotation at the N nucleus. It has a compact size of \( \sim 300 \) pc and a velocity of \( \sim 500 \) km s\(^{-1}\). Although the origin of this gas is not clear, we suspect it is an outflow driven by the AGN. Our estimated star formation rate limits, \( \text{SFR} < 16 \ M_\odot \ \text{yr}^{-1} \) from the CO molecular content and \( \text{SFR} < 21 \ M_\odot \ \text{yr}^{-1} \) from the FIR SED decomposition, disfavor star formation as the driving mechanism. A molecular outflow with \( \dot{M} \approx 350 \ M_\odot \ \text{yr}^{-1} \) could expel all gas in the N nucleus in \( \sim 1 \) Myr and all the molecular gas in the system in \( \sim 3 \) Myr. It is one of the most compact CO molecular outflows discovered, and the corresponding dynamical time is short \( \sim 0.6 \) Myr. The kinetic luminosity of this outflow \( \dot{E} \approx 3 \times 10^{43} \ \text{ergs s}^{-1} \) is only \( \sim 0.3\% \) of the AGN bolometric luminosity \( L_{\text{bol}} \approx 10^{46} \ \text{ergs s}^{-1} \). Its low momentum boost rate \( \dot{p}/(L_{\text{bol}}/c) \approx 3 \) is consistent with the prediction that compact AGN outflows tend to be momentum conserving (Zubovas & King, 2012). The compact molecular outflow discovered here and the extended ionized outflow (Greene et al., 2012) are likely induced from two episodes of AGN activity, varying on a time scale of 10 Myr.

SDSS J1356+1026 is an example of a molecular outflow that can effectively disturb or deplete the molecular reservoir in the galaxy. Molecular outflows identified by high velocity OH absorption features are found to be common among AGN (Sturm et al., 2011; Veilleux et al., 2013). As demonstrated in this work, spatially resolved CO observations provide a complementary and model independent technique to measure the size and mass, and to infer the mass-lost rate of the outflow (\( \dot{M} \)). In the end, whether AGN feedback is a successful model to account for the absence of luminous blue galaxies and the cut-off of the galaxy luminosity function depends on both the frequency and the mass-lost rate of molecular outflows as a function of AGN luminosity. Furthermore, both molecular and ionized outflows are found to be ubiquitous in luminous quasars (Liu et al., 2013a,b; Harrison et al., 2014), and can coexist (Davis et al., 2012; Rupke & Veilleux, 2013), but we do not fully understand how they are related. Also, the connection between the compactness and the low momentum boost rate of molecular outflows, as hinted by SDSS J1356+1026, requires confirmation from a larger spatially resolved sample. These outstanding questions could be answered with systematic and spatially resolved observations of molecular gas in a sample of AGN covering a range of luminosities and ionized outflow properties.
As demonstrated in this work, with its great sensitivity and resolution, ALMA is well suited for resolving molecular outflows on sub-kpc scales to as far as $z = 0.1$, and is therefore a powerful tool to bring our understanding of AGN feedback to the next level.

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Chapter 3: Bibliography


Chapter 3: Bibliography


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Sizes and Kinematics of Extended Emission-Line Regions in Obscured AGN

abstract

To study the impact of active galactic nuclei (AGN) feedback on the galactic interstellar medium, we present Magellan long-slit spectroscopy of 12 luminous nearby type 2 AGN ($L_{\text{bol}} \sim 10^{45.0-46.5}$ ergs s$^{-1}$, $z \sim 0.1$). These objects are selected from a parent sample of spectroscopically identified AGN to have high [O III]$\lambda 5007$ and WISE mid-IR luminosities as well as extended emission in the SDSS $r$-band images, suggesting the presence of extended [O III]$\lambda 5007$ emission. We find extended [O III] emission (2 - 35 kpc from the nucleus) in 9 out of 12 of these objects. Ten objects have broad [O III] with line-widths, $w_{80} = 600 - 1500$ km s$^{-1}$, indicating ionized outflows, seven of which are resolved extended outflows. Combined with samples of higher luminosity type 2 AGN, we confirm the flattening of the narrow-line region size - mid-IR luminosity relation at about $\sim 10$ kpc. On the other hand, the radius of the outflow, the region with non-virial [O III] linewidths, scales with the AGN luminosity with no break and a power index of $0.33^{+0.16}_{-0.17}$. The velocities and energetics of the outflows are also positively correlated with the AGN luminosities, yielding an outflow energy efficiency of $\eta = \dot{E}/L_{\text{bol}} = 0.01\% - 30\%$. We find no evidence for an AGN luminosity threshold below which outflows are not launched, and there is no evidence that the outflow energy efficiency depends on the AGN luminosity. To explain the sizes, velocity profiles, and the high occurrence rate of the outflows in the most luminous AGN, we propose a scenario where energy-conserving outflows are driven by AGN episodes with $\sim 10^8$-year duration. Within
each episode the AGN flickers on shorter timescales, with a cadence of \( \sim 10^6 \) year active phases separated by \( \sim 10^7 \) years.

## 1 Introduction

Feedback from active galactic nuclei (AGN) is a key ingredient in modern models of galaxy evolution (Silk & Rees, 1998; Springel et al., 2005). It has been invoked to regulate star formation in massive galaxies (e.g., Croton et al., 2006; Bower et al., 2006), while the tight correlation between the supermassive black hole (SMBH) masses and their host galaxy properties (Gebhardt et al., 2000; Ferrarese & Merritt, 2000; Sun et al., 2013; McConnell & Ma, 2013) also suggests that feedback processes enforce the coevolution between SMBHs and galaxies (Di Matteo et al., 2005; DeBuhr et al., 2010; Somerville et al., 2008).

As direct evidence of AGN feedback, outflows on galactic scales have been found in local and distant luminous AGN. These galactic outflows have a multi-phase structure, ranging from cold molecular (Feruglio et al., 2010; Sturm et al., 2011; Veilleux et al., 2013; Sun et al., 2014; Cicone et al., 2014) to warm atomic and ionized gas (Alexander et al., 2010; Greene et al., 2011; Maiolino et al., 2012; Davis et al., 2012; Rupke & Veilleux, 2013; Cano-Díaz et al., 2012), and could be related to nuclear X-ray emitting outflows (Gofford et al., 2013; Tombesi et al., 2015). While we now have compelling evidence that AGN drive outflows, many questions remain about how they are driven and their relationship with the AGN luminosities.

The warm ionized component of the outflow \( (T \sim 10^4 \text{ K}) \) emits strong forbidden emission lines, in particular \([\text{O III}]\lambda 5007\), which makes it possible to study AGN outflows via optical spectroscopy. Studies using long-slit and IFU spectroscopy have identified a number of extended ionized outflows in luminous AGN (Greene et al., 2012; Liu et al., 2013a,b, 2014; Harrison et al., 2014; Hainline et al., 2014b), particularly among obscured type 2 AGN (Zakamska et al., 2003; Reyes et al., 2008), where the occultation of the active nuclei makes it easier to detect emission lines from the extended ionized nebula. While it is encouraging that extended ionized outflows are found to be common among the most luminous AGN \( (L_{\text{bol}} > 10^{46} \text{ ergs s}^{-1}) \), a larger sample is
required to understand the demographics of the outflows, including their size distribution and occurrence rate, across a more representative range of AGN luminosities.

Spatially resolved spectroscopy is too expensive for a large survey, but broadband photometry could be a complementary method to help find extended AGN outflows in large numbers. Since the \([\text{O III}] \lambda 5007\) line in obscured luminous AGN is bright enough to be detectable in broadband images, optical photometric surveys, such as the Sloan Digital Sky Survey (SDSS; York et al., 2000), have been used to find \([\text{O III}] \lambda 5007\) emission in extended narrow-line regions (e.g., Schirmer et al., 2013; Davies et al., 2015).

However, not all the extended narrow-line regions have disturbed kinematics. Some luminous AGN are capable of ionizing gas out to tens of kpc from the host galaxy (Fu & Stockton, 2008; Villar-Martín et al., 2010), including gas in small companion galaxies and tidal debris left from a prior galaxy interaction, thus creating extended ionized regions that are kinematically quiescent. For this reason, we also need spectroscopy to confirm the kinematic state of the extended gas and identify outflows.

To test if broadband images can help identify extended outflows, in this paper we select a sample of 12 SDSS-identified luminous obscured (type 2) AGN that have extended \(r\)-band emission, indicating extended \([\text{O III}] \lambda 5007\). We observe them with Magellan IMACS long-slit spectroscopy to measure the extent and kinematic state of the ionized gas. We study the outflow occurrence rate, and constrain the outflow properties, including the sizes, velocities, and energetics, as well as their dependence on the AGN luminosity. In future work we will examine the correspondence between the broadband images and the ionized gas nebula, and evaluate the performance of the extended outflow selection.

In Section 2, we describe the sample selection and Magellan observations; in Section 3 we present the Magellan spectra and measure the extents and the kinematics of the ionized gas nebulae, and in Section 4 we infer the outflow properties, including the energetics, and analyze their dependence on the AGN luminosities. We discuss the outflow occurrence rate and time scales in Section 5 and summarize in Section 6. We use an \(h = 0.7, \Omega_m = 0.3, \Omega_\Lambda = 0.7\) cosmology throughout this paper. We adopt the vacuum wavelengths for the analysis, the same as SDSS, but keep the line notations in air wavelengths, e.g. \([\text{O III}] \lambda 5007\). All error bars represent 1-sigma error.
Chapter 4: Sizes and Kinematics of Extended Emission-Line Regions in Obscured AGN

2 Observations and Data Reduction

2.1 Sample Selection

The sample was selected from SDSS spectroscopically identified AGN (Mullaney et al., 2013) that are below redshifts \( z < 0.2 \) with AGN luminosities above \( L_{\text{bol}} > 5 \times 10^{44} \text{ erg s}^{-1} \) (Fig. 4.1). We infer the AGN bolometric luminosity from both the \([\text{O III}]\) luminosity (Mullaney et al., 2013) and the mid-infrared (mid-IR) luminosity from the Wide-field Infrared Survey Explorer (\textit{WISE}; Wright et al., 2010) as described in Sec. 2.5. To maximize the chance of finding extended AGN outflows, we looked at the SDSS images to identify the ones with extended morphology, particularly extended \( r \)-band emission (colored green), as the strong \([\text{O III}]\) lines fall in the \( r \)-band.

In total, twelve type 2 AGN (narrow-lines only) and eight type 1 AGN (with nuclear blue continuum and broad Balmer lines) are successfully observed with Magellan. While the type 1 AGN could be analyzed using methods that handle the nuclear emission (e.g., Husemann et al., 2015), it is beyond the scope of this paper. In this paper, we will focus on the sample of twelve type 2 AGN (Tab. 4.1), where the \([\text{O III}]\lambda 5007\) line measurement is less affected by the bright nuclei.

2.2 Magellan Long-Slit Observations

Our sample was observed with the Inamori-Magellan Areal Camera & Spectrograph (IMACS) spectrograph (Dressler et al., 2011) at the Magellan Baade telescope on Las Campanas on 23-24 June 2014. The typical seeing was between \( 0''.5 \) and \( 1'' \). We used the Centerfield Slit-viewing mode with the 300 lines/mm grating on the f/4 camera. We placed objects on the adjacent 1.0'' and 1.3'' slits\(^1\), each about 17'' long and separated by 1'', to simultaneously cover the central and extended regions of our galaxies. The spectral resolutions are 5.1 and 6.7 \( \AA \) (FWHM) for the two slits respectively, which corresponds to about 260 and 340 km s\(^{-1}\) for the \([\text{O III}]\lambda 5007\) line measurements. The \( 0''.75 \) slit is also used for background subtraction, but not for measurements.

\(^1\)This widest 1''3 slit, referred to in the IMACS User Manual as the 1''5 slit, was confirmed to have an actual slit width of 1''3, see Appendix 7.1.
Table 4.1. The Sample

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Note. — Details of the Magellan sample of luminous type 2 AGN. Column 1: Object SDSS Name. Column 2, 3: Object coordinate from SDSS DR7 (J2000). Column 4: Systemic redshift from the stellar absorption features in the Magellan spectra, see Sec. 2.1. Column 5, 6: The total $\text{[OIII]}\lambda5007$ luminosity in units of $10^{42}$ ergs s$^{-1}$ from the SDSS spectrum (Mullaney et al., 2013) and its corresponding bolometric luminosity in units of $10^{45}$ ergs s$^{-1}$ converted using the bolometric correction by Liu et al. (2009). Column 7, 8: The mid-IR rest frame 15 $\mu$m luminosity in units of $10^{44}$ ergs s$^{-1}$ from WISE and the corresponding bolometric luminosity in units of $10^{45}$ ergs s$^{-1}$ with a bolometric correction factor of 9, see Sec. 2.5. Column 9, 10: The position angles and exposure times of the Magellan long-slit exposures.

$^a$ The object is observed with the 1.3$''$ slit instead of the 1.0$''$ slit.
Figure 4.1 Selection of luminous type 2 AGN based on two bolometric luminosity indicators - [O III]λ5007 luminosities from the SDSS spectra and mid-IR rest frame 22 µm luminosities from WISE. The big dots are the targets for Magellan follow-up selected from the parent sample of SDSS spectroscopically identified type 2 AGN shown by small dots (Mullaney et al., 2013). Only low-redshift (z < 0.2) objects in the observable sky during the Magellan run (RA < 2h or > 10h, Dec < 15 deg) are shown. The thick lines show cuts in the [O III]λ5007 and 22 µm luminosities that corresponds to a bolometric luminosity of $10^{44.7}$ ergs s$^{-1}$.

The wavelength coverage is 3800 to 9400 Å with three CCD chip gaps, each 75 Å wide. Each object is observed for 15 to 60 minutes with one to three slit positions, as listed in Table 4.1. The slit positions are chosen based on the SDSS image to cover extended $r$-band emission. For each object, there is at least one slit position along the major axis. The atmospheric dispersion corrector is used. Two flux calibrator stars Feige 110 and EG 274 and a set of velocity template stars consists of K to A giants/dwarfs are also observed with the 1.3′ slit.

2.3 Data Reduction

Basic data reduction, including bias subtraction, flat fielding, wavelength calibration, rectification, and 2-D sky subtraction (Kelson, 2003) are performed using the Carnegie Observatories reduction
package COSMOS\textsuperscript{2}. Cosmic ray removal using LACosmic\textsuperscript{3} (van Dokkum, 2001) is applied before rectification. We found an excess of red continuum background at $\lambda > 8200$ $\AA$ that was independent of slit width, which is most likely due to scattered light in the spectrograph. This red background excess can be well-subtracted by the 2-D sky subtraction if there are emission-free regions on both sides of each slit. In cases where one slit is full of galaxy light, we subtract the background by inferring the sky spectrum from the convolved 0\arcsec.75 slit and correcting for the red background excess. This excess background does not affect the [O III]$\lambda$5007 and H$\beta$ line measurements.

The flux calibration and atmospheric extinction corrections are performed using PyRAF\textsuperscript{4} version 2.1.7. We use the flux standard stars to determine the sensitivity functions and the atmospheric extinction function. We compare the calibrated spectrum of the galaxies with the SDSS spectra. The fluxes of the SDSS spectra are on average 1.7 times higher (with a scatter of 20\%) than the Magellan spectra extracted from the central 3\arcsec, as we would expect given that the SDSS fibers are wider than the Magellan slits. We adopt a fractional uncertainty on the flux calibration of 20\%. For the slit positions that have multiple exposures, we align and stack those spectra of the same position together. The wavelength solution is applied after heliocentric-correction and air-to-vacuum conversion using PyAstronomy\textsuperscript{5}.

For the emission line measurements we subtract the stellar continuum using a featureless 2-D model for the continuum spectrum. This model is determined by smoothing and interpolating the line-free part of the stacked 2-D spectra, excluding the contamination from the AGN emission lines and sky lines. This method can operate at the outskirts of the galaxies where the signal-to-noise ratio is low. As the H$\beta$ emission line is affected by the stellar absorption, we correct for this effect using the absorption line profiles obtained from the pPXF stellar population synthesis fits described in Sec. 2.4. Two systems have no H$\beta$ measurements (SDSS J0141−0945 and J2133−0712) due to chip gaps and strong sky lines.

\textsuperscript{2}http://code.obs.carnegiescience.edu/cosmos
\textsuperscript{3}http://www.astro.yale.edu/dokkum/lacosmic/
\textsuperscript{4}http://www.stsci.edu/institute/software_hardware/pyraf
\textsuperscript{5}https://github.com/sczesla/PyAstronomy
2.4 Position and Velocity References

The position and velocity measurements in this paper are defined relative to the stellar component of the galaxies. The center position is defined as the peak of the stellar continuum light profile (nucleus), which has an uncertainty comparable to one pixel (0.2″, or 0.3-0.6 kpc in our sample).

The systemic velocity of each galaxy is determined using the stellar absorption features. We fit the absorption lines with single stellar population (SSP) templates from Bruzual & Charlot (2003) using the stellar kinematics fitting code pPXF (Cappellari & Emsellem, 2003). The templates include 10 solar-metallicity SSP spectra of ages ranging from 5 Myr to 11 Gyr with a two degree additive and three degree multiplicative polynomial. To focus on the absorption features, we mask the emission lines, sky lines, galactic absorption, and chip gaps in the spectra. The fits are applied to the nuclear spectra extracted with two aperture sizes, 1″ and 3″.

The fitted redshifts are listed in Table 4.1. Our redshifts agree with the SDSS redshifts within 285 km s\(^{-1}\) with the latter fitted to both the emission and absorption lines.

2.5 AGN Luminosities from [O III] and WISE

We use both the [O III]\(\lambda5007\) and the mid-IR WISE luminosity to infer the bolometric luminosity of these obscured AGN (Tab. 4.1). Our first estimate is based on the [O III]\(\lambda5007\) luminosities that are tabulated by Mullaney et al. (2013) based on the SDSS fiber spectra. We use the empirical \(L_{[\text{OIII}]} - L_{\text{bol}}\) relation by Liu et al. (2009), which is inferred from type 1 AGN, to convert to AGN bolometric luminosity.

Mid-infrared luminosity, e.g., from WISE, can be used to infer the AGN luminosity (e.g. Richards et al., 2006; Hainline et al., 2014a) and in principle could be more robust than emission lines such as [O III]\(\lambda5007\) as it is less affected by dust extinction. However, type 2 AGN typically have redder mid-IR colors and lower mid-IR luminosities than do type 1 AGN (Liu et al., 2013b), presumably due to the anisotropic nature of the infrared emission from the optically thick obscuring dust. As discussed in Appendix 7.2, we find that the differences in mid-IR luminosities of type 1 and type 2 AGN is significant at shorter wavelengths, e.g., rest-frame 8 \(\mu m\), but is milder at longer wavelengths, e.g. 15 or 22 \(\mu m\). Therefore, while mid-IR luminosities can still be...
affected by the dust column densities or geometry, the effect is less severe at longer wavelengths where optical depths are smaller.

We adopt WISE rest-frame 22 μm as the AGN luminosity indicator for our sample selection (Sec. 2.1) with a bolometric correction of 11 (Richards et al., 2006). In Sec. 3 and 4, to compare our work with other narrow-line region studies at higher redshifts (z ≈ 0.5) from Liu et al. (2013a, 2014) and Hainline et al. (2014b), where the rest-frame 22 μm flux is not available, we use the rest-frame 15 μm luminosity as our AGN luminosity indicator with a bolometric correction of 9 (Richards et al., 2006).

These mid-IR luminosities at rest-frame 8, 15, and 22 μm are referred to as $\nu L_{\nu,8}$, $\nu L_{\nu,15}$, and $\nu L_{\nu,22}$. They are interpolated or extrapolated from the ALLWISE source catalog 3-band photometry at 4.6 (W2), 12 (W3), and 22 (W4) μm using a second-order spline in log-log space. We ignore the filter response function and adopt a magnitude to flux density conversion of a flat spectrum, which may lead to a few percent error depending on the source spectral shape (Cutri et al., 2013).

## 3 Sizes of the Narrow-Line and the Kinematically Disturbed Regions

The goal of this section is to quantify the extent of the AGN influence on the interstellar medium of the host galaxy. To evaluate the ionization state of the gas, it is interesting to measure the extent of the photo-ionized region, also called the narrow-line region (NLR). One possibility is to measure the extent of a bright emission line (e.g., [O III]λ5007) down to a fixed surface brightness level ($R_{\text{NLR}}$). Another is to measure the extent of the AGN-ionized region based on ionization diagnostics, e.g., using the [O III]λ5007 to Hβ ratio. These options have been used extensively in long-slit or IFU spectroscopy (e.g., Bennert et al., 2006; Fraquelli et al., 2003; Greene et al., 2011; Liu et al., 2013a; Hainline et al., 2013, 2014b; Husemann et al., 2014), narrow-band imaging (e.g., Bennert et al., 2002; Schmitt et al., 2003), or even broad-band imaging (e.g., Schirmer et al., 2013).
However, to understand whether the energy from the AGN can be coupled kinematically to the interstellar medium or even drive outflows, we need a kinematic measure of the extent of the AGN influence. We introduce a new measure of the radius tied to the region with kinematically disturbed linewidths ($>600$ km s$^{-1}$; $R_{\text{kin}}$). Together, $R_{\text{NLR}}$ and $R_{\text{kin}}$ quantify the scale of the AGN influence on its host galaxy through two different channels: photoionization and mechanical feedback respectively. It is important to investigate how these two radii relate to each other and how they depend on the AGN luminosity.

