UNCOVERING HIDDEN BLACK HOLES: OBSCURED
AGN AND THEIR RELATIONSHIP TO THE HOST
GALAXY

by

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A dissertation submitted to The Johns Hopkins University in conformity with the
requirements for the degree of Doctor of Philosophy.

Baltimore, Maryland

July, 2011
Abstract

Active Galactic Nuclei (AGN) are accreting supermassive black holes at the centers of galaxies. According to the unified model, this accretion disk is surrounded by an obscuring torus of dust and gas. In Type 2, or obscured, AGN this torus is viewed edge on. When the column density of the torus exceeds $1/\sigma_t = 1.5 \times 10^{24}$ cm$^{-2}$, this obscuring medium becomes Compton-thick. Studies indicate that a significant fraction of Compton-thick Type 2 AGN exist but are under-represented in many current samples. We have studied two samples of local type 2 AGN (Seyfert 2 galaxies) to explore issues relevant to finding and characterizing the Compton-thick population. We have also investigated the relationship between type 2 AGN and the galaxies in which they live.

To find this Compton-thick population, selecting samples of AGN based on their inherent flux is necessary. We undertook an empirical approach in identifying the most reliable intrinsic AGN flux proxies. Using infrared spectroscopy from Spitzer, optical spectra from the Sloan Digital Sky Survey (SDSS) and the literature, and radio and hard X-ray ($E > 10$ keV) data from the literature, we demonstrated that
the [OIV] 26µm, [OIII] 5007Å and MIR continuum fluxes agree the best among Type 1 and Type 2 Seyfert galaxies.

Utilizing 2-10 keV X-ray data from Chandra and XMM-Newton, we probed the amount of obscuration that may be present in these systems. We find that a majority of sources exhibit signatures of heavy, and possibly Compton-thick, obscuration: depressed 2-10 keV X-ray emission when normalized by intrinsic AGN flux and large Fe Kα equivalent widths,

Using a sample of ~250 star forming galaxies, ~50 composite systems and an additional ~20 Seyfert 2 galaxies, we examined the connection between AGN activity and star formation. We found that the SDSS derived star formation rates and [NeII] 12.8µm flux accurately probe starburst activity in both quiescent and active galaxies. Using these parameters and diagnostics that accurately trace AGN flux, we have shown that these processes are significantly correlated. This link suggests that supermassive black holes and their host galaxies grow simultaneously in the local universe.

Advisors: Professor Timothy Heckman and Dr. Andrew Ptak
Acknowledgements

I would first like to thank my advisors, Tim Heckman and Andy Ptak, for being excellent instructors and a wonderful source of support over the years. They were always available to answer questions and offer advice, sometimes responding to emails at times when most people would be in their 3rd dream and far from being able to discuss and explain scientific matters effectively and intelligently. I also would like to think Profs. Dick Henry, Nina Markovic and Tom Haine for being part of my thesis defense committee.

The grad students in this department deserve a huge thanks! There is a real community here that makes going through the trials and tribulations of a PhD program not only bearable, but fun. I have had such a great time my past 5 years here and I realize I’m fortunate to have this experience. A huge thanks to all the friends I’ve made here along the way.

I thank my parents for always encouraging my love for science over the years. They were always eager to cultivate this interest by bringing me to planetarium shows, museums and public astronomy lectures; buying me a telescope; enrolling me
in an astronomy summer program for high school students; sharing popular astronomy articles from the NY Times and other periodicals with me; and understanding that I would only apply to colleges where I could major in astronomy. I thank them for traveling from NY to MD to be here for my thesis defense and to celebrate with me.

My amazingly supportive boyfriend, Mark J. Cloherty, CRC, also deserves a very heart-felt thank you. He always believed in my abilities even during rough times when I doubted myself. I thank him for being a great listener and offering sage advice. His sense of humor and rational perspective has been inspirational.

Finally, a big thank you to all the professors I’ve had at BU and at JHU, as well as all the scientists I’ve had the pleasure of working with and meeting at the CfA. The enthusiastic support I’ve received over the years has made me feel both welcome and that a place exists for me in the astronomy community.
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Chapter 1

Introduction

At the center of nearly every massive galaxy lies a supermassive black hole (SMBH), millions to billions of times more massive than our Sun. In some galaxies, this SMBH feeds. Dust and gas from the host galaxy close enough to the black hole cannot escape the gravitational attraction from this compact object. This matter collapses into an accretion disk, spiraling into the central black hole. The energy released by this accretion disk rivals or even surpasses that of the host galaxy, sometimes dominating the emission such that the galaxy in which it lives cannot be seen. These accreting SMBHs are known as active galactic nuclei, or AGN.