In this section, we present our [O III]$\lambda5007$ spectra of twelve type 2 AGN (Sec. 3.1), and measure both the narrow-line region radius $R_{\text{NLR}}$ and the kinematic radius $R_{\text{kin}}$ (Sec. 3.3 and 3.4). With these radii, we can revisit the narrow-line region size-luminosity relation with our lower luminosity objects, and explore the kinematic size-luminosity relation (Sec. 3.5). The kinematic size $R_{\text{kin}}$ will also be used to estimate the outflow energetics (Sec. 4.2) and to study the relationship between AGN luminosity and outflow properties (Sec. 4.3).

### 3.1 Basic Properties of The [O III] Spectra

In the upper left panels of Fig. 4.2, 4.3, and Appendix 7.3, we show the Magellan slit positions on the SDSS images and the continuum subtracted two-dimensional [O III]$\lambda5007$ spectra of our objects. Only one representative slit position per object is shown. The lower left panels show the extracted nuclear spectra of the central 1" covering the H$\beta$, [O III]$\lambda4959$, and [O III]$\lambda5007$ lines.

With the two-dimensional spectra, we can measure the [O III]$\lambda5007$ line intensity profile (upper right panels), which is integrated within a velocity range of $-2000$ to $2000$ km s$^{-1}$ to cover the entire line. We find that the line-emitting gas is mostly AGN-ionized instead of star-formation ionized with a [O III]$\lambda5007$ to H$\beta$ line ratio between 3 and 10. The only exception is part of the nuclear region of SDSS J1255$-$0339, where the ratio is close to two.

In addition to photoionization, we are also interested in the mechanical feedback that can disturb or accelerate the gas, which can be traced by the emission line profiles. From the two-dimensional spectra, we can measure the line velocity and velocity dispersion as a function of position (upper and middle right panels). These two quantities are represented
non-parametrically by the median velocity $v_{\text{med}}$ and the 80 percent linewidth $w_{80}$, which is the velocity width between the 10th and 90th percentiles of the line flux. $w_{80}$ roughly corresponds to the FWHM for Gaussian profiles, but is more sensitive to line wings and therefore suitable to capture high velocity motions (Liu et al., 2013b; Harrison et al., 2014). We do not correct for the increased linewidth due to finite spectral resolution, which is under 15% except for SDSS J1351+0728, where the correction can be up to 30%. The velocities and velocity dispersion are measured in every 0.6′′ bins to achieve a good signal-to-noise ratio.

Figure 4.2 The [O III]λ5007 spectrum and measurements for SDSS J1000+1242. Left: The SDSS image with the black lines showing the Magellan slit position (top left), Magellan [O III]λ5007 2-D spectrum (top right), and Magellan nuclear 1″ spectrum covering the Hβ, [O III]λ4959, and [O III]λ5007 lines (bottom, in units of $10^{40}$ erg s$^{-1}$ Å$^{-1}$). Top Right: The [O III]λ5007 surface brightness profile for the entire line (black), the blue wing of the line (blue, $v < -300$ km s$^{-1}$), and the red wing of the line (red, $v > 300$ km s$^{-1}$) in units of $10^{41}$ erg s$^{-1}$ kpc$^{-2}$, overplotted with the scaled PSF (gray dotted line) and the $R_{\text{NLR}}$ isophotal cut (dashed line). Middle Right: The profile of the [O III]λ5007 line width $w_{80}$ (blue) and median velocity $v_{\text{med}}$ (red) in units of km s$^{-1}$, overplotted with the $R_{\text{kin}}$ line width threshold of 600 km s$^{-1}$ (dashed line). Bottom Right: [O III]λ5007 integrated 1-D spectrum in units of $10^{40}$ erg km$^{-1}$, overplotted with dashed lines marking the velocities of ± 300 km s$^{-1}$.
Figure 4.3 Same as Fig. 4.2 but for SDSS J1010+1413.

3.2 Spatial Resolution

We are interested in measuring the spatial extent of the [O III]λ5007 ionized emission line, particularly its high velocity components that signal outflows. Depending on the spatial resolution, the size measurements could be exaggerated by the smearing effect of the seeing, especially if a compact nuclear component dominates the flux.

Qualitative analysis that subtracts the nuclear point-spread function (PSF) is one way to properly recover the size of the extended emission, as shown by Husemann et al. (2013, 2015). Using the broad emission lines to estimate and subtract the nuclear PSF, Husemann et al. (2015) reveals that many objects in their type 1 AGN sample still retain their extended high velocity [O III] nebula. While the same technique cannot be easily applied to our type 2 sample, we do determine whether or not the high-velocity gas is spatially resolved as described below. For the objects that are resolved, we also adopt very conservative size errors comparable to the PSF, so that the marginally resolved objects have size uncertainties comparable to the size itself.

To determine if the high velocity [O III]λ5007 emission is spatially resolved, we compare the surface brightness profiles with the PSF. The fiducial PSF model is conservatively taken from a flux calibration star of the worst seeing (FWHM = 1″0), while the median seeing for the targets is 0″7. An object is classified as resolved if either the blue wing (v < −300 km s⁻¹) or red wing
(v > 300 km s$^{-1}$) surface brightness profile is broader than the PSF, see the upper right panel of Fig. 4.2, 4.3, and Appendix 7.3. Three out of twelve systems are determined to be unresolved: SDSS J2102$-$0647, J2133$-$0712, and J2142+0001. For the rest, we adopt half of the FWHM of the PSF as the 1-$\sigma$ size uncertainty. In one system, SDSS J1419+1039, although both wings appear to be more compact than the fiducial PSF, it is classified as resolved, as the blue side is significantly more extended than the red side.

We also incorporate studies of type 2 AGN at higher AGN luminosities (Liu et al., 2013a; Hainline et al., 2014b). These samples are at higher redshifts (z~0.5) and thus suffer more from seeing, resulting in size over-estimation of typically 0.1-0.2 dex (Hainline et al., 2014b). We adopt the same conservative size error bars comparable to the seeing, which encompass the size overestimations. Liu et al. (2013a) determined that all of their sample are spatially resolved based on either the surface brightness or the velocity profiles. In Hainline et al. (2014b), five systems are classified as unresolved.

### 3.3 Narrow-Line Region Radius $R_{\text{NLR}}$

The size of the influence of AGN photoionization can be quantified by the narrow-line region radius $R_{\text{NLR}}$. We adopt a common definition of $R_{\text{NLR}}$ as the semi-major axis of the $10^{-15} \ (1 + z)^{-4} \ \text{erg s}^{-1} \ \text{cm}^{-2} \ \text{arcsec}^{-2}$ isophote of the $[\text{O \ III}]$ $\lambda$5007 line. This definition is used by Liu et al. (2013a) and Hainline et al. (2013, 2014b) and corresponds to an intrinsic surface brightness of $5.1 \times 10^{39} \ \text{erg s}^{-1} \ \text{kpc}^{-2}$. This measurement can be compared across studies as it is independent of the redshift or the depth of the observation, provided the observations reach this depth. As our slits are placed along the major axis of the $r$-band emission in the SDSS images, the measured $R_{\text{NLR}}$ roughly corresponds to those measured with IFU observations (e.g., Liu et al., 2013a). As narrow-line regions are often round (Liu et al., 2013b), the sizes $R_{\text{NLR}}$ may not depend strongly on the slit orientation. The measured $R_{\text{NLR}}$ are listed in Table 4.2 and demonstrated on the upper right panels of Fig. 4.2 and 4.3, etc. The three unresolved objects in our sample are treated as $R_{\text{NLR}}$ upper-limits. One object SDSS J1255$-$0339 has a particularly large $R_{\text{NLR}}=33$ kpc because it has a pair of extended but kinematically cold tidal features (Appendix 7.3).
We incorporate 14 $R_{\text{NLR}}$ measurements of luminous type 2 AGN from Liu et al. (2013a), as well as 20 $R_{\text{NLR}}$ measurements and 5 unresolved upper-limits from Hainline et al. (2014b) (Fig. 4.4). Liu et al. (2013a) uses the Gemini GMOS IFU while Hainline et al. (2014b) uses Gemini GMOS long-slit spectroscopy and both reach similar depths as ours. Five objects in Hainline et al. (2014b) are excluded due to duplication with Liu et al. (2013a) (4/10) or WISE source confusion (1/10).

### 3.4 Kinematic Radius $R_{\text{kin}}$

To quantify the size of the kinematically disturbed region, we define a kinematic radius $R_{\text{kin}}$ based on the width of the [O III] $\lambda 5007$ line. In order to identify high velocity non-virialized motions, $R_{\text{kin}}$ is defined to be the radius over which the [O III] $\lambda 5007$ velocity dispersion $w_{80}$ is larger than a threshold of 600 km s$^{-1}$, similar to the definition of $D_{600}$ in Harrison et al. (2014). While this value of 600 km s$^{-1}$ is somewhat arbitrary, it is also conservative, since galaxy velocity dispersions rarely exceed 300 km s$^{-1}$. Typical ellipticals have velocity dispersion $\sigma \sim 200$ km s$^{-1}$ (Sheth et al., 2003), thus their $w_{80}$ should be under 500 km s$^{-1}$ assuming virialized motions with Gaussian profiles.

The resulting $R_{\text{kin}}$ are tabulated in Table 4.2 and plotted in Fig. 4.4. Four out of the twelve objects have $w_{80}$ profiles that drop below 600 km s$^{-1}$ at large radii, giving valid $R_{\text{kin}}$ measurements (plotted as circles in Fig. 4.4). Three objects are treated as $R_{\text{kin}}$ lower limits and plotted as triangles, as their $w_{80}$ are still above 600 km s$^{-1}$ at the largest measured radii, and therefore it is not known whether (or at what distance) the linewidth drops below the 600 km s$^{-1}$ threshold. The three unresolved objects all have high $w_{80}$, but their $R_{\text{kin}}$ are unconstrained and plotted as empty diamonds. Two objects, SDSS J1055+1102 and SDSS J1351+0728, do not show disturbed kinematics with $w_{80}$ always below 600 km s$^{-1}$, so their $R_{\text{kin}}$ are not defined, and shown as empty squares.

To increase the sample size, we also calculate $R_{\text{kin}}$ from the sample of Liu et al. (2013a), where the median $w_{80}$ as a function of radius is also measured. Among the fourteen objects in Liu et al. (2013a), thirteen have high linewidths ($w_{80} > 600$ km s$^{-1}$), yielding ten $R_{\text{kin}}$ measurements and
three lower limits. Only one object, SDSS J0842+3625, does not have $w_{80}$ above 600 km s$^{-1}$, as tabulated in Table 4.3. The combination of these two samples covers a wide dynamic range in AGN luminosity from $10^{45}$ to $10^{47}$ ergs s$^{-1}$.

3.5 The Size-Luminosity Relations

In this section we investigate the relationship between AGN luminosity and our two size measurements - $R_{\text{NLR}}$, which depends on photoionization, and $R_{\text{kin}}$, which is based on kinematics. These two radii typically extend from a few to 15 kpc (with the exception of SDSS J1255$-0339$ where $R_{\text{NLR}} = 33$ kpc), corresponding to light travel time of $\sim 10^4$ years.

The relation between $R_{\text{NLR}}$ and the AGN luminosity has been studied extensively and there are tentative signs that it flattens at high AGN luminosity (Hainline et al., 2013; Liu et al., 2013a; Hainline et al., 2014b; Liu et al., 2014). In Fig. 4.4, left, we revisit this relation, supplementing it with our new sample with high quality $R_{\text{NLR}}$ measurements. Our objects populate a lower luminosity range compared to previous studies, allowing us to extend the luminosity baseline. Furthermore, we use a different AGN luminosity indicator - $15 \mu$m luminosity $\nu L_{\nu,15}$, which is arguably less sensitive to the anisotropy of the infrared emission (Appendix 7.2).

On the right-hand side of Fig. 4.4 we show the dependence on AGN luminosity of our newly derived kinematic radius $R_{\text{kin}}$, which illustrates the effect of the AGN luminosity on the mechanical feedback operating on galaxy scales. We find that both radii are positively correlated with the $15 \mu$m luminosity, with Pearson’s $r$ correlation coefficient above 0.6 and the $p$-values below 0.01.

An essential property of $R_{\text{NLR}}$ is that it includes any photoionized gas in the vicinity of the galaxy, independent of its origin, including tidal features or illuminated companion galaxies. As an extreme example of illuminated tidal features, SDSS J1255$-0339$ has a pair of extended tidal tails emitting in [O III]. They can be seen in the SDSS $r$-band image and they yield a very large $R_{\text{NLR}}$ measurement. This object is a distinct outlier in the $R_{\text{NLR}} - \nu L_{\nu,15}$ relation (blue cross in the left panel of Fig. 4.4). But in the $R_{\text{kin}} - \nu L_{\nu,15}$ space, this object follows the trend defined by other AGN because this extended feature has quiescent kinematics.
Chapter 4: Sizes and Kinematics of Extended Emission-Line Regions in Obscured AGN

Table 4.2. The Measurements

<table>
<thead>
<tr>
<th>Name</th>
<th>$R_{\text{NLR}}$ [kpc]</th>
<th>$R_{\text{kin}}$ [kpc]</th>
<th>$w_{80}$ [km s$^{-1}$]</th>
<th>$t_{\text{dyn}}$ [yr]</th>
<th>$E_{\text{kin}}$ [erg]</th>
<th>$\dot{E}_{\text{kin}}$ [erg s$^{-1}$]</th>
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Note. — Measurements of the Magellan sample of luminous type 2 AGN. Column 1: SDSS Name. Column 2: Radius of the narrow line region. Column 3: Radius of the kinematically disturbed region (outflow), that has high [O III]$\lambda$5007 line widths $w_{80}> 600$ km s$^{-1}$. Column 4: Averaged [O III]$\lambda$5007 line width $w_{80}$ (the width that encloses 80% of the flux). It is used to infer the outflow velocity $v =w_{80}/1.3$ assuming quasi-spherical outflows (Liu et al., 2013b). Column 5: Outflow dynamical time scale $t_{\text{dyn}}=R_{\text{kin}}/v = 1.3\times R_{\text{kin}}/w_{80}$. Column 6, 7: Outflow kinetic energy $E_{\text{kin}}$ and its power $\dot{E}_{\text{kin}}=E_{\text{kin}}/t_{\text{dyn}}$ based on the ionized gas mass inferred from the H$\beta$ intensity. These numbers are underestimates as the mass in the more diffuse gas is not accounted for. Column 8: Sedov-Taylor kinetic power $\dot{E}_{\text{ST}}$ for a supernova like bubble of size $R_{\text{kin}}$ and velocity $v =w_{80}/1.3$. This is an overestimation of outflow kinetic power as it assumes all the enclosed gas mass participates in the outflow.

a The $R_{\text{NLR}}$ measurement is treated as an outlier and excluded in the regression analysis, as it is affected by extended tidal features. This object is marked as a cross in Fig. 4.4.

b Spatially unresolved objects. All of these three objects also happen to have high line widths ($w_{80}> 600$ km s$^{-1}$) but the sizes of their kinematically disturbed region $R_{\text{kin}}$ cannot be constrained. They are marked as empty diamonds in Fig. 4.5.

c $R_{\text{kin}}$ lower-limits, as the line width $w_{80}$ stays high at the largest measured radius.

d $R_{\text{kin}}$ is undefined, as the line width is always low and there is no kinematically disturbed region. They are marked as empty squares in Fig. 4.5.

e $E_{\text{kin}}$ is not available as the H$\beta$ measurement is affected by observational defects.
Table 4.3. The Measurements for the Liu 2013 Sample

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Note. — Details and measurements of the Liu et al. (2013b) sample. The attributes are as described in Tab. 4.1 and 4.2. Column 5, 6, and 7 are taken from Liu et al. (2013a): column 5 is directly from $R_{int}$ of Table 2; column 6 $R_{kin}$ is read from Fig. 5; column 7 is $w_{80}$ from Table 1. The later columns are derived from these two using the same formulas as for the main sample. The H$\beta$ luminosities for $E_{kin}$ and $\dot{E}_{kin}$ are from the [O III]$\lambda 5007$ luminosity and [O III]$\lambda 5007$-H$\beta$ line ratios from Liu et al. (2013a).

- $R_{kin}$ lower-limits, as the line width $w_{80}$ stays high at the largest measured radius.
- $R_{kin}$ is undefined, as the line width is always low and there is no kinematically disturbed region, marked as empty squares in Fig. 4.5.
- $E_{kin}$ is not calculated as the [O III]$\lambda 5007$ to H$\beta$ ratio is not available.
- $R_{kin}$ is intermediate.

Radio loud or intermediate.
Chapter 4: Sizes and Kinematics of Extended Emission-Line Regions in Obscured AGN

As our new sample can improve the constraints on the low end slope of the $R_{\text{NLR}}$ size-luminosity relation, and we are interested in quantitatively comparing the $R_{\text{NLR}}$ and $R_{\text{kin}}$ size-luminosity relations, we fit these two relations with a single power-law (gray lines in Fig. 4.4) and a flattened power-law (black line). To determine whether the flattening of the size-luminosity relations is significant, we use the Bayesian Information Criteria (BIC) to distinguish which model is preferred by the data (Tab. 4.4). Only objects with valid size measurements (circles in Fig 4.4) rather than limits are included for this analysis.

We find that the $R_{\text{NLR}} - \nu L_{\nu,15}$ relation prefers a flattened power law beyond a luminosity of $\nu L_{\nu,15} = 10^{44.8}$ ergs s$^{-1}$ or $R_{\text{NLR}} > 12$ kpc, with a BIC difference of 3.5. The $R_{\text{kin}}$ size-luminosity relation slightly prefers a single power-law, with a BIC difference of only 0.4.

Therefore, we confirm the findings of Liu et al. (2013a) and Hainline et al. (2013, 2014b) that, beyond a luminosity of about $L_{\text{bol}} > 10^{46}$ ergs s$^{-1}$, the $R_{\text{NLR}} - \nu L_{\nu,15}$ relation flattens such that $R_{\text{NLR}}$ is a constant with respect to the AGN luminosity. One possible explanation of the observed limit to the narrow-line region size is the change in the ionization state at large radii. For example, as the density of the gas drops, the clouds can transition from an ionization-bounded to matter-bounded state, such that the O$^{2+}$ ions become ionized to O$^{3+}$ (Liu et al., 2013a). Our measured slope of the $R_{\text{NLR}} - \nu L_{\nu,15}$ relation at the low luminosity end (0.84) as fitted by the flatted power-law is steeper than the value of 0.47 found by Hainline et al. (2013), likely due to our objects providing a better sampling of the relationship at lower luminosities.

Although the $R_{\text{kin}}$ measurements are still limited by the availability of a strong [O III] line, we find no evidence that the $R_{\text{kin}} - \nu L_{\nu,15}$ relation saturates at high luminosities. The kinematic size of the AGN-disturbed region seems to scale with the AGN luminosity across the luminosity range of $L_{\text{bol}} = 10^{45}$ to $10^{47}$ ergs s$^{-1}$ with a power index of $\sim 0.39$. With a wider dynamic range in $L_{\text{bol}}$, we will be able to learn more about how the kinematically disturbed gas depends on the AGN luminosity.

It is possible that the size of the kinematically disturbed region continues to decrease in lower luminosity AGN. NGC 1068, a local type 2 AGN at a lower AGN luminosity of $L_{\text{bol}} \sim 10^{44-45}$ (Goulding et al. 2010; Alonso-Herrero et al. 2011; Garcia-Burillo et al. 2014 and references
hosts ionized outflows with deprojected velocities as fast as $\sim 1300$ km s$^{-1}$, but with a much smaller outflow size on the scale of $\sim 200$ pc (Cecil et al., 1990; Crenshaw & Kraemer, 2000).

In summary, we find that both $R_{\text{NLR}}$ and $R_{\text{kin}}$ correlate with the AGN luminosity. There is evidence that $R_{\text{NLR}}$ saturates at about 10 kpc at high AGN luminosities, but there is no evidence that $R_{\text{kin}}$ saturates as well. $R_{\text{kin}}$ is also less affected by the presence of tidal tails or companions.

![Figure 4.4](image-url)

Figure 4.4 The comparison of two size luminosity relations, based on the radius of the narrow line region $R_{\text{NLR}}$ defined by the surface brightness of the [O III]$\lambda 5007$ line (left) and the radius of the kinematically disturbed region $R_{\text{kin}}$ defined by high [O III]$\lambda 5007$ linewidth of $w_{80} > 600$ km s$^{-1}$ (right). Three samples are used: this paper (blue), Liu et al. (2013b) (red), and Hainline et al. (2014b) (green). On the horizontal axis is the mid-IR rest frame 15 $\mu$m luminosity $\nu L_{\nu, 15}$ as a proxy of the AGN luminosity. The solid circles are valid size measurements. On the left panel, the downward triangles are $R_{\text{NLR}}$ upper-limits for unresolved objects. On the right panel, the upward triangles are $R_{\text{kin}}$ lower-limits for objects with linewidths that stay high at the largest measured radius. The empty squares represent objects with no high velocity [O III]$\lambda 5007$ features and thus $R_{\text{kin}}$ undefined, and the empty diamonds are unresolved objects with high velocity [O III]$\lambda 5007$ thus having $R_{\text{kin}}$ unconstrained. The blue cross is the source SDSS J1255$-$0339 with ionized tidal tails. The error bars represent the size of the PSF. The gray and black lines show the best-fit single power-law and flattened power-law models fitting only solid circles. The $R_{\text{NLR}}-\nu L_{\nu, 15}$ relation on the left prefers a flattened power-law while the $R_{\text{kin}}-\nu L_{\nu, 15}$ relation slightly prefers single power-law (Sec. 3.5).
## Table 4.4. Comparison of the $R_{\text{NLR}}$ and $R_{\text{kin}}$ size-luminosity relations

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<th>$\nu L_{\nu,15}$</th>
<th>$R_{\text{kin}}$</th>
<th>$\alpha$</th>
<th>$\beta$</th>
<th>$\alpha$</th>
<th>$\beta$</th>
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<tr>
<td>$\Delta \text{BIC}$</td>
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</tbody>
</table>

Note. — The best-fit model parameters of the $R_{\text{NLR}}$ and $R_{\text{kin}}$ size-luminosity relations, see Fig. 4.4. Column 1 and 2: The parameters and the Bayesian information criterion of the power-law model $\log(y) = \alpha + \beta \log(x)$. Column 4 and 5: Same as Column 1-3 but for a power-law that flattens beyond the point $[\log(L), \log(R)]$. Column 6: The difference between the Bayesian information criteria of the two models, where positive means that the data prefers the flattened power-law and negative means otherwise, as shown in Column 10. Only valid size measurements (not upper/lower-limits) are used in these fits. The units are ergs s$^{-1}$ for the luminosity and kpc for the radius.
4 Outflow Properties and Energetics

The large [O III] $\lambda 5007$ linewidths ($w_{80} = 600 - 1500$ km s$^{-1}$) commonly seen in our sample suggest that many of these systems have high velocity non-virialized gas motions, likely outflows. While AGN outflows on galactic scales are thought to be an important agent to regulate star-formation, their size distributions, energy efficiencies, and dependence on the AGN luminosity are not well-understood. Therefore, it is important to measure the properties of these outflows, including size, velocity, and energetics, and study their dependence on the AGN luminosity.

In Sec. 4.1, we discuss kinematic models to explain the observed [O III] $\lambda 5007$ velocity profiles. In Sec. 4.2, we define and calculate the outflow properties including the sizes, velocities, and time scales. We also use two methods to estimate the outflow kinetic power. In Sec. 4.3, we study the correlation between the outflow properties and the AGN bolometric luminosities and discuss the outflow energy efficiency.

We find that the outflow size, velocity, and energy are correlated with the AGN luminosity. Although the actual outflow efficiency cannot be constrained with high accuracy (we estimate $\eta = \dot{E}/L_{\text{bol}} = 0.01\% - 30\%$), our results are consistent with a hypothesis that the energy efficiencies of AGN outflows are roughly constant for AGN in the luminosity range of $10^{45-47}$ ergs s$^{-1}$.

4.1 Velocity Profiles and Kinetic Model of the Outflow

Many of our targets have gas velocities ($w_{80} = 600 - 1500$ km s$^{-1}$) faster than virialized motions in a typical galactic potential ($w_{80} < 500$ km s$^{-1}$, see Sec. 3.4). In this section, we discuss possible outflow models that can explain the observed linewidth and its profile.

Except for two systems with no high velocity components (SDSS J1055+1102, J1351+0728), most systems in our sample show $w_{80}$ profiles that are constantly high ($w_{80} \sim 600 - 1500$) within the central few kpc (Fig. 4.2, 4.3, and Appendix 7.3). For spherical/quasi-spherical outflows with power-law intensity profiles, this flat $w_{80}$ profile corresponds to a constant deprojected outflow velocity $v \sim w_{80}/1.3 = 460 - 1100$ km s$^{-1}$ (Liu et al., 2013b). Objects that have observations with high signal-to-noise ratio at large radii (SDSS J1000+1242, J1010+1413, J1255−0339) also
demonstrate a sudden velocity drop at radii of 5-10 kpc. Such high linewidth plateau followed by sudden drops are also commonly seen in other studies of type 2 AGN (e.g. Greene et al., 2011; Liu et al., 2013b), where the 2-D distributions of the linewidths are often round when observed with IFU spectroscopy.

King (2005) and King et al. (2011) found that for an energy-conserving (no radiative loss) spherical outflow propagating in a galaxy with an isothermal potential and gas distribution, the outflow’s shock front expands at a constant velocity, which for black holes on the $M - \sigma$ relation accreting at their Eddington rate is of order 1000 km s$^{-1}$. At the same time, gas at large radii that has not yet been shocked and accelerated by the outflow remains at its original velocity. Therefore, there should be a sharp drop in the gas velocity profile corresponding to the shock front.

Our observed linewidths are qualitatively consistent with this simple energy conserving outflow model in both their amplitude and their radial profile. The kinematic radius $R_{\text{kin}}$, defined based on the line width threshold of 600 km s$^{-1}$, is able to capture the location of the velocity drop. For objects in our sample that are unresolved, higher spatial resolution data are required to confirm whether and where the velocity drops. In the following sections, based on the observables $w_{80}$ and $R_{\text{kin}}$, we discuss the outflow properties and the implications of them.

### 4.2 Outflow Properties Definition

In this section, we define the outflow properties, including the radius, velocity, dynamical time scale, and energetics.

As discussed in Sec. 4.1, we adopt the radius of the outflow to be $R_{\text{kin}}$ – the radius of the high $[\text{O III}]\lambda5007$ linewidth region. We adopt the outflow velocity $v$ to be the $v = w_{80}/1.3$ for quasi-spherical outflows following Liu et al. (2013b). The $w_{80}$ adopted is the luminosity-weighted quadratic mean $w_{80}$ measured along the slit. We then derive the outflow dynamical time scale as $t_{\text{dyn}} = R_{\text{kin}}/v$. All of these quantities are tabulated in Table 4.2.

As discussed in Greene et al. (2012), measuring the mass of the outflow can be challenging, which is the biggest uncertainties in estimating the energetics. As the emissivity scales with
density squared, strong emission lines, such as [O III]λ5007 and Hβ, trace only the densest ionized gas clouds. These clouds occupy only a small fraction of the total volume (∼ 10^{-2}), and there can be a large amount of diffuse ionized gas unaccounted for. Parts of the outflows can even be of different phases, such as molecular or hot plasma, that is not traced with these lines.

In order to bracket the range of possible kinetic power, we adopt two methods to infer the outflowing mass. Assumptions of gas densities are made for both methods using reasonable values for type 2 AGN. While the absolute values of energy depend on these assumptions, we focus on trends in outflow properties with AGN luminosity, which do not depend as strongly on these assumptions.

For the first method, we estimate the mass of the dense ionized gas from the Hβ luminosity assuming case B recombination\(^6\). We use equation (1) from Nesvadba et al. (2011), which assumes a line ratio of Hα/Hβ=2.9,

\[ M_{\text{ion}} = 2.82 \times 10^9 L_{\text{Hβ,43}} n_{e,100}^{-1} M_\odot, \]

where \( L_{\text{Hβ,43}} \) is the Hβ luminosity in units of \( 10^{43} \text{ erg s}^{-1} \), and \( n_{e,100} \) is the electron density in units of \( 100 \text{ cm}^{-3} \). We adopt a fiducial value of \( n_{e,100} = 1 \) for our objects, which is typical in these AGN ionized outflows. We then calculate the kinetic power as

\[ \dot{E}_{\text{kin}} = \frac{1}{2} M_{\text{ion}} v^2 \frac{1}{t_{\text{dyn}}} = \frac{1}{2} M_{\text{ion}} R^{-1} v^3, \]

where \( t_{\text{dyn}} \) is the dynamical time scale. \( L_{\text{Hβ}} \) is measured from the Magellan slits assuming the Hβ surface brightness profile is azimuthally symmetric. This method likely underestimates the total outflowing gas mass, as the emission lines trace only the densest gas.

The second method is similar to the Sedov-Taylor solution for a supernova remnant where a spherical bubble is expanding into a medium of constant density. This method is motivated by observations of such organized outflows in similar type 2 AGN, e.g. SDSS J1356+1026 (Greene

\(^6\)As SDSS J0141−0945 and J2133−0712 don’t have Hβ measurements from the Magellan spectra, their \( M_{\text{ion}} \) and \( \dot{E}_{\text{kin}} \) estimates are not available.
et al., 2012). We adopt a simple definition of $\dot{E}_{ST}$ as

$$\dot{E}_{ST} = \frac{1}{2} \dot{M} v^2 = 2\pi \rho_0 R^2 v^3,$$

(4.3)

where

$$\dot{M} = 4\pi \rho_0 R^2 v$$

(4.4)

is the rate at which ambient gas enters the outflow. The ambient gas density $\rho_0$ is assumed to be a constant $\rho_0 = m_p \times (0.5 \text{ cm}^{-3})$. Such a density is supported by scattering measurements of type 2 AGN by Zakamska et al. (2006). This definition is within 20% of the Sedov-Taylor solution described in Eq. 39.9 of Draine (2011), and e.q. 7.56 of Dyson & Williams (1980), and about 30% lower than the one adopted by Nesvadba et al. (2006) and Greene et al. (2012). This method likely overestimates the kinetic power, as it assumes that all of the ambient gas is entrained in the outflow.

### 4.3 Relation between the Outflow Properties and the AGN Luminosities

In this section, we investigate how outflow size, velocity, dynamical time-scale, and energy correlate with AGN luminosity. We adopt the 15 $\mu$m luminosity $\nu L_{\nu,15}$ as the AGN luminosity indicator (as discussed in Sec. 2.5). The outflow size, velocity, dynamical time scale, and energetics are defined in section 4.2.

The relations between these outflow quantities ($y$) and the AGN luminosity indicator $\nu L_{\nu,15}$, are quantified by a single power law,

$$\log(y) = \alpha + \beta \times \log(\nu L_{\nu,15}).$$

(4.5)

We adopt a Bayesian linear regression approach developed by Kelly (2007) using Markov chain Monte Carlo sampling method, which accounts for the measurement errors, intrinsic scatter, and upper- or lower-limits.
For the measurement errors, to reflect the fact that smaller objects have larger fractional size errors, we conservatively adopt the HWHM of the typical PSF as the 1-sigma error for the radius. The PSF FWHM is typically 1″ for our and the Hainline et al. (2014b) sample and 0′′7 for the Liu et al. (2013b) sample. Likewise for \( w_{80} \), we conservatively adopt the HWHM of the instrumental line profiles as the 1-sigma error for \( w_{80} \), where the FWHM is about 260 (340) km \( s^{-1} \) for our sample observed with the 1″(1″3) slit and 150 km \( s^{-1} \) for the (Liu et al., 2013b) sample. These errors are propagated to the dynamical time scales and energetics calculations. For the energetics, we further assume 20% and 50% fractional errors for the H\( \beta \) luminosities and the electron densities \( n_e \). We assume there is no error in the AGN luminosity indicator \( \nu L_{\nu,15} \).

As shown in Fig. 4.5 and Table 4.5, both the outflow radius \( R_{\text{kin}} \) and the velocity \( w_{80} \) correlate positively with the AGN luminosity, with a power-law index of \( \beta = 0.33^{+0.16}_{-0.17} \) and \( \beta = 0.12^{+0.07}_{-0.07} \), respectively. There is no evidence that the dynamical time \( t_{\text{dyn}} \), which is of order 10\(^7\) years, correlates with the AGN luminosity.

The \( \dot{E}_{\text{ST}} \) are typically two orders of magnitudes higher than \( \dot{E}_{\text{kin}} \), meaning that we cannot constrain the outflow energetics precisely. However, as shown in Fig. 4.6, the kinetic power inferred from either method is consistent with being linearly proportional to the AGN luminosity, supporting a constant feedback energy efficiency. These two methods bracket a very large range of feedback energy efficiency \( \eta = \dot{E}/L_{\text{bol}} = 0.01\% - 30\% \), reflecting the big uncertainties in the outflowing mass. Most AGN in the luminosity range of \( L_{\text{bol}} \sim 10^{45-47} \) ergs \( s^{-1} \) are capable of driving outflows with energy proportional to their AGN luminosity.

As we find that the outflow properties, including the radius, velocity, and energy, correlate and increase steadily with the AGN bolometric luminosity, an AGN outflow should be a common phenomenon within the luminosity range of \( L_{\nu, 15\mu m} \sim 10^{44-46} \) ergs \( s^{-1} \) or \( L_{\text{bol}} \sim 10^{45-47} \) ergs \( s^{-1} \). If there is a critical luminosity threshold for AGN feedback, above which outflows are driven, it must occur at yet lower AGN luminosities.
Table 4.5. Relation between the Outflow Properties and the AGN Luminosities

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<th>p-value</th>
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</tbody>
</table>

Note. — Statistics of the relation between the outflow properties and the mid-IR luminosity νLν,15. The outflow properties and their units are as described in Tab 4.2 and Sec. 4.2. Column 1 and 2: The Pearson’s r correlation coefficient between log(x) and log(y) and its p-value, calculated using only the valid measurements (solid circles in Fig. 4.5). Except for tdy, the outflow properties are positively correlated with the luminosity in a statistically significant sense. Column 3 and 4: The posterior mean and the 68% confidence interval of the parameters of the power-law model log(y) = α + β log(x). All the measurements and upper/lower-limits (solid circles and triangles in Fig. 4.5) are used with error bars taken into account.
Chapter 4: Sizes and Kinematics of Extended Emission-Line Regions in Obscured AGN

This paper
Liu 2013b

Figure 4.5 The outflow properties versus the AGN luminosity. The outflow properties are: radius $R_{\text{kin}}$ (upper left), velocity $v = w_{80}/1.3$ (upper right), ionized gas kinetic power $\dot{E}_{\text{kin}}$ (middle left), Sedov-Taylor kinetic power $\dot{E}_{\text{ST}}$ (middle right), and dynamical time $t_{\text{dyn}}$ (bottom). On the horizontal axis is the mid-IR rest frame 15 µm luminosity $\nu L_{\nu, 15}$ used as a proxy of the AGN luminosity. Except for $t_{\text{dyn}}$, all the properties are positively correlated with the AGN luminosity. The symbols and their colors are as described in Fig. 4.4. The gray lines sample the posterior distribution of the power-law model, and the black line shows the model corresponding to the posterior mean. The model parameters and correlation coefficients are listed in Tab. 4.5 and discussed in 4.3.
43.5 44.0 44.5 45.0 45.5 46.0
log(νLν, 15 µm) [erg s−1 ]
40
41
42
43
44
45
46
47
log( ˙E) [erg s−1 ]
100%
10%
1%
0.1%
0.01%
This paper
Liu 2013b
Sedov-Taylor
Kinetic
Figure 4.6 The outflow kinetic power versus the AGN luminosities. The outflow kinetic power is bounded by two estimates: the ionized gas kinetic power ˙E_{kin} (empty symbols), and the supernova-like Sedov-Taylor kinetic power ˙E_{ST} (solid symbols). On the horizontal axis is the mid-IR rest frame 15 µm luminosity νLν,15 used as a proxy of the AGN luminosity. The symbols and their colors are as described in Fig. 4.4. The diagonal dashed lines show different energy efficiencies η = ˙E/L_{bol}, where L_{bol} = 9×νLν,15. The kinetic powers from both methods, although may differ by up to two orders of magnitudes, are consistent with being linearly proportional to the AGN luminosity. The outflow energy efficiency is bracketed within the range of η = ˙E/L_{bol} = 0.01% − 30%.

5 Outflow Occurrence Rates and Timescales

In this section we discuss the occurrence rate of the extended ionized outflows in luminous type 2 AGN and implications for characteristic timescales and variability of accretion. In short, we estimate that extended (few - 10 kpc) ionized outflows are present in ∼ 80% of luminous type 2 AGN. Given that the outflow formation times are ∼ 10^7 years, such a high occurrence rate implies a long duration for each outflow episode of ∼ 10^8 years. As we argue below, it is unlikely that the AGN maintains a high luminosity (L_{bol} > 10^{45} ergs s^{-1}) throughout this 10^8-year episode. Instead, our observations suggest that AGN flicker on a shorter time scale (∼ 10^7 years) and spend only ∼ 10% of their time in such a high luminosity state, and still maintain a high occurrence rate of extended outflows. We spell out our reasoning in the following paragraphs.
Kpc-scaled ionized outflows are found to be common among luminous type 2 AGN. Based on our kinematic requirement of \( w_{80} > 600 \text{ km s}^{-1} \), in our sample ten out of the twelve systems host outflows, seven of which are clearly extended, while the other three are unresolved and thus their outflow sizes are unconstrained, giving an extended outflow occurrence rate of \( \gtrsim 60\% \). While our sample may be biased by our broadband image selection, homogeneously selected samples (e.g., Liu et al., 2013b; Harrison et al., 2014) also show a high fraction of resolved high velocity features. Liu et al. (2013b) argues that all 14 of their targets are resolved, among which 13 have high line widths (90%); Harrison et al. (2014) finds all 16 of their type 2 AGN have outflows > 6 kpc.

While it is a concern that beam smearing could lead to an overestimation of the outflow sizes, the occurrence rate of extended outflows is still high after such effects are taken into account. After subtracting the unresolved nuclear component, Husemann et al. (2015) still recover high line widths \( (w_{80} > 600 \text{ km s}^{-1}) \) in the extended nebula in seven out of twelve (60%) type 1 AGN from Liu et al. (2014). In the \( z \sim 0.5 \) sample of Liu et al. (2013b), where the effect can be most severe, if we conservatively take out all four objects that could be considered as being marginally resolved\(^7\) we still arrive at a occurrence rate of 60%. Therefore, while most type 2 AGN studies suggest a high extended outflow occurrence rate of \( \sim 80\% \) among luminous AGN, we can place a conservative lower-limits of 60% accounting for the beam-smearing effect.

To maintain such a high occurrence rate, each AGN outflow episode must be much longer than the outflow dynamical timescale, to reduce the probability of catching undersized outflows as they grow. As it takes \( t_{\text{dyn}} \sim 10^7 \text{ years} \) (Sec. 4.3 and Fig. 4.5) to inflate a 10 kpc-scale bubble with an observed velocity of \( \sim 1000 \text{ km s}^{-1} \), these extended outflows have to be launched at least \( \sim 10^7 \text{ yr} \) in the past. If 80% of the luminous AGN were active \( \sim 10^7 \text{ yr} \) ago, the entire outflow episode has to last for \( \gtrsim 5 \times 10^7 \text{ years} \).

It seems unlikely that the AGN stay luminous \( (L_{\text{bol}} > 10^{45} \text{ ergs s}^{-1}) \) throughout the entire \( \sim 10^8 \text{ yr} \) episode, as this timescale is very similar to the total growth time of a massive black hole \( \sim 10^{7\text{--}8} \text{ yr} \) (e.g., Soltan, 1982; Martini & Weinberg, 2001; Yu & Tremaine, 2002, inferred from the quasar clustering and black hole mass density). Also, with this constant energy supply, the

\(^7\)SDSS J0841+2042 and J1039+4512 have [O III]\(\lambda 5007 \) surface brightness profiles close to the PSF; SDSS J0149–0048, J0841+2014, and J0210–1001 have flat \( w_{80} \) profiles that could be dominated by the nuclear component.
outflow would continue to expand at a velocity of $\sim 1000 \text{ km s}^{-1}$ and eventually reach a size of $\sim 100 \text{ kpc}$ in $10^8 \text{ years}$, if the outflow is described by the energy-conserving model of King et al. (2011). However, most systems in our sample and the Liu et al. (2013b) sample with good signal-to-noise ratio at large radii do not show signs of extended outflows beyond $\sim 10 \text{ kpc}$, but rather have clear velocity drops on these scales.

Instead, we suggest it is far more natural that the AGN flickers on and off throughout this $\sim 10^8 \text{ yr}$ episode. In an analytical model by King et al. (2011) of an energy conserving outflow expanding in an isothermal potential of $\sigma = 200 \text{ km s}^{-1}$, when the AGN is on, the outflow will expand at a constant velocity $\sim 2000 \text{ km s}^{-1}$. If the AGN is shut off after $10^6 \text{ years}$, the outflow will still continue to expand due to its internal thermal energy, but it will slowly decelerate, until $\sim 10^7 \text{ years}$ later the velocity will drop below, say, $300 \text{ km s}^{-1}$ and then stall. At this point the outflow has reached a size of $\sim 10 \text{ kpc}$, as calculated by King et al. (2011). Therefore, to maintain the high observed duty cycle of outflows with sizes few to $10 \text{ kpc}$ and velocities about $1000 \text{ km s}^{-1}$, there should be several AGN bursts each $\sim 10^6 \text{ year}$ long with $\sim 10^7 \text{ year}$ intervals, so that if we observe a high luminosity AGN, often times it lights up the extended bubble driven by the previous AGN burst. Each AGN burst may even be shorter (e.g., $10^5 \text{ years}$, Schawinski et al., 2015) and more frequent, as long as it supplies enough energy to sustain extended outflows throughout the episode.

There are other reasons to favor such an AGN flickering model. Theoretically, it is expected due to the episodic nature of gas cooling and feedback (Novak et al., 2011). We have posited an AGN cadence of $\sim 10^6$-year bursts with $10^7$-year intervals to explain a system with multi-scaled ionized and molecular outflows (Sun et al., 2014). AGN variability on timescales $\lesssim 10^7 \text{ years}$ has also been proposed to statistically tie star formation and AGN activity, in a model that can successfully reproduce observed AGN luminosity functions (Hickox et al., 2014). Therefore, short-term AGN variability ($\lesssim 10^7 \text{ yr}$) over a long-term episode ($\sim 10^8 \text{ yr}$) appears to be a feasible scenario to explain the sizes and the occurrence rate of extended outflows.