What signatures distinguish galaxies harboring accreting SMBHs from those that are dormant? Inactive galaxies emit mostly in the optical and ultraviolet (UV), from star formation, and in the infrared (IR), from dust in the galaxy absorbing optical and ultraviolet photons and re-radiating in the IR. In contrast, AGN emission is over a much broader range, from the radio through X-ray and even gamma ray range. Prominent emission lines are usually visible in the optical spectra of AGN, resulting from accretion disk photons ionizing the surrounding gas. In some systems, narrow optical emission lines are present, with a full-width half maximum (FWHM) around several hundred km/s. These features are produced in gas hundreds of parsecs away from the accretion disk, in a region referred to as the narrow line region (NLR). Some systems exhibit broad optical emission lines (FWHM around several thousand km/s). These lines originate in gas much closer to the supermassive black hole, in
a region dubbed the broad line region (BLR). Narrow emission lines are often seen superimposed upon these broad features. When broad optical emission lines are present, an AGN is classified as Type 1. In contrast, Type 2 AGN only have narrow emission lines visible.

The unification model posits that Type 1 and Type 2 AGN are physically the same: a supermassive black hole fed by an accretion disk which is in turn surrounded by an obscuring “torus” of dust and gas, about 1 to 10 parsecs in radius (Antonucci (1993), Urry & Padovani (1995)). Subsequently, the orientation of this system to our line of sight then determines the observable properties, such as whether both broad and narrow emission lines are visible or only narrow emission lines are seen. When viewed face-on, emission from the accretion disk, BLR, NLR and the obscuring medium are visible, classifying the system as Type 1. Conversely in Type 2 AGN, the system is oriented edge-on, blocking the central engine from view. These systems are consequently referred to as “obscured” AGN. The observed emission is then limited to gas from the narrow line region, obscuring medium and any photons energetic enough to penetrate through the “torus.”

In the early universe, emission from the active nucleus outshines the host galaxy, and these sources are classified as quasars. Their local, less luminous (L < 10^{44} erg/s) counterparts are Seyfert galaxies (Sys). In these systems, the host galaxy is visible, providing a useful laboratory in studying the interplay between AGN activity and host galaxy properties. Seyfert 2s in particular are ideally suited for such an investigation as the accretion disk is hidden from view, allowing circumnuclear host galaxy starbursts to be well probed. Studies have also indicated that type 2 systems constitute the majority of local AGN (Comastri, 2004).

1.1 AGN Identification

As AGN are broadband emitters, they can be identified via a variety of multi-wavelength techniques. Below, we briefly review several multi-wavelength diagnostics used to identify AGN.
In the optical, type 2 Seyfert galaxies (Sy2s) can be identified by the ratios \(\log\left(\frac{[\text{OIII}]_{5007} \AA}{H\beta}\right)\) and \(\log\left(\frac{[\text{NII}]_{6583} \AA}{H\alpha}\right)\) using the diagnostic plot known as the Baldwin-Phillips-Terlevich, or BPT diagram (Baldwin et al., 1981). An example is shown in Figure 1.1 using a subset of sources from the main galaxy sample from the Sloan Digital Sky Survey (SDSS), Data Release 7 (Abazajian et al., 2009). The former ratio parametrizes ionization field hardness and the latter traces metallicity. The emission lines in each ratio are close in wavelength, minimizing the effects of reddening, where shorter wavelength emission lines are preferentially extincted. The majority of sources follow a sequence of decreasing ionization with increasing metallicity. This emission can be explained by host galaxy star formation and these sources are therefore known as quiescent, or star-forming galaxies. The upper line in Figure 1.1 represents the theoretical maximum starburst line from Kewley et al. (2001), where the emission in objects above this line can not be explained by star formation processes. “Pure” Sy2s live in this parameter space. Kauffmann et al. (2003) defined an empirical boundary based on where sources start to deviate from the sequence of star-forming galaxies, shown as the bottom curve. The sources between these two boundaries are referred to as composites: though star-formation can not be ruled out as being responsible for the emission, a comparable amount of nuclear activity may also be likely, moving these sources off the sequence of star-forming galaxies and closer to AGN.

The obscuring medium enshrouding the AGN absorbs optical and UV accretion disk photons and re-radiates the emission in the IR. The mid-infrared (MIR) emission constitutes 20\% of the bolometric flux for both type 1 and type 2 AGN (Spinoglio & Malkan, 1989). AGN can thus be identified based on their IR emission, providing a useful tool for selecting those sources where the optical and UV emission are blocked from the line of sight due to the obscuring “torus.” These identification methods include selecting AGN based on a minimum flux density, with optical spectroscopy to confirm the AGN nature (e.g. \(F_\nu > 0.3\) Jy at 12\(\mu\)m, Spinoglio & Malkan (1989)); mid-IR color from Spitzer photometry, using ratios of flux densities (Lacy et al., 2004) or the difference in flux densities (Stern et al., 2005); a power-law shape of the mid-infrared spectral energy distribution (Donley et al. (2007), Donley et al. (2010)); or
a large ratio of IR to optical flux (e.g. Dey et al. (2008), Houck et al. (2005), Yan et al. (2005), Weedman et al. (2006)).

X-ray emission in AGN is thought to form in a hot corona around the accretion disk. Electrons in the corona inverse-Compton scatter optical and UV accretion disk photons to higher (i.e. X-ray) energies. These X-rays can readily pierce through the obscuring medium, provided that the column density of the “torus” is not Compton-thick (i.e. $N_H \geq 1/\sigma_t = 1.5 \times 10^{24}$ cm$^{-2}$, where $\sigma_t$ is the Thomson cross section). Extinction due to the host galaxy also generally has a negligible impact on X-ray attenuation. Subsequently, X-ray selection can be a valuable tool for identifying AGN. Deep X-ray surveys from Chandra and XMM-Newton ($E = 0.5 - 10$ keV) and wide surveys from Swift-BAT ($E = 14 - 195$ keV) have been successful in revealing thousands of AGN (Tozzi et al. (2001), Alexander et al. (2003), Giacconi et al. (2002), Hasinger (2004), Mainieri et al. (2007), Corral et al. (2011), Tueller et al. (2010)).

These different selection methods have various biases. Dusty host galaxies can attenuate the optical emission lines (e.g. [OIII]5007Å ) used to identify AGN, thus causing some AGN to be missed. AGN samples selected by IR methods can be contaminated by star-forming galaxies. X-ray emission will be extincted in Compton-thick sources due to both photo-electric absorption of X-ray photons and Compton scattering of photons out of the line of sight. Even hard X-ray surveys will then be biased against the Compton-thick population.

1.2 X-ray Background

In the 1960s, it was discovered that the night sky was bathed in soft X-ray radiation (Giacconi et al., 1962), an emission now known as the X-ray background (XRB). With the deep field surveys of Chandra and XMM-Newton (Alexander et al. (2003), Giacconi et al. (2002), Hasinger (2004)), it has become clear that this emission is extragalactic in origin. Indeed, the majority of the 0.5 to 8 keV emission has been resolved into individual point sources, largely AGN (Hickox & Markevitch, 2006). However, the resolved portion of the XRB decreases with energy, leaving the peak of
the XRB at 30 keV unresolved. Accounting for the sources responsible for this unresolved peak is necessary to more accurately constrain the AGN luminosity function, providing valuable insight into the energy released via accretion over cosmic time.

As the integrated emission from unobscured and Compton-thin AGN fail to explain the 30 keV peak of the XRB, a significant fraction of Compton-thick AGN are often invoked to accommodate this unresolved emission: modeling of Compton-reflection in these heavily obscured sources demonstrate that their emission peaks at 30 keV (Magdziarz & Zdziarski, 1995). However the exact number of Compton-thick sources required by the XRB is a matter of debate. Gilli et al. (2007) explored the parameter space for Compton-thin AGN by varying the mean X-ray spectral index. They demonstrated that this can increase the Compton-thin contribution to the XRB by \(\sim 30\%\), but this still under-predicts the 30 keV peak. They therefore conclude that a sizable population of Compton-thick AGN, on the same order of moderately obscured AGN, is therefore necessary. Conversely, Treister et al. (2009) pointed out that model parameters of the XRB are degenerate and can rely heavily on input parameters that may be poorly constrained, such as the normalization of the Compton reflection component. The number of Compton-thick AGN can then not be accurately determined by XRB synthesis models. They fix the Compton-thick AGN fraction based on the number of Compton-thick AGN detected in Swift and INTEGRAL surveys, which are sensitive to energies above 10 keV and should ideally represent an unbiased estimate of heavily and mildly obscured sources. Treister et al. (2009) demonstrate that the XRB can be accurately fit using a 9\% fraction of Compton-thick AGN, rather than the \(\sim 20\%\) fraction claimed by Gilli et al. (2007). However, the Treister et al. (2009) Compton-thick numbers are based on high energy X-ray surveys which may not provide a fair sampling of the heavily obscured population (e.g. Weaver et al. (2010)).
1.3 Co-evolution of AGN and Host Galaxies