However, if the type 2 AGN studies (this paper, Liu et al., 2013b; Harrison et al., 2014) underestimate the impact of seeing and the occurrence rate is actually $60\%$ or lower, long outflow episodes with $\sim 10^8$-year duration would no longer be required. On the other hand, flickering may
be in conflict with the energy requirements inferred from SZ observations of luminous AGN (Crichton et al., 2016). Finally, we note that these objects are all selected by virtue of their high [O III] luminosities, so we may be biased to objects in an outflow-dominated phase.

6 Summary

We observe twelve luminous ($L_{\text{bol}} \sim 10^{45.0-46.5}$) nearby ($z \sim 0.1$) type 2 (obscured) AGN with the Magellan IMACS long-slit spectrograph to study their ionized outflows properties using primarily the [O III]λ5007 line. These objects are selected from a parent sample of $\sim 24,000$ $z < 0.4$ spectroscopically identified AGN from SDSS (Mullaney et al., 2013) to have high [O III] and WISE mid-IR luminosities as well as extended emission in SDSS images signaling extended ionized nebula.

To increase the sample size for statistical and correlation analysis, we include two external samples from Liu et al. (2013b); Hainline et al. (2014b) of luminous type 2 AGN to cover AGN luminosities from $L_{\text{bol}} = 10^{45}$ to $10^{47}$ ergs s$^{-1}$. The AGN luminosities in this paper are inferred from WISE mid-IR luminosity at rest-frame 15 $\mu$m.

The main results are as follows:

(i) The radius of the narrow-line regions $R_{\text{NLR}}$, as defined by the [O III]λ5007 isophotal radius, are 2 - 16 kpc in our sample. The exceptions are three unresolved objects and one that has a particularly large $R_{\text{NLR}}$ of 33 kpc, which is most likely an ionized tidal feature. We find that $R_{\text{NLR}}$ increases with the AGN luminosity at low AGN luminosities but flattens beyond a radius about 10 kpc, possibly due to change in the ionization state (Sec. 3.5; Fig. 4.4). Also, $R_{\text{NLR}}$ is sensitive to the presence of gas at large radii such as extended tidal features.

(ii) A large fraction (10/12) of our objects have wide [O III]λ5007 line-widths ($w_{80} > 600$ km s$^{-1}$) indicating disturbed motions that are most likely outflows, seven of which are spatially resolved. To quantify the size of these outflows, we define $R_{\text{kin}}$ as the radius of the kinematically disturbed region with [O III]λ5007 line-widths $w_{80} > 600$ km s$^{-1}$. The typical $R_{\text{kin}}$ are a few to ten kpc in our sample, and are positively correlated with the AGN luminosities with a power index of
Unlike $R_{\text{NLR}}$, the $R_{\text{kin}}$-$L_{\text{bol}}$ relation does not saturate at high luminosities (Sec. 3.5; Fig. 4.4).

(iii) Both the velocities and energetics (estimated by two methods described in Sec. 4.2) of the outflows are positively correlated with AGN luminosity, while the dynamical time-scales are roughly constant at about $t_{\text{dyn}} \sim 10^7$ years (Sec. 4.3, Fig. 4.5). Within the luminosity range of $L_{\text{bol}} = 10^{45-47}$ ergs s$^{-1}$, there is no evidence for an AGN luminosity threshold above which outflows suddenly occur or intensify.

(iv) While the outflow energy efficiencies cannot be well constrained by the observations ($\eta = \dot{E}/L_{\text{bol}} = 0.01\% - 30\%$) due to the unknown clumping factor of the [O III] emitting gas, both of our energy estimates, which provide upper and lower limits on the outflow energy, are linearly proportional to the AGN luminosity. There is no evidence that the outflow energy efficiency depends on the AGN luminosity (Sec. 4.3, Fig. 4.6).

(v) In our sample, the [O III] linewidth profiles, a proxy of the outflow velocity profile for quasi-spherical outflows, often have a high velocity plateau of $w_{80} \sim 600 - 1500$ km s$^{-1}$ at the center, followed by a sudden velocity drop at a few kpc. This is consistent with energy-conserving outflows driven by AGN accreting at close to their Eddington rates (King et al., 2011), where the outflows expand with a fixed velocity of order 1000 km s$^{-1}$. The velocity drop would correspond to where the outflow shock fronts encounter the undisturbed galactic medium (Sec. 4.1).

(vi) The occurrence rate of extended outflows is high among luminous type 2 AGN ($\sim 80\%$), after combining with higher luminosity samples from Liu et al. (2013b) and Harrison et al. (2014). Given the outflow dynamical time scales of $\sim 10^7$ years, to have such a high occurrence rate, each outflow episode should last for $\sim 10^8$ years. While the AGN is unlikely to remain at a high luminosity the entire time, the AGN could flicker on shorter time scales. For example, it can have several $\sim 10^6$-year-long bursts with $\sim 10^7$-year intervals, each of which drives a kpc-scale outflows lasting for $\sim 10^7$ years assuming energy-conservation (King et al., 2011). The AGN bursts could even be shorter and more frequent as long as the averaged luminosity is high throughout the episode (Sec. 5).
In this paper, we find that extended ionized outflows are common among luminous type 2 AGN, with their sizes, velocities, and energetics positively correlated with the AGN luminosities. It is important to extend these measurements to lower luminosity AGN to test if these relations continue. On the other hand, the extended outflows identified in this paper (e.g., SDSS J1000+1242, SDSS J1010+1413) provide good candidates for multi-wavelength follow-up, e.g. in the sub-millimeter and X-ray, that can probe the other relevant phases of the outflow (e.g., cold molecular and hot plasma) and provide a more complete picture of the feedback processes. This work also confirms that optical broadband images can help identifying extended ionized nebula. It is important to explore the potential of broadband imaging selection to find extended outflows in large imaging surveys, e.g., SDSS, HSC, or in the future LSST. Such technique could help us explore the demographics of the most energetic AGN feedback systems.

7 Appendix

7.1 Slit Widths of the Magellan IMACS Centerfield Slit-viewing Spectroscopy

We inspect the slit widths of the Magellan IMACS Centerfield Slit-viewing Spectroscopy, and find that the widest of its five slits, referred to as the 1.5" slit in the IMACS User Manual, has an actual slit width of 1.3".

This result is confirmed by comparing the line widths of the calibrating arc lamp observed through these five slits. As shown in Fig. 4.7, the line widths of the first four slits follow the relation

\[ w_l^2 = w_0^2 + rW_s^2, \]  

(4.6)

where \( w_l \) is the observed arc line width, and \( W_s \) is their slit widths – 0.25", 0.50", 0.75", and 1.0". The intercept \( w_0^2 \) and the slope \( r \), are fixed by linear regression of these four slits. However, the fifth slit has an arc line width narrower than expected if the slit width were 1.5". It is instead consistent with a slit width of 1.3".
Chapter 4: Sizes and Kinematics of Extended Emission-Line Regions in Obscured AGN

Figure 4.7 To examine the slit widths of the Magellan IMACS Centerfield Slit-viewing Spectroscopy, we plot the slit widths $W_s$ against the observed arc line widths $w_l$ through those slits. The four slits of widths 0.25″, 0.50″, 0.75″, and 1.0″ (solid blue dots) follow the relation $w_l^2 = w_0^2 + rW_s^2$ (black solid line) as expected, whereas the fifth slit would lie on the same relation only if its width were 1.3″ (empty blue dot) instead of 1.5″ (empty red dot).

7.2 WISE Luminosities of Type 1 and Type 2 AGN

WISE mid-IR luminosities have been used to determine the AGN bolometric luminosities. However, type 2 AGN in general have redder WISE colors compared to their type 1 counterparts (Yan et al., 2013; Liu et al., 2013b), such that the inferred bolometric luminosities for type 2 AGN can be underestimated compared to type 1 at shorter mid-IR wavelengths. Therefore, one should be cautious when using mid-IR to compare the luminosities between type 1 and type 2 AGN.

We investigate the difference in WISE mid-IR luminosities between type 1 and type 2 AGN at three different wavelengths – rest-frame 8 µm, 15 µm, and 22 µm – using the sample of SDSS spectroscopically selected luminous AGN from Mullaney et al. (2013). We use the most luminous 935 AGN with [O III]λ5007 luminosities above $L_{[OIII]} > 5 \times 10^{41}$ ergs s$^{-1}$ at redshifts $0 < z < 0.2$. As shown in Fig. 4.8, at those fixed [O III] luminosities, we find that the 8 µm luminosities of the type 1 AGN are higher than the type 2 AGN by 0.2 dex. This difference is statistically significant with a KS-test $p$-value of $4 \times 10^{-10}$. This discrepancy is much smaller at 15 µm (0.07 dex, $p$-value of 0.02), and negligible at 22 µm (0.002 dex, $p$-value of 0.67). At a fixed X-ray luminosity, such a
Figure 4.8 Comparison of the WISE mid-IR luminosities between type 1 (outlined histogram) and type 2 (shaded gray histogram) AGN at three rest-frame wavelengths – 8 $\mu$m (upper-left), 15 $\mu$m (upper-right), and 22 $\mu$m (lower-left). The sample comprises spectroscopically selected SDSS AGN with a fixed [O III] luminosity ($L_{[\text{OIII}]} > 5 \times 10^{41}$ ergs s$^{-1}$) from Mullaney et al. (2013). The type 1 AGN have higher 8 $\mu$m luminosities than type 2 AGN by 0.21 dex on average, which is statistically significant with a KS-test p-value of 0.22. Such a discrepancy becomes less significant towards longer wavelengths as shown in the 15 and 22 $\mu$m panels, see Appendix 7.2.

A discrepancy has also been found between type 1 and type 2 AGN (Burtscher et al., 2015). These tests suggest that at a given intrinsic luminosity, the mid-IR luminosity of an AGN depends on its spectral type. Such an effect is especially severe at lower wavelengths, e.g. 8 $\mu$m, and grows less significant for longer wavelengths, e.g. 15 - 22 $\mu$m.

With a sample of both type 1 and type 2 AGN, Liu et al. (2014) find a flattening at the high luminosity end of the [O III] nebula size - 8 $\mu$m luminosity relation. However, they suspect that the flattening is an artifact caused by the higher mid-IR luminosity of type 1 AGN. We revisit
Figure 4.9 The narrow line region size $R_{\text{NLR}}$ and mid-IR luminosity relations based on 8 $\mu$m (left) and 15 $\mu$m (right). The type 1 (empty symbols) and type 2 (solid symbols) AGN follow different size luminosity relations, as type 1 AGN tend to have higher mid-IR luminosities, especially at 8 $\mu$m, resulting in an apparent flattening of the relation at the high luminosity end. Four samples are used: this paper (blue), Liu et al. (2013b) (red), Liu et al. (2014) (yellow), and Hainline et al. (2014b) (green). Circles and triangles are size measurements and upper-limits. The blue cross is the object with ionized tidal tails SDSS J1255−0339.

This relation with a larger sample of objects from this paper, Liu et al. (2013a), Liu et al. (2014), and Hainline et al. (2014b). We also include the eight type 1 AGN observed in the same Magellan run as in this paper. As shown in Fig. 4.9, we find that the type 1 and type 2 AGN follow different nebula size - 8 $\mu$m luminosity relations, such that adding luminous type 1 AGN to a sample of type 2 AGN can indeed result in or exaggerate the apparent flattening of the relation. However, if we use longer mid-IR wavelengths, say, 15 $\mu$m (right panel), where the effect is less significant, the separation between the size - luminosity relations of the type 1 and type 2 AGN becomes smaller, and the flattening becomes less obvious.

Therefore, combining type 1 and type 2 AGN sample to study their nebula size - mid-IR luminosity relations can be misleading, especially at shorter wavelengths such as 8 $\mu$m. To use mid-IR luminosities as an AGN luminosity indicator, longer wavelengths, such as 15 $\mu$m can be more robust against variations in AGN spectral types.
7.3 Individual Objects

The Magellan spectroscopic data for all of our sources are displayed in this appendix (Fig. 4.10 to 4.19), except for the two objects SDSS J1000+1242 and J1010+1413 that are shown in Fig. 4.2 and 4.3, as they are described in the main text. The majority of the objects have not been studied in detail in the literature, except for SDSS J1000+1242, SDSS J1010+1413, and SDSS J1419+0139, described below. Another object, SDSS J1255–0339 is also discussed here for its abnormally extended narrow line region.

**SDSS J1000+1242.** This system was observed by Harrison et al. (2014) with Gemini GMOS IFU. Their IFU observation reveals regions of broad line widths (up to $w_{80}$ of 850 km s$^{-1}$) with kinematic size of 14 kpc, roughly consistent with our observation. As this broad component shows a clear velocity gradient, they suggest that it is a pair of bi-polar super-bubbles.

The more extended narrow-line component is also partly seen in this IFU data, but is limited to the central 3-4$''$ due to its small field-of-view. Our observation confirms that this component extend to about 10$''$ in size, roughly the same as the SDSS optical image.

**SDSS J1010+1413.** As J1000+1242, this system was observed by Harrison et al. (2014) with the Gemini GMOS IFU, which reveals a very broad [O III] component of $w_{80}$=1450 km s$^{-1}$, an unambiguous sign of high velocity outflows. The size of outflow was not constrained by Harrison et al. (2014) due to the limited field-of-view, but is measured in our Magellan to have a radius of $R_{\text{kin}} = 10$ kpc.

Our Magellan slit is placed along the minor axis of the galaxy to capture the two bright green blobs in the SDSS image which signal [O III] emissions. Harrison et al. (2014) captured the inner parts of these two features and found narrow [O III] emissions separated by $\sim 350$ km s$^{-1}$ in velocity. Our Magellan spectra confirms that these narrow emission clouds extent to $\sim 16$ kpc each from the nucleus. They could be galactic medium being passively illuminated by ionization cones or parts of bipolar outflows.

While Harrison et al. (2014) selects targets based on broad [O III] line widths and ours are based on the [O III] extent, it is interesting that both samples pick up the two powerful outflows
J1000+1242 and J1010+1413. Possibly both the high velocity and extended [O III] are results of powerful AGN feedback.

SDSS J1255−0339. This object has received little attention in the literature, but it has a spectacular pair of extended green spiral features of size about 60 kpc in the SDSS image, most likely tidal tails. Our Magellan spectra reveal narrow [O III] of width $w_{80} \lesssim 300$ km s$^{-1}$ all along these features, making it the most extended narrow line region in the sample. These tidal features are likely ionized by the central AGN, as the [O III] to H$\beta$ ratios are about 10. The system’s high infrared luminosity (classified as a ULIRG by Kilerci Eser et al. (2014)) and complex nucleus morphology also suggest that it may be in the late stages of a merger.

SDSS J1419+0139. This target was observed by McElroy et al. (2014) with AAT’s SPIRAL IFU, which finds a spatially resolved [O III] emitting region with a moderate line width $w_{80,\text{max}}$ of 529 km s$^{-1}$, consistent with our observations. Its SDSS image reveals a extended tidal tail indicating merging activities.
Figure 4.10 The [O III]λ5007 spectrum and measurements for SDSS J0141−0945. **Left:** The SDSS image with the black lines showing the Magellan slit position (top left), Magellan [O III]λ5007 2-D spectrum (top right), and Magellan nuclear 1′′ spectrum covering the Hβ, [O III]λ4959, and [O III]λ5007 lines (bottom, in units of 10^{40} erg s^{-1} Å^{-1}). The Hβ line is affected by a strong sky line for this object. **Top Right:** The [O III]λ5007 surface brightness profile for the entire line (black), the blue wing of the line (blue, v < −300 km s^{-1}), and the red wing of the line (red, v > 300 km s^{-1}) in units of 10^{41} erg s^{-1} kpc^{-2}, overplotted with the scaled PSF (gray dotted line) and the RNLR isophotal cut (dashed line). **Middle Right:** The profile of the [O III]λ5007 line width w80 (blue) and median velocity v_{med} (red) in units of km s^{-1}, overplotted with the R_{kin} line width threshold of 600 km s^{-1} (dashed line). **Bottom Right:** [O III]λ5007 integrated 1-D spectrum in units of 10^{40} erg km^{-1}, overplotted with dashed lines marking the velocities of ± 300 km s^{-1}.

Figure 4.11 Same as Fig. 4.10 but for SDSS J1055+1102. Only one representative slit position out of the three slits is shown.
Figure 4.12 Same as Fig. 4.10 but for SDSS J1255−0339. Only one representative slit position out of the three slits is shown.

Figure 4.13 Same as Fig. 4.10 but for SDSS J1351+0728.
Chapter 4: Sizes and Kinematics of Extended Emission-Line Regions in Obscured AGN

Figure 4.14 Same as Fig. 4.10 but for SDSS J1419+0139.

Figure 4.15 Same as Fig. 4.10 but for SDSS J2102−0647.
Figure 4.16 Same as Fig. 4.10 but for SDSS J2133−0712. Only one representative slit position out of the three slits is shown. The H$\beta$ line is not observed as it falls in the chip gap.

Figure 4.17 Same as Fig. 4.10 but for SDSS J2142+0001.
Figure 4.18 Same as Fig. 4.10 but for SDSS J2154+1131.

Figure 4.19 Same as Fig. 4.10 but for SDSS J2333+0049.
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Study Extended Emission Line Regions with Photometric Surveys

abstract

[O III] emission line regions created by AGN photoionization or outflows leaves footprint on their broadband images, allowing morphological studies of these systems with large-area photometric surveys. We experiment on a new technique to reconstruct the 2D distribution of AGN emission line regions using their SDSS images and fiber spectrum. The [O III] light profiles constructed by this photometric method agree reasonably well with long-slit spectroscopic data in two known extended emission line systems. This technique is applied to a sample of 3194 type 2 AGN at $z=0.2$, and the result shows that the fraction of AGN hosting extended [O III] regions and the sizes of these regions increase steeply with the AGN bolometric luminosity as traced by the [O III] and mid-IR 15 $\mu$m luminosities. There is also tentative evidence that at a fixed AGN luminosity the radius of the emission line region correlate with the outflow velocity traced by the [O III] FWHM. We discuss the prospect of this technique when it is applied to the on-going and future photometric surveys, such as the Subaru Hyper-Suprime Camera Survey and the Large Synoptic Survey Telescope, and how will it open a new parameter space for the studies of AGN emission line regions and outflows.
1 Introduction

Modern models of galaxy evolution require feedback from active galactic nuclei (AGN) to explain a number of phenomena, including the relationship between the mass of the central supermassive black hole and the surrounding host galactic bulge (e.g., Silk & Rees, 1998). AGN feedback can take various forms, but perhaps the most effective version is the driving of massive galactic outflows. Recent observations have found direct evidence for galaxy-wide outflows and their impact on the interstellar medium of their host (e.g., Rupke & Veilleux, 2011; Fabian, 2012; Greene et al., 2012). However, detailed investigations are limited to a handful of systems. To have a complete view on AGN outflow demographics, we first need a larger sample of outflow systems.

One of the most immediate impacts of an AGN is that its intense radiation heats and ionizes the galaxy interstellar medium. The ionized galactic gas forms a so-called narrow line region that is easily observable with optical spectroscopy. While the narrow line regions of Seyfert galaxies are typically confined sub-kpc scales (e.g., Schmitt et al., 2003), very luminous AGN are capable of ionizing gas out to a radius comparable to the host galaxy and creating extended emission line regions (EELR) with sizes $\gtrsim 10$ kpc (e.g., Bennert et al., 2002; Fu & Stockton, 2008).

As it takes $\sim 10^4$ years for the AGN radiation to ionize the entire galaxy, the occurrence rate of EELRs provides a unique probe of AGN variability on the time scale of $\sim 10^5$ years. Moreover, there are cases where extended outflows driven by AGN winds or jets can also emit strong narrow-line emission and appear as EELRs (Rosario et al., 2010; Greene et al., 2012), such that an EELR sample would serve as a great candidate pool for the search of extended outflows.

While these investigations require a statistical sample of EELRs, there are only dozens of EELRs known so far, as they are among the rarest populations in the universe (a few per Gpc$^{-3}$ Schirmer et al., 2013). To constrain AGN variability and search for extended outflows, we must search a large cosmological volume in an efficient way. Optical imaging surveys are currently the most effective way to cover large areas of the sky and are advancing rapidly with ever larger telescopes, e.g. the Sloan Digital Sky Survey (Alam et al., 2015, SDSS), the Dark Energy Survey (Collaboration: et al., 2016, DES), the Hyper-Suprime Camera Survey (Miyazaki et al., 2012, HSC), and the Large Synoptic Survey Telescope (Ivezic et al., 2008, LSST). Thanks to high
equivalent width emission lines, in particular the $\text{[O III]} \lambda 4959, 5007$ doublet, these EELRs can stand out in broadband images with distinctive colors. In fact, some of the most well known EELRs were first spotted by citizen scientists looking at the SDSS composite images (e.g., Hanny’s Voorwerp and the Teacup Galaxy; Lintott et al., 2009; Keel et al., 2012; Gagne et al., 2014).

Inspired by these discoveries, other studies have performed catalog-based searches to select emission line objects by $g$-, $r$-, or $i$-band excess in the color-color diagrams (Cardamone et al., 2009; Schirmer et al., 2013), finding a number of extreme star forming galaxies and extended AGN-ionized clouds. However, as the catalog photometry is most sensitive to the bright nucleus rather than the faint outskirts of the image, such searches mostly pick up compact emission line systems instead of diffused EELRs. Image-based selections and analysis, on the other hand, are not only more sensitive to the diffuse emission, but also capable of characterizing the morphology and sizes of the EELR.

These broadband searches depend on strong line emission with very high equivalent widths $\gtrsim 100$ Å. However, the exposed nucleus in a typical unobscured (type 1) AGN radiates strong blue continuum that can easily mask the emission line features. Obscured or type 2 AGN, where the accretion disk is not directly in the line of sight of the observer, represent the best observational targets for EELR and extended AGN outflow searches. Intensive spectroscopic studies of emission line region and outflows around these type 2 AGN, including Liu et al. (2013a); Hainline et al. (2013); Harrison et al. (2014) and Chapter 4, can serve as validation data for tests of the photometric searches and characterization.

In this Chapter, we explore a new image-based technique that not only automates the selection of EELRs in large optical imaging surveys, but also characterizes their sizes and shapes with photometric data, and thus saves resources for further spectroscopic follow up. This technique will be able to leverage the large volume of ongoing photometric surveys, build a statistical sample of EELRs, constrain their occurrence rate and size distributions, and provide a sample of candidate extended outflows. Here we test the technique using the SDSS survey with a sample of low redshift obscured type 2 AGN. With further development, the same concept can be extended to current and future surveys such as DES, HST, and the LSST.
2 Overview

In this section we present the basics of using broadband photometric images to study AGN emission line regions. In Sec. 2.1, we review photometric studies of emission line systems in general. In Sec. 2.1, we discuss the capabilities and limitations of the [O III]$\lambda5007$ emission line as a tracer of the AGN emission line region. Lastly, we introduce our sample of nearby type 2 AGN in Sec. 2.3.

2.1 Using Broadband Images to Study Emission Lines

With the capability of imaging a large area of the sky, photometric techniques, in particular narrow-band imaging, has been widely used in studies of emission lines systems. Applications range from spatial studies of galactic systems such as planetary nebulae to the detection of high redshift Ly-$\alpha$ emitters (e.g., Djorgovski et al., 1985). This method makes use of the flux excess in a particular band due to certain emission lines. While narrow bands optimize the sensitivity to detect certain lines, this can only work for lines that fall in a narrow range of wavelength, which corresponds to a narrow redshift range and a small survey volume for extra-galactic studies. Broad-band imaging, on the other hand, covers a wider cosmological volume and is available from large photometric surveys such as LSST. But this method collects a larger number of continuum photons and thus sacrifices line sensitivity, and there are few lines that are strong enough to be detectable in broad-band imaging.

To quantify this trade-off, we can use the ratio between the equivalent widths of the line and the bandwidth of the band (EW/BW). The signal from the emission lines on top of the continuum will then depend on this ratio according to

$$\Delta m_{AB} = -\frac{5}{2} \log_{10}(1 + \frac{EW}{BW}).$$  \hspace{1cm} (5.1)

To reach a moderate flux excess of 0.1 mag, narrow bands (BW$\sim$ 10 Å) can detect lines of equivalent widths $\gtrsim 1$ Å, but for a broad band (BW$\sim$1000Å) it needs very strong lines with equivalent widths $\gtrsim 100$ Å.
Because of the large survey volume and available data sets, broadband imaging has already proven useful in a number of studies of strong emission line systems. In fact, some of the most famous AGN light echo (Hanny’s Voorwerp, Teacup Galaxy), and a class of strong [O III] emitters called “Green Peas” was found by citizen scientists in the Galaxy Zoo project looking at SDSS broadband images (Lintott et al., 2009; Gagne et al., 2014; Cardamone et al., 2009). Inspired by these discoveries, Schirmer et al. (2013) apply color selection to the SDSS photometric catalog and found another group of extended [O III] emitters called “Green Beans” between redshifts 0.1 < z < 0.3. Because the catalog measurements consist of parametric fits to the central few arcsec of the images, many of the objects are compact systems. They discovered one galaxy, SDSS J2240−0927, that host an AGN light echo with a 40 kpc-scaled [O III] emission line region (Davies et al., 2015). Broad band imaging has also been applied to higher redshifts. Using deep broadband imaging and wavelet transformations, Prescott et al. (2012a,b) found five giant Ly-α nebulae in a wide redshift range of 2 < z < 3. Their works have proven the feasibility of a blind broadband search for diffuse emission line regions.

It is a natural next step to automate the search for extended emission line regions using broadband images from photometric surveys such as SDSS, HSC, DES, or LSST. By searching in image space instead of at the catalog level, we can be sensitive to diffuse and extended emission. We can also constrain the size and morphology of the emission line regions with the images. In this Chapter, we explore this possibility using SDSS imaging of a sample of spectroscopically identified type 2 AGN, which could host extended emission line regions. In the future, it is also possible to conduct blind search of emission line regions with photometric data alone, see Sec. 5.3.

2.2 The Strong Emission Line [O III]λ5007 in Type 2 AGN

The strong ionizing radiation from the AGN excites and powers a range of emission lines in the optical, that fall into two categories – the broad lines and the narrow lines. The broad lines, which are kinematically broadened to \( \sim 10^4 \) km s\(^{-1}\), come from the broad line region at the black hole vicinity (\( \lesssim 1 \) pc). Due to the dense environment, those only include lines that have high critical density, such as hydrogen recombination lines Hα and Hβ. On the other hand, the narrow lines
Figure 5.1 The spectrum of a luminous type 2 AGN SDSS J1000+1242 at $z = 0.15$ with SDSS filter response functions overlaid. As the continuum is relatively faint, the strong narrow lines are the most distinct spectral features in a type 2 AGN. The strong [O III]$\lambda$5007 and [O III]$\lambda$4959 lines at redshifted wavelengths around 5700 Å create flux excess in the r-band. The z-band covers no strong emission lines but only the galaxy continuum.

come warm interstellar medium at scales are AGN ionized warm galactic medium on larger scales of $\gtrsim 100$ pc. Apart from the the hydrogen recombination lines, the narrow lines also include collisionally excited metal cooling lines, such as [O III]$\lambda$5007, [O III]$\lambda$4959, and the [N II] doublet. These narrow lines are the most direct tracer of the AGN ionized gas on the galactic scale, and are useful for studying the impact of AGN radiation on the galactic interstellar medium.

Indeed, the strongest narrow line [O III]$\lambda$5007 (see Fig. 5.1) has long been used to study the ionization state, sizes, and kinematics of the AGN ionized narrow line regions (e.g., Baldwin et al., 1981; Bennert et al., 2002; Heckman et al., 1981). In particular, many of these studies are targeting type 2 AGN, where the obscuration of the AGN blue continuum and broad lines facilitates observations of the [O III]$\lambda$5007 line. With samples of type 2 AGN, the size of the narrow line regions as traced by the [O III]$\lambda$5007 line are found to correlate with the AGN bolometric luminosity (e.g., Liu et al., 2013a; Hainline et al., 2014). Most recently, [O III]$\lambda$5007 has been used as an important kinematic diagnostic for AGN outflows, that has lead to the
discovery of outflow systems from low to high redshifts \((z = 0 - 2\), e.g., Greene et al., 2011; Liu et al., 2013b; Harrison et al., 2014; Zakamska et al., 2015).

One advantage of using the \([\text{O III}]\lambda 5007\) as the emission line region tracer is its high equivalent width. The adjacent \([\text{O III}]\lambda 4959\) line, that is three times fainter, also contributes to boost the emission line signal. For type 1 AGN, which have strong AGN continuum and broad lines, the \([\text{O III}]\lambda 5007\) equivalent widths are typically tens of Å. But for type 2 AGN where both the AGN continuum and the broad lines are obscured, their equivalent widths can be of order a hundred Å or higher (Caccianiga & Severgnini, 2011). Indeed, the \([\text{O III}]\lambda 5007\) equivalent widths of type 2 AGN are roughly proportional to the \([\text{O III}]\lambda 5007\) luminosity Zakamska et al. (2003). With a moderately high \([\text{O III}]\lambda 5007\) luminosity of \(\gtrsim 10^{8.5} L_\odot\) \((L_{\text{bol}} \gtrsim 10^{45.5}\ \text{ergs}\ \text{s}^{-1})\) a type 2 AGN can have \([\text{O III}]\lambda 5007\) EW \(\gtrsim 100\ \text{Å}\), that is strong enough to be detectable by broadband imaging (Sec. 2.1) At the outskirts of the galaxy, where the stellar continuum drops, the equivalent width could even be higher than at the nucleus and even easier to detect.

The \([\text{O III}]\lambda 5007\) line still has limitations. As the \([\text{O III}]\) lines are collisionally excited, their emissivity is strongly dependent on the electron density \(I \propto n_e^2\), such that only dense ionized gas \((n_e \gtrsim 100\ \text{cm}^{-3})\) can efficiently emit in \([\text{O III}]\). This may be the reason for the truncated sizes of \(\sim 10\ \text{kpc}\) (Liu et al., 2013a; Hainline et al., 2014, Chapter 3). Beyond that radius, the ionized gas usually becomes too dilute to effectively emit in \([\text{O III}]\). For emission line regions more extended than 10 kpc, other extended structures, such as tidal tails, merging galaxies, outflows, or even inflows, may be needed to supply the dense gas to support the \([\text{O III}]\) line emission.

### 2.3 The Sample

To test the feasibility of our proposed photometric method, we use the low redshift \((z<0.4)\) optically selected type 2 AGN sample compiled by (Mullaney et al., 2013, hereafter M13). This sample is used because of its low redshift coverage compared to other type 2 AGN samples such as Zakamska et al. (2003); Reyes et al. (2008); Yuan et al. (2016). The AGN in M13 are selected from the SDSS DR7 spectroscopic catalog Abazajian et al. (2009) based on their \([\text{O III}]\lambda 5007,\ [\text{N II}]\lambda 6584,\ \text{H}\alpha,\ \text{and H}\beta\) line ratios, and the type 2s are required to have narrow H\(\alpha\) (FWHM <
Figure 5.2 The redshift and bolometric luminosity distribution of the type 2 AGN in the M13 sample. Colored shaded areas represent the four redshift bins where the emission line maps can be reconstructed. The labels and numbers are the band configuration (line-band/continuum-band) and the number of objects in the redshift bin.

Table 5.1. SDSS Redshift Ranges for [OIII] Lines

<table>
<thead>
<tr>
<th>Line-band</th>
<th>Conti-band</th>
<th>z_{med}</th>
<th>z range</th>
<th>log(L_{bol, med})</th>
<th>N_{total}</th>
<th>N_{L&gt;46}</th>
</tr>
</thead>
<tbody>
<tr>
<td>g</td>
<td>i</td>
<td>0.007</td>
<td>0.000 – 0.014</td>
<td>41.65</td>
<td>171</td>
<td>0</td>
</tr>
<tr>
<td>g</td>
<td>r</td>
<td>0.051</td>
<td>0.040 – 0.061</td>
<td>43.46</td>
<td>1336</td>
<td>0</td>
</tr>
<tr>
<td>r</td>
<td>z</td>
<td>0.174</td>
<td>0.135 – 0.213</td>
<td>44.50</td>
<td>3247</td>
<td>15</td>
</tr>
<tr>
<td>r</td>
<td>i</td>
<td>0.300</td>
<td>0.257 – 0.343</td>
<td>44.98</td>
<td>314</td>
<td>6</td>
</tr>
<tr>
<td>i</td>
<td>z</td>
<td>0.571(^a)</td>
<td>0.521 – 0.621</td>
<td>(\ldots)</td>
<td>(\ldots)</td>
<td>(\ldots)</td>
</tr>
</tbody>
</table>

Note. — Within the redshift range of 0–0.4, there are four redshift bins that can be used for the emission line map reconstruction. Column 1, 2: the band covering the [OIII] lines and the continuum for the emission line map reconstruction. Column 3, 4: the median redshift and the redshift range. Column 5: the median log AGN bolometric luminosity in units of ergs s\(^{-1}\) converted from [OIII]. Column 6, 7: the number of obscured AGN from the M13 sample, and the number of luminous ones with bolometric luminosity \(\geq 10^{46}\) ergs s\(^{-1}\).

\(^a\) the mean of the redshift limits instead of sample median.
600 km s$^{-1}$). There are in total 13,716 type 2 AGN selected, with the redshift and luminosity distributions as plotted in Fig. 5.2.

Fig. 5.1 shows an example spectrum of such a type 2 AGN at $z = 0.2$ and the transmission functions of the SDSS filters. At this redshift the strong [O III] doublet falls in the SDSS r-band (line-band). But the r-band image contains not only flux from the [O III] emission lines but also the continuum emission, which has to be subtracted. Fortunately, the z-band is emission-line free and consists of only the continuum, so the z-band image serves as a continuum model that can be used for the subtraction (hereafter, the continuum band). Depending on the redshift, other combinations of filters are needed to reconstruct the [O III] map. For example, at a redshift of 0.3, one can use r-band for the [O III] line and the i-band for the continuum. A list of filter combinations and their corresponding redshifts and sample numbers is in Tab. 5.1 and shown in Fig. 5.2. In total, there are 5,068 AGN in the M13 sample that fall in redshift ranges where their [O III]λ5007 map can be reconstructed.

As shown in Figure 5.2, M13 is roughly a flux limited sample, so the AGN luminosity distribution depends on the redshift. The lowest redshift bin ($z = 0.02$, g/i-band) contains mostly low luminosity AGN ($L_{bol} \sim 10^{42}$ ergs s$^{-1}$), whereas the $z = 0.3$ (r/i-band) bin has a median luminosity of $L_{bol} \sim 10^{45}$ ergs s$^{-1}$. If we are interested in the most luminous population ($L_{bol} > 10^{46}$ ergs s$^{-1}$), we should focus on the $z = 0.2$ (r/z) and $z = 0.3$ (r/i) samples where we have 15 and 6 objects, respectively. For the rest of the Chapter, we will focus on this $z = 0.2$ (r/z) bin.

3 Methodology

In this section, we describe the details of our method to construct and characterize the maps of the [O III] emission line regions. The reconstruction and validation of the maps are described in Sec. 3.1. In Sec. 3.2, we discuss parametric and non-parametric methods to measure the emission line maps and conclude that isophotal measurements are suitable for the irregular nature of the emission line regions. Lastly, in Sec. 3.3 we describe the details of the isophotal radius and area
measurements and discuss the uncertainties due to the noise, PSF, and continuum subtraction residuals. A simulation to quantify these uncertainties is described in Appendix Sec. 7.1.

3.1 Reconstruction of the Emission Line Map

We use two broadband images – the line-band that cover the [O III] doublet, and a line-free continuum-band for the continuum subtraction – and the SDSS spectrum to determine the proportion of the continuum level between these two bands. In principle, it is also possible to reconstruct the other emission line maps such as [NII] and H\(\alpha\) lines, but it is beyond the scope of this chapter. Possibilities of constructing the map without the spectrum is discussed in Sec. 5.3.

As shown in the spectrum of Fig. 5.1, the line-band images are not clean but also contain fluxes from the galaxy or AGN continuum that needs to be subtracted. Fortunately, as described in Sec. 5.2, at certain redshifts one can find a line-free continuum-band and use it for the continuum subtraction. For example, at a redshift of about 0.2, one can use the \(r\)-band as the [O III] line band, and the \(z\)-band for the continuum-band. If one assumes that the continuum color does not change significantly across the galaxy, the images of the continuum-band can trace the continuum distribution in the line-band. If, however, there is color gradients across the galaxy, the galaxy continuum cannot be perfectly subtracted but leaves residual in the emission line map, an affect that is discussed in Sec. 3.3.

Depending on the spectral shape of the continuum, the intensity of the continuum in the line-band and the continuum-band may differ, such that one needs to scale the image from the continuum-band before subtracting it from the line-band image. For our sample of SDSS selected type 2 AGN, we use their SDSS spectra to calculate the scaling of the continuum. As we expect the stellar continuum color not to vary dramatically across the galaxy, such a constant scaling should be appropriate to apply to the entire image.

Our procedure of reconstructing the [O III] emission line map is as follows. First, we download the corrected frames images from SDSS DR12, which are already calibrated and sky-subtracted. We then align the images from different bands according to their WCS headers. All the other bands are shifted to match the \(r\)-band position. Sub-pixel shifts are made by 3rd order
spline-interpolation. Rotation and higher order polynomial distortion terms are not applied. We do not degrade the resolution of the line band to match with the continuum band, which may results in continuum subtraction residuals that is discussed in Sec. 3.3. We then make stamp images centered on each object of size $25 \times 25$ arcsec$^2$ ($64 \times 64$ pix$^2$) which corresponds to about 1′ at redshift of 0.2.

To calculate the continuum ratio between the line-band and the continuum-band, we use the science primary spectrum of each object from SDSS DR12. The spectral lines are first masked by a median filter, and the remaining continuum spectrum is averaged with weights according to the filter response functions of each band. For z-band, the spectrum does not extend to the red end of the band, so the continuum level is calculated only from the parts of the band that has spectrum coverage. As the stellar spectral shape is relatively flat at the z-band, we don’t expect it to be a major source of error. We then scale the continuum-band image by the continuum ratio between the two-bands, and then subtract it from the line-band. The subtracted image ideally contains only fluxes from the [O III]+Hβ lines weighted by the filter response function. This image is then scaled to the [O III]$_{\lambda 5007}$ intensity according to the line ratios in the SDSS spectrum and the filter response function.

As an example of the resulting maps, Fig. 5.3 shows the reconstructed [O III] line map of two known extended ionized outflow systems SDSS J1000+1242 and SDSS J1010+1413 from our previous Magellan observations. This map not only recovers the extended component of the emission line region but also reveals it patchy and irregular morphology. As a sanity check, we compare this map with our previous Magellan long-slit spectrum. We extract a 1D light profile from the map using a ‘fake long-slit’ that is matched to the Magellan observation. It can be seen that our map qualitatively reproduces the shape of the light profile and quantitatively matches with its amplitude within a factor of two.

As demonstrated in these two examples the light distributions of EELRs could be faint and highly irregular in morphology. At a redshift of about 0.2, the brightness of the extended component are of the order of few times $10^{-15}$ erg s$^{-1}$ cm$^{-2}$ arcsec$^{-2}$. This is comparable to the mean RMS noise level in the map of $1.3 \times 10^{-15}$ erg s$^{-1}$ cm$^{-2}$ arcsec$^{-2}$, giving it a low SNR of at most a few per pixel.
Figure 5.3 Examples of the $g$, $r$, $i$-color composite images (left) and the reconstructed $\text{[O III]}$ emission line maps (middle). On the right is the comparison of $\text{[O III]}$ light profiles extracted from the SDSS emission line map and from the Magellan long-slit spectrum.
It is also about 10 times fainter than the bright unresolved component of the emission line nucleus. For a typical SDSS PSF (FWHM \( \text{sim} 1.4 \) arcsec), that means the measurements within about 1 arcsec of the nucleus can be affected.

The most extended EELR can have sizes of the order of 10 kpc, or about 5 arcsec at the redshift of 0.2, so these size measurements should be robust against the PSF. But as those sizes are comparable to the size of the galaxy, one needs to consider the effects of imperfect continuum subtraction. The challenges of the characterizing these EELRs are then to robustly identify the extended features that are very faint and irregular at the presence of continuum subtraction residuals, high nucleus contrast ratio, and the PSF.

### 3.2 Parametric or Non-parametric Methods of Size Measurements

We have experimented on a few different methods to measure the sizes of the EELRs from the emission line maps, including parametric model fits, second moments of image, and the sizes of the isophotal contours. As discussed in the following, we find that the most effective method to capture the faint and irregular extended structure is the isophotal contours.

Parametric model that assumes a certain function form of the light profile has been widely used in studies of galaxy morphologies. It has several advantages – it can be sensitive to faint features and is robust against noise. However, it requires knowing the function form of the light distribution a priori, otherwise it introduces biases that could dominate over the noise. For the EELRs, which exhibits a wide variety of irregular morphologies, it is hard to find parametric models that capture these features without introducing biases.

As a demonstration, we fit a simple 2-dimensional Gaussian model to the emission line maps for some of our EELR systems. As shown in Fig. 5.4 in magenta ellipses, these fits fail to capture the irregular extended emissions in the maps. The main reason is that these light distributions are centrally concentrated, so the model pick out the brightest nucleus instead of the wings. One can imaging using models that decompose the source into unresolved and resolved components. However, it is still not clear what models are flexible enough to adapt to a variety of morphologies. This is Chapter we do not explore this possibility.
Figure 5.4 Examples of size and shape measurements on the emission line map for SDSS J1000+1242 (top) and SDSS J1010+1413 (bottom). Left: the magenta ellipses show the best fit 2D Gaussian, and the orange ellipses show the 2D image moments, none of which captures the extended irregular morphology of the extended emission. Right: The isophote (white contours) at the center outlines the extended emission. The gray contours show the isolated isophotes caused by the noise. The isophote level is $3 \times 10^{-15} (1 + z)^{-4} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ arcsec}^{-2}$. 
Non-parametric methods, on the other hand requires less assumptions about the source and can be more flexible to encapsulate a variety of distributions. One simple way to calculate the 2nd moment of the image, as shown in Fig. 5.4 in orange ellipses. These measurements are more sensitive to the extended features than the Gaussian fit. But as it weight points at large radii heavily ($\propto r^2$), this measurement is susceptible to noise or artifacts towards the edge of the image, where we expect little signal from the system.