One of the most impressive discoveries over the past decade has been the tight correlation between the mass of SMBHs and the velocity of stars in their galactic bulges, the so-called $M-\sigma$ relation (Ferrarese & Merritt (2000), Gebhardt et al. (2000), Tremaine et al. (2002)). Such a correlation points to a co-evolution of SMBHs and their host galaxies. One model that describes mechanisms responsible for this link include mergers of galaxies which can propel gas into central SMBH while triggering star formation (e.g. Hopkins et al. (2008)). Other explanations include “secular” evolution where the black hole is fed and star formation is turned on by spiral arms or galactic sized bars funneling gas to the galactic center (e.g. Kormendy & Kennicutt (2004), Cisternas et al. (2011), Schawinski et al. (2011)).

Seyfert 2 galaxies provide an ideal laboratory for exploring the connection between AGN activity and starbursts. As these sources are local and the accretion disk is blocked from view, the host galaxy can be studied in detail while signatures of AGN activity can also be easily observed.

1.4 Areas of Exploration

This work addresses the issues discussed above, focusing on the study of Seyfert 2 galaxies to address the following themes:

1. What methods best locate heavily toroidal obscured AGN while fairly sampling the unabsorbed population? To what extent are diagnostics of the intrinsic AGN power truly isotropic? In order to most accurately probe accretion throughout cosmic history, the unresolved emission of the XRB has to be better understood. Constraining the number of Compton-thick AGN is an important piece to this puzzle, and sample selection to find such sources ought to be based on robust indicators of inherent AGN flux. These intrinsic luminosity proxies also provide value insight into the physical nature of the AGN and can be used to probe not
only the inherent power of the source, but also the accretion rate, or the rate at which the supermassive black hole feeds and grows.

2. What fraction of unbiased samples of Seyfert 2 galaxies are potentially Compton-thick? Are these sources unique in terms of their AGN properties? Do they inhabit unique host galaxies in terms of star formation, suggesting an interplay between toroidal obscuration and the gas responsible for engendering star birth? If there is a link between toroidal obscuration and AGN or host galaxy characteristics, and heavily obscured sources are under-represented in current samples, then our knowledge about AGN in general and the link between AGN and their parent galaxies can be subsequently skewed.

3. Can we find an empirical link between host galaxy star formation and AGN activity, which would indicate a common mechanism for the growth of a galactic bulge while feeding the SMBH? In order to address this issue, we must first identify parameters that cleanly describe star formation in both quiescent and active galaxies and are not biased by AGN emission. For diagnostics that have contributions from both starburst and AGN activity, can we reliably disentangle these two processes? Which parameters most effectively quantify the relative contributions of these two processes and do they agree among multiple wavelength bands?

We address the first question in the following chapter, using two samples of Sy2s selected based on parameters that trace the inherent AGN power. These homogeneous samples are complete to a certain flux limit, providing 51 Sy2s to study, and to first order, unbiased in terms of system orientation and column density of the obscuring medium. To probe the amount of toroidal obscuration present in these AGN, we utilize 2-10 keV X-ray analysis on a subset of these samples. We present the X-ray reduction and analysis techniques in Chapter 3 and discuss the results in Chapter 4. However, since this energy band is below 10 keV and therefore misses a telltale mark of Compton reflection (i.e. the peak in the X-ray spectrum at 30 keV), we are unable to confirm if any individual source is indeed Compton-thick but instead
identify candidates that harbor signatures of heavy obscuration. Using an extend sample of \(\sim 250\) star-forming galaxies, \(\sim 50\) composites and an additional \(\sim 20\) Seyfert 2s, in Chapter 5 we explore the unique multi-wavelength parameter space in which these sources live, addressing the third theme above. In Chapter 6, we look ahead to what insight future missions will bring to our understanding of the hidden Compton-thick population and the link between AGN activity and star formation.
Figure 1.1 BPT diagram: a diagnostic plot used to separate Sy2s from star-forming galaxies. The upper line represents the theoretical maximum starburst line from Kewley et al. (2001). Objects above this line are Sy2s. The bottom curve is an empirical boundary from Kauffmann et al. (2003). Objects below this line are star-forming galaxies. The sources between these two boundaries are composites.
Chapter 2