The third method we use is the isophote size. Spectroscopic studies of extended emission line regions typically define sizes according to an isophotal size. Particularly because it is sensitive to the wings and that it can be interpreted physically as the real extent of the emission line region down to certain surface brightness. In the case of photometric image, we can obtain an isophotal contour that captures the 2D morphology of the EELR. Once the isophotal contours are found it is then straight forward to define the size of the EELR as, say, its largest radius from the center.

As demonstrated in Fig. 5.4, using an isophote cut similar to the RMS noise level we successfully captures the faint and extended components of the EELRs. The median the signal-to-noise ratio at the isophote is 1.3 as shown in Fig. 5.5. This threshold is at a surface brightness of $3 \times 10^{-15}(1 + z)^{-4} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ arcsec}^{-2}$, which is three times higher than the
isophote limits typically used in spectroscopic literatures on EELR. Although not as deep as the spectroscopic observations such as Liu et al. (2013a), this demonstration shows that SDSS images are already adequate to quantify the sizes of EELRs. With deeper photometric data, such as HSC, one can push the isophote limit to lower levels approaching the spectroscopic data. We therefore adopt isophote as our method of quantifying EELR sizes. Details of the isophote measurements are described in the next section.

### 3.3 Isophotal Measurements and Uncertainties

In this section, we describe in detail our procedure of making the isophotal radius and area measurements, the sources of uncertainties for these measurements, and the methods adopted to constraint or mitigate these uncertainties.

We are interested in measuring the sizes and morphologies of emission line regions. For the purpose of this Chapter, we focus on two measurements – isophotal radius and area. Other shape measurements such as aspect ratio, symmetry, clumpiness, can also be inferred from the isophotes, but are beyond the scope of the current study. The radius here is defined as the distance between the galaxy center and the furthest point away from the center in the isophote, where the galaxy center is defined as the SDSS object center in the $r$-band. The area is just the net area enclosed by the isophote contours.

The isophotes and the derived measurements are subject to a number of random and systematic uncertainties. First of all, the PSF sets a limit to the smallest size that can be constrained from the image. The PSF wing of the bright nucleus contributes to fluxes at larger radii and artificially enlarge the isophotes. Second, noise contribute errors to the isophotes, especially in this low signal-to-noise ratio regime. Noise pattern adjacent to the source will shift the boundary of the center contour, introducing uncertainties and biases in the size measurements. The bright noise peaks that are away from the source forms, on the other hand, form isolated isophote contours that can resemble extended emission. Lastly, imperfect continuum subtraction will leave imprints on the resulting map, which also could be false identified as emission line signal.
We discuss the following topics in order: 1. Signal Detection and Contour Selection, 2. PSF Subtraction and Determining Extendedness, 3. Masking for Continuum Subtraction Residuals, and 4. Imaging Denoising. All of these analysis procedures are summarized at the end of this section. The results are presented in Sec. 4.

**Signal Detection and Contour Selection**

As seen from Fig. 5.4, isophote contour automatically select regions of the sky where the intensity is high. While some of these regions correspond to real signals, some may just be results of random noises. It is important to distinguish between contours coming from signals and noises, otherwise the results will be affected by false detections and noise dominated radii measurements.

To exclude noise isophotes that are at large radii as well as other possible contaminants from nearby sources, we consider only contours that overlap with the image center – the central contours. To accommodate objects where the emission line signal is patchy at the center, here the center is loosely defined as a circular region of radius 1 arcsec around the SDSS source position. However, small central contours can still be a result of noise peaks. To determine the possible sizes of noise contours, we run a Monte Carlo simulation with 1000 realizations of Gaussian i.i.d noised image, and find that 95% of the time at the defined center there is no isophote contour at 1 \( \sigma \) level that is larger than 3 pixel. Therefore, finally only the center contours with an area larger than 3 pixels (0.5 arcsec\(^2\)) are confidently considered as detection (95% confidence level).

A major caveat of excluding contours away from the center is that disconnected emission line signals will be missed. Light echoes, where gas at large radii is illuminated by past AGN activity but the nucleus is quiescent, will be one type of these systems missed. To go around this problem, one could still consider including disconnected contours but set a high area cut to exclude the noise. However, in this case nearby sources – stars and galaxies – become the dominant source of contamination. 54% of the 3212 objects from the \( z = 0.2 \) \( r - z \) sample are contaminated by nearby sources that are brighter than 21 magnitude – bright enough to show up in the isophote contours. Therefore, unless one identifies and masks out these contaminating sources individually,
a significant portion of the sample will be affected. Considering only center contours, although potentially can miss some light echoes, seems to be a working approach.

**PSF Subtraction and Determining Extendedness**

![Isophote and PSF Mask](image)

Figure 5.6 Demonstrations of the PSF subtraction with SDSS J1000+1242. Left: the original map. Right: the residual after PSF subtraction. The white and gray contours are the isophotes as described in Fig. 5.4, and the red contours show the “PSF Mask”.

To interpret the measured isophote sizes, it is important to distinguish between resolved and non-resolved sources. As shown by simulations described in Appendix 7.1, bright unresolved point sources can have misleadingly large isophote sizes as a result of the PSF. The light distribution of the EELRs are often centrally peaked with an unresolved bright nucleus (Fig. 5.3). It is then important to subtract the central PSF from the emission line maps.

For each object, we find the minimum chi-square best fit PSF model to the central region of the emission line map and subtract it from the map. We use the real PSF profile of the line-band provided by SDSS and use 3rd order spline interpolation for the sub-pixel shifts of the model. To focus on the nucleus source, the position of the PSF is only allowed in the central region – within 2 arcsec from the center. In order to avoid over-subtraction, which happens as the model tends to match the extended component of EELR with the PSF wing, we fix the peak of the PSF model to the peak of the central region in the image. As judged from the residual of the PSF subtraction shown in Fig 5.6, this treatment successfully match and remove the central PSF component.
Figure 5.7 The size distribution of the galaxy residual masks (gray histogram) and the PSF mask (white histogram). Most of the PSF masks have zero sizes and are not shown. The galaxy masks have a median radius of 5 kpc, which sets the limit of the smallest emission line region size that can be measured.

After the PSF subtraction, we apply the same isophote threshold to the residual map to identify extended emission.

In case if the PSF subtraction is not perfect, we create a “PSF Mask” to mark regions where the isophote can be affected by the PSF subtraction (red contours in Fig. 5.6). It is defined as the isophote contour of the PSF model with an isophote threshold that is ten times higher than the emission line isophote, such that within this region subtraction errors that are 10% or higher will result in errors of the EELR isophote.

**Masking for Galaxy Continuum Subtraction Residuals**

One major source of uncertainty for the emission line map is the galaxy, which can dominate the flux where the galaxy continuum is strong. As mentioned in 3.1, the continuum subtraction is not perfect, and there can be residuals as a result of intrinsic color gradient or PSF mismatch. These residuals leave imprints on the emission line map and affect the emission line measurements. To properly understand the residuals, one can perform tests using real or simulated galaxies with
color gradients and apply the same continuum subtraction scheme, which will be discussed in Sec. s5.3. As our focus here is the isophote measurements, we instead take a simplistic but careful masking approach to highlight the “galaxy mask” region around the galaxy center where the isophote measurements can be affected by the residuals.

We conservatively assume that the continuum subtraction residual is less than 10% of the original continuum intensity. With this assumption, we can define a “galaxy mask”, within which the residual could be of comparable level to the isophote and can affect the isophote measurements. In practice, to make the mask, we first renormalize the continuum model map using the filter response function to match with the emission line map, such that the same intensity on these two maps corresponds to the same number of photons received in the broadband detector. The residual mask is then defined as the isophote contour on the continuum model map with an isophote cut that is ten times higher than the one for the emission line map, i.e., $3 \times 10^{-14}(1 + z)^{-4}$ erg s$^{-1}$ cm$^{-2}$ arcsec$^{-2}$. Examples of the mask is shown as the red contours in Fig. 5.10.

Figure 5.7 shows the size distribution of the galaxy masks, which has a median of 5 kpc in radius. This mask is always larger than the PSF mask discussed in Sec. 3.3, so the galaxy residual is the limiting factor for the the smallest emission line region sizes that can be constrained by our method. One could potentially improve on the galaxy mask and lower this limit with a more quantitative understanding of the galaxy residual by doing tests proposed above.

**Image Denoising**

As shown by the noise simulations in Appendix 7.1, noises can substantially affect our isophote radius measurements, introducing a bias of 1.9 arcsec and an random uncertainty of 0.5 arcsec. However, the situation can be improved if the noise can be suppressed. As we expect the EELR signal, although patchy or irregular in shape, are more spatially coherent than the random noise, there are denoising methods that can be applied to suppress the noise and bring out the signal. In particular, Wavelet Denoising is a non-parametric denoising method that requires few
Figure 5.8 An example of image denoising using wavelets. The left column is before denoising and the right column is after. The upper row shows the emission line maps and the bottoms are their corresponding wavelet coefficients. By thresholding the wavelet coefficients that are low in amplitudes, the noises in the images are suppressed.
assumptions on the spatial scale and the morphology of the source, making it a suitable method for this application.

As a proof of concept, we here apply a simple and generic Wavelet Denoising procedure using Discrete Wavelet Transformation (DWT) and soft thresholding, as demonstrated in Fig. 5.8. The noise simulation described in Appendix 7.1 suggests that this procedure can improve the random uncertainty and the bias of isophote radius by 20%. There are more sophisticated methods tailored to astronomical images which could further improve the performance, such as the Undecimated Wavelet Transformation (Starck et al., 2007). But this possibility is not explored in this Chapter.

Wavelet Denoising is based on the sparsity of the real signal in the wavelet space. After the wavelet transformation, the image is transformed to wavelet coefficients representing structures of a range of spatial scales and at various spatial positions. The real signal, because of its spatial coherence, are concentrated in a few coefficients, whereas the noise is spread out in all the coefficients. By setting the coefficient below certain threshold zeros, a step called thresholding, one suppresses the noises while preserving the signal. The image reconstructed back from the thresholded coefficients effectively has higher signal to noise ratio.

We use Python package PyWavelets version 0.4.0\textsuperscript{1} for the wavelet transformation. We adopt the Coiflets-1\textsuperscript{2} as the wavelet bases and decompose the image into three levels of detailed coefficients. We apply soft thresholding and use a threshold value that equals to the RMS noise level $\sigma$. It means that the coefficients lower than $\sigma$ are replaced by zero, and the ones higher than $\sigma$ are replaced by the value minus $\sigma$. Fig. 5.8 shows the image and wavelet coefficients for SDSS J1000+1242 before and after denoising. One can notice the suppressed noise level after denoising.

Denoising is applied to all of the emission line maps, PSF subtracted or not, before we obtain its isophote contours and make shape measurements. Although it effectively increases the signal-to-noise ratio of the image, we still conservatively adopt the detection threshold derived from the non-denoised images.

\textsuperscript{1}https://pywavelets.readthedocs.io/en/v0.4.0/contents.html
\textsuperscript{2}http://wavelets.pybytes.com/wavelet/coif1/
Table 5.2. The Rate of Detected and Resolved Objects

<table>
<thead>
<tr>
<th>Total</th>
<th>Non-detected</th>
<th>Unresolved</th>
<th>Residual Affected</th>
<th>Robustly Extended</th>
</tr>
</thead>
<tbody>
<tr>
<td>3194</td>
<td>1826</td>
<td>1012</td>
<td>27</td>
<td>329</td>
</tr>
<tr>
<td>(57%)</td>
<td>(32%)</td>
<td>(1%)</td>
<td>(10%)</td>
<td></td>
</tr>
</tbody>
</table>

Note. — The number and fraction of the objects in each of the four categories as described in Sec. 3.3.

Figure 5.9 The detection rate of the [O III] emission in the line maps as a function of the [O III] equivalent widths (left) and the luminosities (right).

The Wavelet technique is beyond just denoising applications. One can imagine using the wavelet coefficients to design a detection scheme that is more sensitive to the diffuse faint emission than the isophotes. Studies have also used similar transformations to separate sources of different SED on the image plane (Joseph et al., 2016), a technique that can be useful for constructing emission line map from photometric data alone. As we focus on measuring isophote sizes in this Chapter, we leave this investigation to future work.
Summary

We here summarize the procedure of our isophote analysis. Using the steps described in previous sections, we distinguish the emission line map of each object into one of the four categories: 1. Undetected, 2. Unresolved, 3. Residual Affected, and 4. Robustly Extended. The shape measurements are made for the Robustly Extended objects, and the others are treated as either non-detections or upper-limits.

An object is labeled as undetected if its emission line map has no isophote contour at the center that is larger than the area threshold. A detected object is resolved if its PSF subtracted residual map is still detected – indicating that there are extended components beyond the PSF. Even if a source is considered resolved, its isophotes might still be affected by the galaxy residual. So we further split these objects into two categories: residual affected are the ones that has detected contours all within the galaxy residual mask, and robustly extended are those ones with isophote contours beyond the mask such that the isophote radius is considered a robust measurement.

Table 5.2 shows the number of objects in each category for the r-z sample at redshift 0.2.

After excluding objects that are contaminated by nearby bright stars and those ones with incorrect redshifts, we end up with a sample of 3194 type 2 AGN for the analysis. Among them, 43% of the objects are detected. The detection rate is a strong function of [O III] equivalent-widths and luminosities (Fig. 5.9). For systems with [O III] equivalent width higher than 100 Å, the detection rate is above 80%. Among these detected objects, a majority of them are unresolved (32% of total). 1% of the systems, although possibly resolved, can be affected by the galaxy residual. In the end, a total of 329 objects (10%) are considered as robustly extended.

We measure the shape measurements – the radius, area, aspect ratio, and the position angle for the robustly extended objects from their PSF subtracted emission line map. For the unresolved and residual affected objects, we assign them conservative upper-limits for their radius and area using the galaxy residual mask. As the mask is typically larger than the size of the PSF, this is a very conservative upper-limit for the unresolved sources. However, as these sources can also be affected by the galaxy residual, we consider it a safer option than the PSF size. These results are presented in the next section.
4 Results

We here present the results of the extended emission line measurements. In Sec. 4.1 we present six of the extended emission line candidates that are of particular interest, three of which are found to host extended ionized outflows. In Sec. 4.2 we show the relation between the measured isophotal sizes (radius and area) in our sample and their AGN bolometric luminosity. Sec. 4.3 presents the relation between the isophotal sizes and the [O III] line widths. The implications of these findings are discussed in the next Section (Sec. 5).

4.1 Candidates of Extended Emission Line Regions

One important goal of this study is to select interesting candidates of extended emission line regions for future follow-up studies. As this technique is only dependent on the strengths and sizes of the emission line regions, objects of a wide variety of origins can be selected. Potentially, those include extended ionized outflows, AGN light echoes, AGN light cones, dual AGN, mergers, etc. In this section, we present six spectacular candidates that are among the most extended in our $z = 0.2$ sample (Tab. 5.3, Fig. 5.10). Three of them have already been found to have extended outflows (SDSS J1000+1242, J1010+1413, and J1517+3353), while the others, possibly hosting outflows or light-cones, have received little attention so far in the literature. Another fourteen extended emission line region candidates are presented in Appendix 7.2. These results highlight the potential of this broadband technique to find these peculiar systems and improve our understandings of the extended emission line systems and AGN feedback.

SDSS J1000+1242

With a bolometric luminosity of $\sim 1 \times 10^{46}$ ergs s$^{-1}$, SDSS J1000+1242 is among the most luminous AGN at low redshifts, that are capable of driving outflows on galactic scales. Harrison et al. (2014) observed this object with the Gemini GMOS IFU and find signs of extended high velocity outflows. Our Magellan long-slit spectroscopy finds that the outflow is indeed extended
Table 5.3. Properties of Six Example EELR Candidates

<table>
<thead>
<tr>
<th>SDSS Name</th>
<th>z</th>
<th>$L_{\text{bol, [OIII]}}$ [ergs s$^{-1}$]</th>
<th>$L_{\text{bol, 15 µm}}$ [ergs s$^{-1}$]</th>
<th>FWHM$_{[\text{OIII}]}$ [km s$^{-1}$]</th>
<th>$r_{\text{iso}}$ [kpc]</th>
<th>$A_{\text{iso}}$ [kpc$^2$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>J1000+1242</td>
<td>0.148</td>
<td>$1.0 \times 10^{46}$</td>
<td>$1.2 \times 10^{46}$</td>
<td>641</td>
<td>14.7 (10.8)</td>
<td>198</td>
</tr>
<tr>
<td>J1010+1413</td>
<td>0.199</td>
<td>$3.4 \times 10^{46}$</td>
<td>$2.7 \times 10^{46}$</td>
<td>1011</td>
<td>12.9 (8.0)</td>
<td>98</td>
</tr>
<tr>
<td>J1203+2006</td>
<td>0.212</td>
<td>$7.5 \times 10^{45}$</td>
<td>$5.6 \times 10^{45}$</td>
<td>424</td>
<td>14.8 (9.7)</td>
<td>212</td>
</tr>
<tr>
<td>J1352+6541</td>
<td>0.206</td>
<td>$1.2 \times 10^{46}$</td>
<td>$8.0 \times 10^{45}$</td>
<td>650</td>
<td>19.9 (14.9)</td>
<td>359</td>
</tr>
<tr>
<td>J1517+3353</td>
<td>0.135</td>
<td>$6.4 \times 10^{45}$</td>
<td>$1.2 \times 10^{45}$</td>
<td>1139</td>
<td>11.2 (7.6)</td>
<td>228</td>
</tr>
<tr>
<td>J1616+3716</td>
<td>0.151</td>
<td>$9.1 \times 10^{45}$</td>
<td>$5.5 \times 10^{45}$</td>
<td>370</td>
<td>11.6 (7.6)</td>
<td>83</td>
</tr>
</tbody>
</table>

with a radius 6 kpc and has a high velocity of \( w_{80} = 790 \) kms. There is also an extended emission line region reading a radius of 15 kpc that has lower line widths. ³

³This radius is measured along the major axis of the galaxy with an isophote threshold that is three times deeper than the one used in this Chapter.
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>SDSSJ1352+6541</td>
<td><img src="image1" alt="Emission Line Map" /></td>
<td><img src="image2" alt="PSF Residual" /></td>
<td><img src="image3" alt="Log Intensity" /></td>
</tr>
<tr>
<td>SDSSJ1517+3353</td>
<td><img src="image4" alt="Emission Line Map" /></td>
<td><img src="image5" alt="PSF Residual" /></td>
<td><img src="image6" alt="Log Intensity" /></td>
</tr>
<tr>
<td>SDSSJ1616+3716</td>
<td><img src="image7" alt="Emission Line Map" /></td>
<td><img src="image8" alt="PSF Residual" /></td>
<td><img src="image9" alt="Log Intensity" /></td>
</tr>
</tbody>
</table>

Figure 5.10 (Continued.)

Its [O III] emission line map shows elongated and patchy morphology that is along the same direction as the galaxy continuum emission. As mentioned in Sec 3.1, the light profile from the emission line map agrees well with the Magellan long-slit spectrum that there are clumpy structures at the outskirt of the system. It is not clear whether these clumps reflect galactic structures such as tidal tails or are results of outflows shocking with the galactic medium. Also, it is possible that both the irregular morphology of the galaxy and the presence of an energetic
AGN are results of an late stage merger. More follow-up observations are proposed for this objects as described in the next section.

**SDSS J1010+1413**

Similar to SDSS J1000+1242, SDSS J1010+1413 is another luminous AGN with high velocity extended outflows. It is three times more powerful in terms of its AGN bolometric luminosity \((3 \times 10^{46} \text{ ergs s}^{-1})\). Harrison et al. (2014) reveals a very high [O III] line width of \(w_{80}= 1450\) km s\(^{-1}\) at the nucleus. Our Magellan long-slit spectrum further constraints the size of this high velocity [O III] component to be 10 kpc in radius. We also discovered a even more extended but narrow [O III] component with a radius of 16 kpc. This more extended component coincides with the two blobs in our broadband reconstructed [O III] map, and is more likely to be passively illuminated galactic gas than outflows.

To have a more comprehensive view of the feedback phenomenon in these two intriguing systems – SDSS J1000+1242 and SDSS J1010+1413, we have proposed the following multi-wavelength studies that will shed light on various components of the galaxy: Chandra X-ray observations to study the hot gas an AGN accretion (P.I.: K. Pardo), SMA molecular CO observations to search for the cold gas content and potentially molecular outflows (P.I.: A. Sun), and HSC narrowband imaging to resolve sub-kpc-scaled [O III] emission line structure (P.I.: A. Goulding). There is also VLA radio data available for the studies of the jet. In particular, the HSC narrowband imaging will provide [O III] line maps of much better qualities that can be used to calibrate and improve our broadband technique.

**SDSS J1203+2006**

This system has a moderately high AGN bolometric luminosity of \(\sim 6 \times 10^{45} \text{ ergs s}^{-1}\) but its narrow [O III] line widths of \(\sim 400\) km s\(^{-1}\) shows no sign of outflows. However, its [O III] map reveals a distinct structure of strong [O III] emission perpendicular to the galaxy. It is not clear whether this structure is a AGN ionizing cone or a merging system with a low metallicity star.
forming galaxy like the green peas (Cardamone et al., 2009). This system has no other spectroscopy follow-up studies.