Intrinsic AGN Flux Proxies

How can unbiased samples of AGN be selected? Ideally, selection criteria should not be affected by toroidal obscuration, AGN inclination, or host galaxy contamination. Such features should also be easily measurable to enable detection at a significant level. Various emission fluxes have been claimed to accurately trace the intrinsic AGN power. These diagnostics can not only be used to select complete and relatively unbiased samples of AGN, but can also provide into the the physical characteristics of AGN, such as the accretion rate of the central supermassive black hole. Here, we undertake an empirical approach in comparing various proxies of intrinsic AGN flux used in the literature to determine which diagnostics may be most reliable.

The AGN Narrow Line Region extends hundreds of parsecs away from the central source and is therefore not significantly affected by torus obscuration. The luminosities of emission lines formed in the NLR can therefore be used as isotropic indicators of intrinsic AGN power. The flux of the [OIII]λ5007 line is commonly used as such a diagnostic (e.g. Bassani et al. 1999, Heckman et al. 2005) as it is one of the most prominent lines and suffers little contamination from star formation processes in the host galaxy. This line can be attenuated by dust in the host galaxy, though this effect can be somewhat remedied by applying a reddening correction using the observed Balmer decrement (i.e. the observed ratio of the narrow Hα/Hβ emission-lines compared to the intrinsic ratio) and the extinction curve for galactic dust (Osterbrock & Ferland, 2006).
Isotropic indicators of AGN luminosity also exist in the infrared band and are much less affected by dust extinction than the optical [OIII] line. Recently, the luminosity of the [OIV] 25.89\(\mu\)m line has been shown to be a robust proxy of AGN power (e.g. Meléndez et al. 2008, Rigby et al. 2009, Diamond-Stanic et al. 2009): it is formed in the NLR, so it is not affected by torus obscuration, and with an ionization potential of 54.9 eV, starburst activity does not significantly contribute to this line. AGN also emit over 20% of their bolometric flux in the mid-infrared (MIR), where photons produced by the continuum are absorbed by the torus and re-radiated (e.g. Spinoglio & Malkan 1989). This MIR emission from the dusty torus can also be a proxy for the intrinsic AGN luminosity. Two potential issues with the MIR continuum are contamination by emission from dust heated by stars (e.g. Buchanan et al. 2006; Deo et al. 2009) and possible anisotropy in the torus emission (e.g. Pier & Krolik 1992, Buchanan et al. 2006, Elitzur & Shlosman 2006, Nenkova et al. 2008).

Radio and hard X-ray (E > 10 keV) flux can serve as proxies of the intrinsic AGN continuum. Radio emission has been shown to be similar between type 1 and type 2 AGN (e.g. Giuricin et al. 1990, Diamond-Stanic et al. 2009, Meléndez et al. 2010) and correlated with optical luminosity, in particularly the [OIII] flux (Xu et al., 1999), making high resolution radio observations that isolate emission from the nucleus another diagnostic of intrinsic AGN power. Hard X-rays can pierce through the obscuring torus, provided that the object is not heavily Compton thick (\(N_H < 10^{25}\) cm\(^{-2}\)), and has therefore been used as a method to select AGN samples (e.g. Winter et al. 2008, Treister et al. 2009).

For this analysis, we use two complete and homogeneous Sy2 samples selected based on isotropic indicators of AGN luminosity (one [OIII]-selected sample and one MIR-selected sample). We compare the various diagnostics of intrinsic AGN luminosity and probe for biases resulting from sample selection criteria, starburst contamination, errors introduced from extinction correction, and scatter due to the various physical mechanisms producing these emission features. Such biases are likely minimized in the diagnostic ratios with the smallest dispersion. Where available, we compare these ratios with the Sy1 values to probe for differences due to the inclination of the system, thus testing to which extent these indicators of intrinsic AGN lumi-
nosity are truly “isotropic.” We also examine the possibility that the fraction of the AGN ionizing luminosity that is converted into [OIII] and [OIV] emission is systematically higher in systems in which there is a copious supply of dense gas associated with starburst activity.