**SDSS J1352+6541**

SDSS J1352+6541 with a [O III] isophotal area of $\sim 360$ kpc$^2$ is probably the largest emission line region at redshift=0.2. Its AGN bolometric luminosity ($\sim 1 \times 10^{46}$ ergs s$^{-1}$) and [O III] line width (FWHM = 650 km s$^{-1}$) are similar to those of SDSS J1000+1242. It is also identified as a spectroscopically double-peaked AGN by Liu et al. (2009). Its kinematically disturbed [O III] emission suggest that it could host ionized outflows. It is classified as flat-spectrum radio source from the Cosmic Lens All-Sky Survey (CLASS) Marcha et al. (2001), suggesting the presence of a compact radio source.

The morphology of its [O III] emissions is elongated and slightly bent with both sides more extended than the galaxy itself. More detailed observations are needed to confirm whether these extended structure are indeed outflows, or just passively illuminated gas.

**SDSS J1517+3353**

This object has two distinct knots close the the galactic nucleus in its [O III] emission line map, and is also a spectroscopically double-peaked AGN as found by Wang et al. (2009), Liu et al. (2009), Comerford et al. (2011), and Ge et al. (2012). It has a moderate AGN luminosity (few $\times 10^{45}$ ergs s$^{-1}$) but a broad [O III] line width (FWHM=1139 km s$^{-1}$) and large isophotal area ($\sim 230$ kpc$^2$) suggesting the presence of extended outflows.

While these evidences put this system on top of the list of binary black hole candidates, in a comprehensive study using SDSS images, Keck/HIRES long-slit spectroscopy, and VLA, Rosario et al. (2010) suggests that these two [O III] line knots are actually ionized outflows shocked by a bi-polar radio jet instead of a pair of binary AGN. This idea is supported by that the location of the two [O III] components coincide with the edges of the two sides of the radio jet imaged by VLA. Another attempt to confirm the nature of the two [O III] features is by Tingay et al. (2011) using VLBI, but the result is inconclusive as only a single point source was detected.
Chapter 5: Study Extended Emission Line Regions with Photometric Surveys

SDSS J1616+3716

This system is included in the section not for the size of its emission line region but for its peculiar morphology. The emission line region is one sided and has a cone-like shape with relatively sharp edges. Its kinematics is quiescent with an [O III] line width of only 370 km s\(^{-1}\), suggesting that this feature is possibly passively illuminated. As this feature is morphologically similar to the AGN UV light-cones (e.g. Zakamska et al., 2006), it is possible that this emission line region is ionized by an AGN light-cone. More observations are needed to confirm its nature but this object does not have other follow-up studies.

4.2 Size-luminosity Relations

As the [O III] emission line regions in type 2 AGN are created by the AGN ionizing radiation, one would expect the sizes and areas of our measured emission line regions to correlated with the AGN bolometric luminosity. We test this hypothesis by comparing our measured isophotal radius and area to the AGN bolometric luminosity. We use two common indirect indicators to infer the AGN bolometric luminosities: the [O III]\(\lambda 5007\) luminosities from SDSS fiber spectrum by Mullaney et al. (2013) and the mid-IR WISE rest frame 15 micron luminosities as described in Chapter 4. The correlation with the [O III] spectroscopy luminosity serves as a sanity check of our technique. As the [O III] spectroscopy luminosity is also based on the same [O III] line, one would expect to see a correlation whether or not AGN is the cause of the line (an alternative example would be shock heated [O III] emission). The mid-IR radiation from AGN heated hot dusts, however, is a cleaner tracer of the AGN power than [O III].

Fig. 5.11 shows the [O III] isophotal radius and area against the two AGN bolometric luminosities from [O III] and WISE. Also shown is the relative fraction of objects in each categories – undetected (gray), unresolved (cyan), residual affected (red), and robustly extended (blue) – also as a function of the AGN luminosities.

The isophotal radius for the robustly extended objects are measured from the PSF subtracted denoised maps and are corrected for the biases due to noise according to Eq. 5.2 (see Appendix 7.1). Its random uncertainty of \(\pm 0.5\) arcsec (\(\sim \pm 1.4\) kpc) and the systemic uncertainty of 1.5
Figure 5.11 The size-luminosity relations of [O III] emission line regions. The x-axes are AGN bolometric luminosities inferred from [O III] (left) and WISE 15 μm luminosities (right). The first row show the fraction of non-detection (gray), unresolved (cyan), residual affected (red), and robustly extended (blue) objects. The second row show the relation between the isophotal radii with the AGN luminosities, and the third row is for the isophotal area. The two error bars show the systemic uncertainty (1.5 arcsec, with no dot) and random uncertainty (±0.5 arcsec, with blue dot), respectively.
arcsec (∼ 4.2 kpc) from the noise are also shown in the plot. For the unresolved and residual affected sources, we conservatively use the maximum radius of the galaxy residual mask as their radius upper-limits.

The area, because of its wide dynamical range, is shown in log scale. Same as the radius, we use the PSF subtracted denoised map to infer the area for the robustly extended objects, which is likely an under-estimation as extended signals close to the nucleus could be potentially fitted and over-subtracted. For the unresolved and residual affected sources, we also use the area of the galaxy residual mask as their upper-limits, which are very conservatively. We don’t have a good constraint for the random and systemic uncertainties of the area measurements. The random uncertainty of ±6 arcsec² (±47 kpc²) suggested by the simulation in Appendix 7.1 seems too large especially for those small measured area of few kpc². This over-estimation of the uncertainty could be a result of the simulated Gaussian profile being too flat compared to the real systems, and thus making the isophote susceptible to noise over a larger area. A more precise estimation of the errors requires a more realistic simulation. Apart from noise and PSF, both the radius and area measurements are also subject to other effects such as merging galaxies and nearby blending sources, etc., that are not accounted here.

Despite the uncertainties in the measurements, several trends are supported by the data:

1. The fraction of robustly extended objects increases with both the [O III] and the mid-IR WISE luminosities. The fraction rises from below 20% to approaching 100% within the AGN luminosity range of 10^{45} to 10^{46.5} ergs s⁻¹. Which suggests that basically all AGN at luminosities beyond 10^{46.5} ergs s⁻¹ could host extended emission line regions on kpc scales. At the same time, the fraction of undetected objects decreases continuously with the luminosity throughout the entire luminosity range. One exception is at the low luminosity end for the WISE luminosity, which can be affected by small number statistics. Most moderately luminous AGN (10^{45} ergs s⁻¹), although cannot create kpc-scaled emission line regions, already have nucleus [O III] emissions that are detectable by broadband images.

2. The isophotal sizes and areas correlate strongly not only with the [O III] luminosities but also the WISE mid-IR luminosities, a confirmation that more luminous AGN indeed power
Table 5.4. Correlation Tests with Spearman’s $\rho$ Correlation Coefficient

<table>
<thead>
<tr>
<th>$\rho$ (p-value)</th>
<th>$L_{[\text{OIII}]}$</th>
<th>$\nu L_{\nu, 15}$</th>
<th>$v_{[\text{OIII}]}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>[O III] Isophotal Radius</td>
<td>0.30 (1.1 × 10$^{-8}$)</td>
<td>0.34 (1.4 × 10$^{-10}$)</td>
<td>0.20 (3.6 × 10$^{-4}$)</td>
</tr>
<tr>
<td>[O III] Isophotal Area</td>
<td>0.47 (1.4 × 10$^{-10}$)</td>
<td>0.52 (3.3 × 10$^{-24}$)</td>
<td>0.17 (1.0 × 10$^{-3}$)</td>
</tr>
<tr>
<td>$v_{[\text{OIII}]}$</td>
<td>0.21 (1.4 × 10$^{-4}$)</td>
<td>0.34 (2.2 × 10$^{-10}$)</td>
<td>···</td>
</tr>
</tbody>
</table>

Note. — The correlation between each pair of variables listed here is statistically significant with $p$-values $\lesssim 10^{-3}$, see descriptions in Sec. 4.2 and 4.3.

larger emission line regions. The correlation coefficients are listed in Table 5.4. The area correlates with the luminosities better than the radius, which could either be a real effect or a result of uncertainties in the radius. Also, it is interesting that the WISE luminosities correlate better with both the [O III] radius and area than the [O III] luminosity, although one may expect the opposite. Given the small error bars on the [O III] luminosities, it is unlikely that this is because of measurement errors in the [O III] luminosities, unless the uncertainty is underestimated. If one is interested in finding extended emission line regions, WISE mid-IR luminosities could be a better indicator than SDSS [O III] luminosities.

4.3 Size-velocity Relations

Another interesting question is whether the size of the extended emission line regions depends on the kinetic state of the ionized gas. As discussed in Chapter 4, energetic outflows driven by AGN can be as large as 10 kpc creating extended emission line regions that has disturbed kinematics. We here compare our size measurements with the [O III] line width from the SDSS spectrum.

Fig. 5.12 shows the relation between the isophotal radius and area as a function of SDSS [O III] FWHM line width ($v_{[\text{OIII}]}$) from Mullaney et al. (2013). Mullaney et al. (2013) uses two Gaussian components to fit the [O III] line profile, and the line width quoted is the luminosity weighted quadratic average of the FWHM of the two components. The median error for this line width measurement is about 0.06 dex.
Chapter 5: Study Extended Emission Line Regions with Photometric Surveys

Figure 5.12 The size-velocity relations of the [O III] emission line regions. Upper left: the relation between the [O III] isophotal radii and the [O III] line widths. Upper right: same as the upper left but for isophotal area. Lower left: the fraction of non-detection (gray), unresolved (cyan), residual affected (red), and robustly extended (blue) objects. Lower right: the correlation between the [O III] line widths and the AGN bolometric luminosity as traced by WISE 15 µm luminosities.

Both the radius and area of the robustly extended sample correlate with the [O III] line width in a statistically significant way (p-value $\lesssim 10^{-3}$, Tab. 5.4), but the correlation is weaker than with the AGN luminosities. Also, although the fraction of robustly extended systems still increases slowly with the line width, the trend is much less clear than in the case of AGN luminosities. Therefore, the AGN luminosities, i.e., photo-ionization, seems to be a more important driver for extended emission line regions than, say, outflows in general. Because the [O III] line width also correlates with the AGN luminosities (lower right panel of Fig. 5.11), it is even unclear whether high [O III] line width by itself enhances the emission line region sizes at all,
or is it merely reflecting higher AGN luminosities that correlates with larger sizes. Distinguishing the role of [O III] kinematics from AGN luminosities requires more detailed analysis as discussed in Sec. 5.3.

However, if one focuses on the most extended objects that are larger than 100 kpc$^2$ in area, all but one of them (6/7) have velocities higher than the average 400 km s$^{-1}$. More than half of them have non-virial kinematics with FWHM higher than 600 km s$^{-1}$, which can be due to outflow activities or merger. This echoes with the finding in Chapter 4 that very extended emission line systems tends to have disturbed kinematics. If one wants to search for AGN with high [O III] line widths for outflow related studies but has no spectroscopy data, isophotal measurements from photometric images can serve as a tracer for disturbed [O III] kinematics.

5 Discussion

In this Chapter, we experimented with a new photometric method tuned to exploit ongoing and future large-area imaging surveys. We here discuss the increased parameter space opened by these new methods, and new science questions that can be addressed. In Sec. 5.1, we discuss how the new data can help us understand AGN emission line regions and AGN variability. In Sec. 5.2, we explore the possibility of studying the demographics of AGN outflows with photometric images. Lastly, we roll out a road map for the future directions of this method in Sec. 5.3.

5.1 Emission Line Regions and AGN Variability Time Scale

The [O III] emission line map is a direct probe of the extent of the AGN photoionization in the host galaxy. Our study with the SDSS images confirms again that the sizes of the emission line regions correlate with the AGN bolometric luminosity (Sec. 4.2). But, the flattening of the emission line region sizes at the high luminosity end (Liu et al., 2013a; Hainline et al., 2014, Chapter 3) is not shown by our data, possibly due to the higher isophotal limit used in this study. With further analysis, one can quantitatively constrain the size-luminosity relation and compare it with previous studies. With the spatially resolved light profiles, we can also constrain the
photoionization models and the distribution of the gas in the galaxy. Furthermore, it is now possible to explore the spatial correlation between the emission lines and the galaxy stellar component with a large sample, and learn about the geometry and covering fraction of the nuclear obscuring material.

AGN flickering time scale is another area we can study with the emission line maps. As it takes about $10^4$ yrs for the AGN radiation to travel across the galaxy and form an EELR, this light travel time can be used as a clock to gauge the AGN flickering time scales on $\gtrsim 10^4$ yr scales. Emission line regions are a unique probe of intermediate time scales that are longer than the directly observable variability of AGN (minutes to years) but shorter than the time scales constrained by the link between AGN and host galaxy properties ($\sim 10^8$ yrs, e.g., Hickox et al., 2014). Schawinski et al. (2015) find that a typical AGN episode should last for $\sim 10^5$ years using the fraction of X-ray AGN that have no AGN-ionized narrow lines (5% in their case). We can apply the same method to our current sample. Among the 15 luminous AGN ($L_{\text{bol}, \text{OIII}}>10^{46}$ ergs s$^{-1}$) where we expect emission line regions of size $\sim 10$ kpc, there are about 10-30% that have emission line regions that are abnormally small (area $< 1$ kpc$^2$). The uncertainty is dominated by the size upper-limits due to the galaxy residual mask. This fraction gives an AGN episode time scale of $\sim 10^{4.5-5}$ yrs. With a larger sample and a better understanding of the galaxy residual, the estimate on the AGN episode time scale can be improved.

If we have a sample of emission line regions that is unbiased by the presence of the AGN, such as by the blind search technique discussed in Sec 5.3, we can also constrain the AGN episode time scale based on the light echo occurrence rate. This method has been demonstrated by Lintott et al. (2009); Keel et al. (2012) using galaxy zoo to identify light echoes that constrain the AGN episode to $0.2 - 2 \times 10^5$ yrs, assuming the fading time scale of extended emission line regions is $\sim 10^4$ yrs. There are a few light echo candidates in our current sample that are outliers above the size-luminosity relation, but our sample is biased by pre-selection of luminous AGN based on SDSS spectra. Interpreting AGN variability from our light echo candidates requires understanding the selection bias.
5.2 Studying AGN Outflows with Photometry

One important goal of developing the broadband photometry technique is to explore whether photometric surveys can improve our understandings of AGN outflows. In the case of SDSS J1356+1026, the super bubble prototype discussed in Chapter 3, the extended ionized outflow emitting in strong [O III] lines can be seen in the SDSS image. One may ask whether the emission line information from the images are useful for studying outflows. Certainly, photometric data does not provide kinematic information, which can only be obtained by spectroscopic follow-up. However, the [O III] emission-line map may help identify and constrain the size and morphology of AGN outflows. If so, we gain access to the large sample sizes available from photometric surveys for a statistical study of the population of AGN outflows.

First of all, one can certainly set upper-limits on the size of the [O III] emitting outflows based on size of the [O III] emission line region. This can rule out the existence of very extended ionized outflows (e.g., $r > 10$ kpc, depending on the size upper-limits) in those [O III] undetected and unresolved systems. However, for the systems that have the most extended [O III] emission, this size upper-limit may not be very informative. As we find in Chapter 3, there are cases where the emission line region can be a few times larger the outflow (for SDSS J1000+1242 the outflow radius is 6 kpc whereas the emission line region is 15 kpc), such that the upper-limit does not provide much constraint on the outflow. Surface brightness is also an intrinsic limitation here. This size upper-limits only apply to [O III] emitting outflows. If there are extended outflows that are too low in density or temperature to efficiently emit in [O III], they can be missed by the emission line map depending on the depth of the photometric data. In our Magellan spectroscopic sample (Chapter 3), three systems have high [O III] line widths even at the edge of their emission line regions. There can be more extended but low surface-brightness parts of the outflow that are missed by the [O III] observation. Because of the depth of the observation, broadband photometry can suffer more from this surface brightness limit than spectroscopy. In this case, absorption line spectroscopy can be a complementary method to study the the low density components of the outflows (e.g., Tremonti et al., 2007).
Can we actually do more than just setting the outflow size upper-limits with photometric data? For example, based on the [O III] map, can we build a predictive model to infer the outflow properties for each AGN? And can we use it to understand the demographics of AGN outflows given a large photometric sample of AGN? The correlation between the [O III] isophotal area and the SDSS [O III] line widths in Sec. 4.3 gives us some clues that large emission line regions are indeed more likely to have disturbed kinematics. Also, in our Magellan study, where we select spectroscopic follow-up samples based on photometry, the two most extended emission line systems, SDSS J1000+1242 and SDSS J1010+1413, turn out to host the most extended and energetic outflows in the sample.

As discussed in Sec. 4.3, it is plausible that if more luminous AGN have both stronger outflows and larger emission line regions, then the emission line map extent may not depend on the outflow properties independently. We can represent this scenario (a.) by the graphical model shown on the left panel of Fig. 5.13. In this graph, we use $L$ to represent the AGN luminosity, $O$ for the outflow properties, and $E$ for the emission line map properties. The arrows represent dependencies and the box stands for multiple ($N$) objects. In this case, if the AGN luminosity is

![Graphical model](image)

Figure 5.13 Graphical model representations of the two scenarios (a. and b.) of the dependencies between the AGN luminosity ($L$), outflow properties ($O$), and the photometric emission line map properties ($E$). Scenario (a.) is when the dependencies between $O$ and $E$ are purely based on $L$, such that $E$ provides no more constraints on $O$ given $L$. Scenario (b.) is where $E$ explicitly depend on $O$ such that more information about $O$ can be gained from $E$ given $L$. $\tau$ denotes the prior distribution on $L$, and the $N$ is the number of objects.
known, then the emission line map provides no extra information about the outflows. If however, the [O III] map is also dependent on the outflows in addition to their dependencies on the luminosity, as shown by the extra arrow in the graphical model (b.), then there is more to be learned about outflows from the emission line maps.

To distinguish between these two scenarios, we can use spectroscopic samples where we have the data $L$, $O$, and $E$ for each object, and apply statistical techniques belonging to the class of structure learning, such as conditional independence tests. As an experiment, we apply a simple conditional independence test based on the linear correlation coefficient Pearson’s $r$ on the 329 robust extended objects in the sample.\(^4\) We find that while there is little evidence that the isophotal area depends on the [O III] line width given the WISE AGN luminosity ($r = 0.045$, $p$-value = 0.42), there is tentative evidence that the isophotal radius is positively correlated with the [O III] line width given the luminosity ($r = 0.099$, $p$-value = 0.073). Therefore, the isophotal radius may be a predictor for the presence of outflows.

This type of test can be extended to other outflow and [O III] map features as well as other AGN samples. With spectroscopic follow-up observations, such as our Magellan sample (Chapter 3), one can explore the relationships between the outflow sizes and the [O III] map properties. But as the sample size for such observations are still small, it may be needed to expand the sample size using, for example, the MaNGA IFU survey. There are also other emission line map properties that could be explored beyond area and radius. The question is what feature (or what set of features) can best predict the outflow properties. One can define more detailed shape measurements, such as clumpiness or asymmetry, that might be more sensitive to outflows. Another alternative is to apply advanced techniques such as the restricted Boltzmann machine (e.g. Hinton & Salakhutdinov, 2006) to automatically select useful features from the image that are related to the outflows. These explorations are beyond the scope of the current study.

In summary, in this Chapter we have successfully constructed emission line maps from broadband images, an important foundation for using photometric surveys to study AGN outflows. These maps can potentially provide size and morphological information about the

\(^4\)We use the R function `bnlearn ci.test` for the test.
outflows, which is otherwise not available from the SDSS spectrum. We show tentative evidence that the isophotal radius is dependent on the velocity of the outflow given the luminosity. To build a predictive model of outflow properties based on the photometric data, more work needs to be done to explore other outflow and [O III] map properties and their dependences. A larger sample of spectroscopic training data may also be needed. If working, such a predictive model can not only inform the design of a future spectroscopy survey of AGN but also extrapolate our knowledge of outflows from a limited set of spectroscopy observations to much larger photometric samples from current and future surveys. This information will improve our understanding of the population of AGN outflows.

5.3 Future Work

The goal of developing this photometric method is to harness the rich data sets provided by on-going and future large-area photometric surveys. In this section we discuss the short-term, middle-term, and long-term possibilities of extending the current study. These directions include: 1. improving the measurements on emission line maps, 2. samples of type 2 AGN at higher Redshifts using the Subaru Hyper-Suprime Camera (HSC) survey, and 3. beyond spectroscopic samples and LSST.

**Improving the Measurements on Emission Line Maps**

As mentioned Sec. 3 and Appendix 7.1, several components of the current analysis implementation can be further improved. These include a better assessment of the residuals in the emission line map, better understanding of the measurement uncertainties, and better denoising methods to improve the image quality. These discussions are summarized here.

First of all, as mentioned in Sec. 3.3, we need to understand the residuals of the galaxy continuum subtraction and its effect on the emission line map. This residual currently is the limiting factor for measuring emission lines regions smaller than 5 kpc. These residuals can arise from the gradient of the galaxy color, a mismatched PSF between the bands, and the errors in the continuum color estimates. In the current analysis, we assume the residual to be less than 10 % of
the continuum level. This assumption needs to be tested with real or simulated data. One could use the SDSS images for a set of normal galaxies that are matched in redshifts and mass, and perform the same continuum subtraction exercise. As long as the test set is representative, this empirical method should represent the real residuals arising from either color gradients or PSF. To disentangle the contributions from these two effects though, image simulations are needed. Galaxy image simulation packages such as GalSim (Rowe et al., 2014) can be used to explore a range of galaxy and PSF properties and their effects on the residuals. With these tools, one can evaluate different continuum subtraction procedures and decide, for example, whether there is a need to match the PSF of the images before the continuum subtraction.