2.1 Sample Selection

Our [OIII]-sample is drawn from a parent sample of the spectra of roughly 480,000 galaxies in the SDSS Data Release 4 = DR4 (Adelman-McCarthy et al., 2006). This parent sample of “SDSS Main Galaxies” (Strauss et al., 2002) is complete over the SDSS DR4 footprint and is selected solely on the basis of the galaxy r-band apparent magnitude (14.5 < r < 17.77). The diagnostic line ratio plot of [NII]/Hα vs. [OIII]/Hβ in Kauffmann et al. (2003 hereafter K03) and Kewley et al. (2001) was used to identify Type 2 AGN based on the SDSS spectra. Our sample was then defined as the 20 such objects having an observed [OIII]λ5007 flux above 4×10^{-14} erg cm^{-2} s^{-1}, corresponding to a luminosity of ~10^{41} erg/s at the median distance for our sample (~150 Mpc).

The mid-IR sample comprises the Seyfert 2 galaxies from the original IRAS 12µm survey (Spinoglio & Malkan, 1989). These Sy2s were selected via a weak color cut (i.e. 12µm flux less than the 60 or 100 µm flux) and is complete down to a flux-density limit of 0.3 Jy at 12 µm with latitude |b| > 25° to avoid contamination from the Milky Way. We have dropped NGC 1097 from this original sample as it has since been classified as a Type 1 Seyfert (Storchi-Bergmann et al. 1993), leaving 31 mid-IR selected Sy2s (hereafter the “12µm sample,” listed in Table 2.2).
2.2 Data Analysis

2.2.1 Optical Data

The optical data for the [OIII]-sample were drawn from SDSS DR4, whereas the optical data for the 12µm sample were collected from the literature or from SDSS Data Release 7 (DR7) where available. The reddening corrected [OIII] flux ($F_{[OIII], corr}$) was calculated using the observed Hα/Hβ ratio and an intrinsic ratio of 3.1 with R=3.1 extinction curve for galactic dust (Osterbrock & Ferland, 2006). Tables 2.3 and 2.4 list the optical emission line fluxes and ratios utilized for this study, as well as the relevant literature citations for the 12µm sample. The black hole masses ($M_{BH}$) were derived for the [OIII] sample by the SDSS velocity dispersion ($\sigma$) and the M-σ relation ($M_{BH} = 10^{8.13} (\sigma/200 \text{ km s}^{-1})^{4.02} M_\odot$, Tremaine et al. 2002). We used literature values for $M_{BH}$ for the 12µm sources, with most of the masses derived using the M-σ relation cited above. For F04385-0828, F05189-2524 and TOLOLO 1238-364, the full width half max (FWHM) of the [OIII] line was used as a proxy for the velocity dispersion (Wang & Ahang 2007, Greene & Ho, 2005), and photometry of the host galaxy was used to estimate $M_{BH}$ for F08572+3915 (see Veilleux et al. 2009 for details).

2.2.2 Infrared Data

The infrared data presented here were obtained from the Infrared Spectrograph (IRS, Houck et al. 2004) on board the Spitzer Space Telescope. Low-resolution spectra were obtained using the Short-Low (SL, $3.6'' \times 57''$ aperture size) and the Long-Low (LL, $10.5'' \times 168''$ aperture size) modules and high-resolution spectra were provided by the Short-High (SH, $4.7'' \times 11.3''$ aperture size) and the Long-High (LH, $11.1'' \times 22.3''$) modules.

The Sy2s in the [OIII]-sample were observed in IRS staring mode in both high and low resolution under Program ID 30773. For the 12-µm sample, high resolution data existed for all 31 Sy2s but low resolution data were only available for 30 galaxies (IRAS 000198-7926 lacked low resolution data). The high resolution data were obtained in
IRS staring mode for 30 of the Sy2s (NGC 5194 had only IRS spectral mapping mode high-resolution data in the archive). Several galaxies had multiple IRS observations: we analyzed these observations independently and compared our results between the two observations. For the low-resolution data, IRS staring mode was used when available with the remainder observed in IRS spectral mapping mode. The Spectral Modeling Analysis and Reduction Tool (SMART, Higdon et al. 2004) was used to reduce the staring mode observations for the 12µm-sample to be consistent with previous IRS analysis of the 12 µm sample (e.g. Tommasin et al. 2008, Wu et al. 2009, Buchanan et al. 2006), Spitzer IRS Custom Extraction (SPICE) was used to analyze the staring mode observations for the [OIII]-sample\(^1\), and the Cube Builder for IRS Spectra Maps (CUBISM, Smith et al. 2007a) was utilized to analyze the spectral mapping observations. Table 2.5 lists the Program ID(s) for each galaxy, the IRS mode used, and spectral extraction area for low-resolution spectral mapping mode data (discussed below).