Second, we can also improve on our understanding of the isophotal measurement uncertainties due to the noise and PSF. As described in Appendix 7.1, we performed simulations to assess the random and systematic uncertainties on the isophotal radius and area. The Gaussian profiles adopted, however, can fail to capture the uncertainties associated with the irregular morphologies and clumpiness of the real emission line systems. In addition, the Gaussian profiles can lead to overestimations of the uncertainties, because the flatter slopes of the Gaussian profiles at the isophotal boundary can make the boundary more easily affected by the noise. To have more realistic estimates of the uncertainties, we need to adopt realistic models of the emission line light profiles, for example, using higher quality spectroscopic or narrow-band imaging data. With more realistic models, we can further explore other more detailed shape measurements and their uncertainties, such as the aspect ratio, symmetry, clumpiness, etc.

Lastly, we can explore better denoising algorithms to improve on the image quality of the emission line maps. In the current implementation we adopt a simple method using Discrete Wavelet Transformation (DWT), which improves the random and systematic uncertainties by 20%. However, using DWT for denoising has some known defects. For example, it creates ringing artifacts in the image. In the future we can explore other more advanced methods, such as the Undecimated Wavelet Transformation (e.g., Starck et al., 2007) and adoptive thresholding (e.g., SureShrink Donoho & Johnstone, 1995) to further improve the image quality. Beyond this denoising application, one can explore the possibility of using wavelet techniques to detect diffuse and faint emissions.
Table 5.5. HSC Redshift Ranges for Photometric Studies of [OIII]

<table>
<thead>
<tr>
<th>Line-band</th>
<th>Conti-band</th>
<th>( z )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( g )</td>
<td>( i )</td>
<td>0.000 – 0.027</td>
</tr>
<tr>
<td>( g )</td>
<td>( r )</td>
<td>0.070 – 0.090</td>
</tr>
<tr>
<td>( r )</td>
<td>( z )</td>
<td>0.095 – 0.259</td>
</tr>
<tr>
<td>( r )</td>
<td>( i )</td>
<td>0.301 – 0.391</td>
</tr>
<tr>
<td>( i )</td>
<td>( z )</td>
<td>0.432 – 0.683</td>
</tr>
<tr>
<td>( z )</td>
<td>( y )</td>
<td>0.722 – 0.858</td>
</tr>
</tbody>
</table>

Note. — The redshift ranges and broadband configurations for photometric studies of [OIII] emissions using HSC.

Samples of Type 2 AGN at Higher Redshift

In this Section, we discuss how to extend the current study to include type 2 AGN samples at higher redshifts. In this Chapter, we studied the systems from the M13 sample in the \( z = 0.2 \) redshift bin with a combinations of SDSS \( r \)-band and \( z \)-band images. With small adjustments, the same analysis procedures can be applied to the other redshift bins using other combinations of SDSS bands as listed in Tab. 5.1. The lower redshift bin at \( z = 0.05 \) contains lower luminosity AGN down to \( L_{\text{bol}} \sim 10^{42.5} \) ergs s\(^{-1}\) that can improve the dynamical range of this study. Due to the proximity of the objects and the better image quality in the \( g \)- and \( r \)-band, we can effectively reach three times better resolution and sensitivity in terms of physical scales (PSF FWHM \( \sim 1.5 \) kpc) and surface brightness. This can allow us to identify galactic structures such as spiral arms and use isophote levels similar to the spectroscopic studies (e.g., Liu et al., 2013a). However, at these lower redshifts, the emission line maps are more sensitive to galaxy color gradients, as the SDSS spectrum only samples the color of the galaxy nucleus on \( \lesssim 3 \) kpc scales. On the higher redshift side, the \( z = 0.3 \) bin using \( r \)- and \( i \)-bands provides three hundreds more luminous 2 AGN that can increase the sample size on the luminous end. The effective resolution is about 50 %
worse than the \( z = 0.2 \) sample, but the sensitivity on the \([\text{O III}]\) surface brightness is similar or better because of the better image quality in the \( r/i \)-bands than the \( r/z \)-bands.

Other than the M13 sample, there are SDSS selected type 2 AGN samples at higher redshifts \((0.3 < z < 1)\), such as Zakamska et al. (2003); Reyes et al. (2008); Yuan et al. (2016). These systems are more luminous than their lower redshift counterparts. Some of them are well studied by IFU or long-slit spectroscopy (e.g., Liu et al., 2013b), and many show signs of extended outflows. With broadband photometry, we can use a combination of \( i \)- and \( z \)-bands to image systems at \( z = 0.6 \). There are 51, 125, and 890 type 2 AGN from these three samples at these redshifts that can be studied by the SDSS, and they all have high luminosities \((L_{\text{bol}} \sim 10^{45.3}, 10^{46.1}, 10^{46.2} \text{ ergs s}^{-1})\). However, due to the higher redshifts, the surface brightness limits will be at least 3 times higher than at \( z = 0.2 \) (isophote limit \( \sim 9 \times 10^{-15} \times (1 + z)^{-4} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ arcsec}^{-2} \)), and the resolvable physical scale will be twice as large (PSF FWHM \( \sim 9 \) kpc), which means that even for these luminous systems only the nuclear \([\text{O III}]\) emission will be detected. To study extended \([\text{O III}]\) emission for these \( z = 0.6 \) systems, better photometric data is needed.

The HSC-wide survey provides photometric data that is four magnitudes deeper than the SDSS, with PSF FWHM up to a factor of two better. These data are much better suited for the study of \([\text{O III}]\) emission line regions at higher redshifts. Furthermore, the additional \( y \)-band extends the redshift range for photometric \([\text{O III}]\) studies to \( z = 0.8 \) (Tab. 5.5), where some of the most luminous AGN are found (e.g., \( L_{\text{bol}} \sim 10^{47.5} \text{ ergs s}^{-1} \) in Yuan et al., 2016). Even at a redshift of 0.8, the surface brightness limits of the \([\text{O III}]\) reached by HSC is still about a factor of 3 deeper than in the current study, allowing isophotal measurements to a similar depth as the spectroscopy studies such as Liu et al. (2013a). At \( z =0.8 \), assuming a PSF FWHM of 0.7 arcsec, we can also resolve structures on 5 kpc scale, similar to the current SDSS study at \( z =0.2 \). At lower redshifts, the quality of the emission line maps will be even better, allowing precise measurements of the emission line regions. However, the HSC-wide survey covers a significantly smaller part of the sky than SDSS. With 1400 deg\(^2\) in area, we expect only about 200 and 10 objects from the Yuan et al. (2016) sample to be covered by HSC in the redshift bins of \( z =0.6 \) \((i/z)\) and 0.8 \((z/y)\).
Although the sample size is not as large as in the current study, these samples will significantly improve the statistics of emission line regions at the highest AGN luminosities and help in identifying extreme emission line and outflow systems.

Beyond Spectroscopic Samples and LSST

The method tested in this study relies on an SDSS spectrum to extract the emission line distribution. However, future photometric survey such as LSST will have no spectroscopic counterparts. To exploit the large sample size offered by current and future photometric surveys, it is necessary to extend the emission line map reconstruction technique beyond spectroscopic samples. We discuss several possibilities here.

In this case, other AGN diagnostics such as mid-IR selections (e.g., from *WISE* Stern et al., 2012) can be used to select obscured type 2 AGN. Such samples are not biased towards [O III] luminous objects, as is the current sample. There will be > 50,000 *WISE* AGN within \( z = 1 \) in the 1,400 deg\(^2\) HSC-wide survey. We expect \( \sim 80\% \) of them to fall in a redshift range where their [O III] can be imaged. Combining HSC and *WISE* can dramatically increase the sample size of AGN with extended emission line regions and allow precise statistical constraints on their demographics and AGN variability time scale. With no biases towards nuclear [O III] emission, we expect to have a more complete sample of [O III] dim systems, such as AGN light echoes, heavily obscured nuclei, or even young AGN that have not had time to form narrow line regions. In the future, the Large Synoptic Survey Telescope (LSST) can also provide AGN selection based on the temporal variability (Choi et al., 2014).

However, there are issues that need to be resolved to construct emission line maps without spectra. First of all, with no redshift information from the spectrum, we need to rely on photometric redshifts (photo-z). There are challenges associated with estimating photo-z for AGN, due to its featureless AGN continuum and a wide range of emission line ratios, but it can be done with good photometry and training samples as demonstrated by Salvato et al. (2011). With photo-z it is also easier to confuse different strong emission lines, and harder to identify and rule out contaminants, for example, [OII] or H\(\alpha\) emitters. Second, with no spectrum, we need to
come up with other ways to constrain the continuum SED to decompose the line and continuum image. Fortunately, type 2 AGN have a narrow range of continuum colors. Most of the color variations are probably due to differing amounts of AGN continuum that is scattered into the line of sight. It is then possible to have a satisfactory estimate of the continuum SED based on our prior knowledge on the range of continuum SEDs and the multi-band photometry data.

If we further release the constraint of having prior AGN selection, with photometry, it is possible to conduct a truly “blind search” of extended emission line regions. Without the prior AGN selection, this method can yield even larger sample sizes and potentially unearth a population of emission line systems not associated with the AGN. Prescott et al. (2012a,b) has demonstrated that it is possible to select Ly-α blobs in broadband images using wavelet transformations to identify extended diffuse emission. This selection is done by masking out the stars and galaxies. Unlike Ly-α blobs, the [O III] regions can be severely blended with their host galaxies, and we need to use the spectral information in the multi-band images to differentiate between the two. The Multi-band morpho-Spectral Component Analysis Deblending Tool (MuSCADeT) by Joseph et al. (2016) has demonstrated an iterative method to decompose multi-band images into components of different SEDs using both the spectral and morphological information. As shown in their example, the SEDs of the objects do not need to be fixed but can be derived from the image. One can imagine combining this method with the prior knowledge of the emission line SED to identify emission line systems. The candidates so found need not be limited to [O III] emitters, but can be, for example, [OII] emitting star forming galaxies or even high-z Ly-alpha emitters. If working, this morpho-spectral decomposition technique can truly unleash the surveying power of future photometric surveys, e.g., LSST, and provide a complete statistical understanding of the population of emission line regions.

6 Summary

In this Chapter, we experiment on a new photometric technique to reconstruct the 2D distribution of emission lines from broadband images. This method utilizes two broadband images – one with the [O III] line and one for the continuum – and a fiber spectrum to separate the line
emission from the continuum. We apply it to the SDSS images of a sample of 3194 nearby type 2 AGN at $z = 0.2$ that are selected based on the SDSS spectrum by Mullaney et al. (2013). This photometric method successfully detects extended [O III] emission with light profiles consistent with long-slit spectroscopy observations. It also reveals the irregular morphologies of the emission line regions that are possibly associated with outflows or light cones.

We detect [O III] in 1368/3194 objects (43%) and find extended emission in 329/3194 (10%), with the effects from noise, the PSF, and continuum subtraction residuals taken into account. The detection rate and the fraction of extended systems increase steeply with the AGN bolometric luminosity (traced by [O III] and WISE 15 μm emission), and the fraction of extended systems approaches 100% at the highest AGN luminosities probed ($L_{\text{bol}} \sim 10^{46.5}$ ergs s$^{-1}$). We adopt a non-parametric isophotal method to measure the radius and area of the emission line regions, and find both of them to correlate strongly with the AGN bolometric luminosity and the [O III] line width. Although the correlation between the [O III] extent and the velocity could be mostly driven by the luminosity, we find tentative evidence that the radius of the [O III] emission line region is positively correlated with the [O III] velocity at a fixed luminosity. If this dependence holds true, this indicates that the emission line maps from broadband images encode information about the AGN outflows, and we can potentially learn about outflow demographics from photometric surveys. From the outliers in the size-luminosity relation, we also find candidates for AGN light echoes that have recently faded and systems where the AGN just turned on. These systems can help constrain the AGN flickering time scale on the scale of $\gtrsim 10^4$ yrs.

This work demonstrates the capability of broadband photometric surveys to study emission line systems in a statistical manner. More work needs to be done to further understand the uncertainties in the line maps, explore other morphological measurements, and apply this method to samples at higher and lower redshifts. In particular, with better imaging quality from current surveys such as HSC, we can extend this study to redshifts up to $z = 0.8$ and improve the dynamic range of the current study to include a luminosity of $L_{\text{bol}} \sim 10^{47.5}$ ergs s$^{-1}$. In the long term, to prepare for the next generation photometric surveys, e.g., LSST, which has no spectroscopic counterpart, it is important to develop more general photometric techniques that apply to a wider sample than just spectroscopically selected AGN. This will require further
development of image decomposition techniques that utilize both the spectral and morphological information in multi-band photometry images. But with such tools we can have a complete view of the population of extended emission line regions and outflows with a large photometric sample.

7 Appendix

7.1 Simulations for Uncertainty Estimations

Figure 5.14 PSF and noise can artificially enlarge the measured sizes of unresolved objects, especially for the bright ones. The y-axis is the measured isophotal radius and the x-axis is the flux of the object. The blue line shows the PSF convolved model, the green line is with the noise added, and the red line is after denoising. The shaded regions show 68% of the scattering due to the random noise.

To understand how the noises and the PSF affect the isophotal measurements we perform a Monte-Carlo experiment using simulated emission line maps. The simulation set up is described as follows. We first create an image of the same size as our stamp images covering an area of 25 arcsec$^2$ (64×64 pix, 1 pix = 0.396 arcsec). We then insert an emission line source, either a point source or an extended 2D Gaussian, at the center of the image. It flux and size are set to cover a range of possible parameters resembling real systems ($F = 10^{-13} - 10^{-15}$ erg s$^{-1}$ cm$^{-2}$, $\sigma = 0 - 10$ arcsec). This Gaussian profile obviously does not mimic the complex and clumpy morphologies of the real emission line systems, but at least it should capture the first order effects on measured sizes caused by the noise and PSF. We convolve this image with a Gaussian PSF
Figure 5.15 For the extended objects, the noises can bias the isophotal radius to larger values by about 2 arcsec but denoising lower the bias to about 1.5 arcsec. Shown on left is the measured isophotal radius (after PSF and noise added) versus the true isophotal radius, and shown on the right is the difference of the two versus the true isophotal radius. The colors are as described in Fig. 5.14. The red dotted line is the function used to correct for the bias as shown in Eq. 5.2.

corresponding to the median SDSS r-band PSF (FWHM = 1.43 arcsec), and add Gaussian white noise with an amplitude of $\sigma = 1.3 \times 10^{-15}$ erg s$^{-1}$ cm$^{-2}$ arcsec$^{-2}$, the median noise level of the emission line maps (Sec. 3.2). We also apply denoising to this image using the same procedure as described in Sec. 5.8. For each source we run 100 noise realizations to explore the random uncertainty. These simulated maps at different stages – the original, the PSF-convolved, the noise-added, and the denoised – are measured using an isophote level of $1.6 \times 10^{-15}$ erg s$^{-1}$ cm$^{-2}$ arcsec$^{-2}$, the mean value of the real sample.

Fig. 5.14 shows the measured isophote radii for the unresolved sources. Although these sources have a true size of zero, depending on the flux, the PSF inflates its isophote radius to a finite size up to 1.5 arcsec. This highlights the importance of the PSF subtraction to distinguish between truly extended and PSF inflated sizes. Furthermore, when the noise is added, besides the random uncertainty introduced, the size is also systematically enlarged by about 30%. This is because as the radius measurement picks only the most distant point in the isophote, chances is that it will select a noise peak that is at a slightly larger radius. Denoising does improve on the random uncertainty on the sizes, but its effect on lowering the bias is significant only at low fluxes.
Fig. 5.15 shows the measured isophote radii for the extended sources with a Gaussian profile. In these cases, the systematic effect of the PSF is basically negligible. However, depending on the shape of the light profile, two sources with the same intrinsic isophote radii may end up having different PSF convolved radius, a variation that can be as high as 0.7 arcsec. The noise still biases the radius measurements toward larger values and introduces random uncertainties. For a typical extended object with a size between 3 and 8 arcsec, the bias due to noise is 1.9 arcsec on average and the random uncertainty is about $1\sigma = 0.5$ arcsec. Thus, any size measurement about or under 2 arcsec are strongly affected by noise. Denoising does improve on the bias slightly to 1.5 arcsec, and decrease the random uncertainty to $1\sigma = 0.4$ arcsec. We use the following function form to approximate the bias in the denoised maps, shown in dash dark red lines in Fig. 5.15:

$$
\begin{align*}
  r_{\text{true}} &= r_{\text{denoised}} - 1.5'' & \text{for } r_{\text{denoised}} > 3.5'' \\
  r_{\text{true}} &= 0.571 \times r_{\text{denoised}} & \text{for } r_{\text{denoised}} < 3.5''.
\end{align*}
$$

(5.2)

Figure 5.16 The same as Fig. 5.14 but for the isophotal areas.

Fig. 5.17 and 5.16 show the same analysis but for the isophotal area measurements. We see a similar trend that bright unresolved sources can be mistaken as extended sources. The bias due to noise is less severe than in the base of isophotal radii, and denoising further reduces the bias to even smaller amount. The random uncertainty of the area due to noise is about 6 arcsec$^2$ on average.
Figure 5.17 The same as Fig. 5.15 but for the isophotal areas. The effect of noise on the isophotal areas is less severe than on the radii, and denoising can improve on both the biases and the random uncertainties.

In conclusion, we find that: first, it is important to apply the PSF subtraction to the images to distinguish between unresolved and resolved sources; second, for the isophotal radius measurements, noise introduces not only random uncertainties ($\sigma \sim 0.5\text{ arcsec}$) but also biases ($\sim 2\text{ arcsec}$), and denoising further improves both the random uncertainties and the biases by about 20%; third, the area measurement is less biased by the noise and have a random uncertainty of 6 arcsec$^2$ on average. Please note that as the assumed Gaussian light profile does not capture the irregular morphologies of real sources, there are extra uncertainties that are not included in these errors, including patchy EELR signal that could be missed by the algorithm or area underestimation due to the PSF subtraction.

To correct for the biased isophotal radius due to the noise, we apply the relation in Eq. 5.2 to systematically lower the radii measurements. We then assign an random error bar of $1\sigma = 0.5$ arcsec to these corrected radii. For the isophotal area, we do not apply bias correction and adopt a 6 arcsec$^2$ random uncertainty. Other effects that are not captured in this simulation, such as non-Gaussian light profiles, irregular morphologies, contamination of nearby sources, over-subtraction of the nucleus PSF, etc, may introduce other systemic uncertainties.
7.2 [O III] Line Maps of the Extended Emission Line Region Candidates

Section 4.1 presents six of the extended emission line region candidates in detail. We here show the [O III] line maps of the other fourteen objects that are among the top twenty most extended candidates, see Fig. 5.18 and Tab. 5.6.

Figure 5.18 Same as Fig. 5.10 but for the other 14 objects that are among the top 20 most extended candidates.
Figure 5.18 (Continued.)
Chapter 5: Study Extended Emission Line Regions with Photometric Surveys

Figure 5.18 (Continued.)
Figure 5.18 (Continued.)
Table 5.6. Properties of 14 EELR Candidates

<table>
<thead>
<tr>
<th>SDSS Name</th>
<th>z</th>
<th>$L_{bol, [OIII]}$ [ergs s$^{-1}$]</th>
<th>$L_{bol, 15 \mu m}$ [ergs s$^{-1}$]</th>
<th>FWHM$_{[OIII]}$ [km s$^{-1}$]</th>
<th>$r_{iso}$ [kpc]</th>
<th>$A_{iso}$ [kpc$^2$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>J0916+2835</td>
<td>0.143</td>
<td>$7.5 \times 10^{45}$</td>
<td>$3.8 \times 10^{45}$</td>
<td>731</td>
<td>9.2 (5.4)</td>
<td>77</td>
</tr>
<tr>
<td>J0927+2018</td>
<td>0.195</td>
<td>$7.9 \times 10^{45}$</td>
<td>$1.7 \times 10^{45}$</td>
<td>304</td>
<td>8.0 (4.6)</td>
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</tr>
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<td>J0948+6848</td>
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<td>$1.3 \times 10^{46}$</td>
<td>446</td>
<td>8.5 (4.8)</td>
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<td>$3.2 \times 10^{46}$</td>
<td>$3.2 \times 10^{46}$</td>
<td>417</td>
<td>11.0 (6.3)</td>
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</tr>
<tr>
<td>J1059+5002</td>
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<td>$5.2 \times 10^{44}$</td>
<td>335</td>
<td>14.7 (11.1)</td>
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</tr>
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<td>$1.4 \times 10^{45}$</td>
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<tr>
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<tr>
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<td>$5.0 \times 10^{45}$</td>
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<td>7.1 (4.1)</td>
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<tr>
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<td>87</td>
</tr>
</tbody>
</table>

Note. — Properties of fourteen extended emission line region candidates, see Appendix 7.2. The columns are the same as in Table 5.3.
Bibliography


Fabian, A. C. 2012, Annual Review of Astronomy and Astrophysics, 50, 455


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