### 2.2.2.1 High-Resolution IRS Staring Spectra

We used the basic calibrated data (BCD) pipeline products as the starting point for our analysis. Rogue pixels were removed using the IDL routine IRSCLEAN, MASK and the rogue pixel mask matching the campaign number of the observation. Dedicated off-source background observations were taken for all sources in the [OIII]-sample and for most of the Sy2s in the 12µm sample. Multiple background observations, if present, were coadded within each nod and subsequently subtracted from the source image. The background-subtracted source images were then coadded between the two nods. The galaxies in the 12µm sample that had dedicated background observations and thus were background subtracted are marked with a “b” in Table 2.5. For sources in the 12µm sample without dedicated off-source observations, no background subtraction was performed.

Spectra were extracted from these combined observations, using the full aperture

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\(^1\)Though the IRS staring data for the 12µm sample was reduced using SMART and the [OIII]-sample with SPICE, the effect of the different reduction software is expected to be negligible on the derived parameters used in this analysis.
extraction mode. The edges of each order were then inspected, removing any data points that fell outside of the calibrated range for that order (IRS Data Handbook, Version 3.1, Table 5.1). The orders were then combined using a 2.5-σ clipping mean, resulting in a final cleaned spectrum.

### 2.2.2.2 Low-Resolution IRS Staring Spectra

The low-resolution data were processed in a similar fashion as the high-resolution data, i.e. we started with the BCD products and removed the rogue pixels with IRSCLEAN\_MASK. However, for these observations a background data set was built for each nod and order by coadding the off-source order and nod position. The background-subtracted nods (following the same procedure as above) were combined for each order and the spectra then extracted using tapered column extraction. The orders were combined using a 2.5-σ clipping average. This procedure was executed separately for the SL and LL module. Fourteen of our galaxies had low resolution IRS staring mode data; the rest were acquired in spectral mapping mode. We note that IRAS 00198-7926 did not have archival low resolution spectral data.

### 2.2.2.3 Spectral Mapping Spectra

The IRS spectral mapping observations were analyzed with CUBISM (Smith et al., 2007a), which uses the BCD data to create 3-D spectral cubes (one spectral dimension and 2 spatial dimensions). For the low resolution data, background observations were built from the other order of the on-source module (e.g. SL 2 was used as the background for SL 1, etc.). After the rogue pixels were removed, using the default “autogen bad pixels” option in CUBISM, a spectral cube was built. Spectra were then extracted using matched apertures among the detectors and centered on the nucleus. The aperture extraction size for these low-resolution spectral mapping observations are listed in Table 2.5. The low resolution spectral mapping data for NGC 1068 was saturated near the nucleus and consequently not included in this analysis.

For the IRS spectral mapping high resolution observation of NGC 5194, no background subtraction was performed. The spectrum was extracted over the full cube,
corresponding to a size of 31.5” × 45” in the LH module and 13.8” × 27.6” in the SH module.

2.2.3 Radio and Hard X-ray Data

The radio and hard X-ray data were drawn from the literature; VLA radio data at 8.4 GHz were only available for the 12µm sample (Thean et al. 2000). In several cases, multiple radio components were analyzed; we included only the flux for the component that was nearest the published center of the galaxy. Twenty-six of the 31 12µm sources had radio data, with 3 additional sources having upper limits. The hard X-ray fluxes originated from the 22-month Swift-BAT Sky Survey (Tueller et al., 2010) and from BeppoSax (Dadina, 2007). Only 11 out of the 31 12µm sources and one of the 20 [OIII] sources (IC 0486) have X-ray detections in the 14-195 keV range. We adopted an upper limit of 3.1 × 10^{-11} erg cm^{-2} s^{-1}, the flux limit of BAT, for the remainder of the sample when an upper limit was not quoted in either Tueller et al. (2009) or Dadina et al. (2007).

2.3 Measurements

2.3.1 IR Emission Line Fluxes

The high resolution spectra were utilized to measure the emission line fluxes: a Gaussian profile was fit to the emission line feature, with the local continuum, centered on the line’s rest-frame wavelength, fit by a zero- or first-order polynomial. The errors were estimated by calculating the root-mean-square (RMS) around this local continuum, re-binned by the full width half maximum of the fitted emission line. The fitted flux had to be at or greater than the 5σ level in order to be considered detected. In the cases where an emission line was not present, a 5σ upper limit was estimated from the RMS around the best-fit local continuum, re-binned by the instrumental resolution at that wavelength (i.e. \( \nu_{\text{nom}}/600 \), where \( \nu_{\text{nom}} \) is the nominal wavelength of the emission feature). In the cases with multiple observations per
galaxy, we measured the emission line fluxes independently and averaged the resulting values; these flux measurements agreed within several percent between most of the individual observations, with at most a factor of $\sim 1.5$ discrepancy, which was only present in one of the sources.\footnote{We note that NGC 1143/4 has two high resolution archival observations, one centered at RA=43.8004, Dec=-0.1839, and the other at RA=43.7985 and Dec=-0.1807, a distance of $\sim 13.4''$. We present the line fluxes from the first region as this corresponds to NGC 1144 which is classified as a Sy2 in SIMBAD. The optical data are for NGC 1144 as well.}

Tables 2.6 and 2.7 list the emission line flux values for the [OIII] and 12$\mu$m samples, respectively. Comparing our line flux values with Tommasin et al. (2008, 2010), we find that our [OIV] flux values largely agree within a factor of 1.5 (with the exception of NGC 1667 and NGC 7582 where their values are a greater than a factor of 2 higher than ours). However, their [NeII] flux values are generally systematically higher by a factor of $\sim 2.5 - \sim 4.5$, though we do obtain consistent values for NGC 424, NGC 5135 and NGC 5506. Despite these differences in the measured [NeII] line strength, we obtain similar results to Tommasin et al. (2010), namely that as the relative contribution of the AGN to the ionization field increases (parametrized by [OIV]/[NeII]), the starburst strength (parametrized by the PAH equivalent width) decreases (see Section 2.4.4).

### 2.3.2 IR Continuum Flux and PAHs

The MIR continuum flux values ($F_{MIR}$) and PAH equivalent widths (EWs) were measured using the low resolution spectra. For the galaxies that had multiple observations, we utilized the observations that had consistent flux values in the overlap region between the SL and LL modules: Program ID 30572 for For NGC 1386, NGC 4388, NGC 5506 and NGC 7130; Program ID 0086 for NGC 5135; and Program IDs 00086 and 30572 for NGC 5347 (for this source, the analysis was done separately for each observation and the results averaged together). The MIR continuum flux was measured at 13.5 $\mu$m (rest-frame), averaged over a 3$\mu$m window; these flux values are listed in Table 2.6 for the [OIII]-selected sample and Table 2.7 for the 12$\mu$m sample. This window was chosen as it is free from strong emission line and PAH features.\footnote{Though this range does include the [NeII] 12.81$\mu$m line, in most cases this comprises less than 1% of the MIR flux, with the exception of NGC 7582 where the [NeII] line is $\sim 1.5\%$ of the MIR}
We used PAHFIT (Smith et al, 2007b) to measure the PAH EWs, a program which uses a model consisting of several components: a starlight component represented by blackbody emission at $T = 5000$ K, a thermal dust continuum constrained to default temperature bins ($35, 40, 50, 65, 135, 200$ and $300$ K), IR emission lines, PAH (dust) features and extinction (we used a foreground extinction screen). As PAHFIT requires a single stitched spectrum, the SL spectrum was scaled to match the LL spectrum, with typical adjustments under 20% (though several galaxies were adjusted by ~40% and NGC 7582 by greater than a factor of 6, indicating the presence of extended IR emission in this object). Here we utilize the EW of the PAH features at $11.3\mu$m and $17\mu$m, which consist of the features within the wavelength range $11.2$-$11.4\mu$m and $16.4$-$17.9\mu$m, respectively (Tables 2.6 and 2.7). However, we note that the current version of PAHFIT has a bug which assumes the PAH EW feature to be Gaussian rather than Drude, which could underestimate the PAH EW by a factor of 1.4. We report the EWs as reported from PAHFIT, with the caveat that these may be lower limits.

We compared our results with the $11.2\mu$m feature from Wu et al. (2009) and the $11.3\mu$m and $17\mu$m features measured by Gallimore et al. (2010), where in the latter, we added their published $11.2\mu$m and $11.3\mu$m EW values. Wu et al. employed a spline fit between $10.8\mu$m and $11.8\mu$m to measure the EW. With this method, the results are widely influenced by the choice of anchor points for fitting the pseudo-continuum and can result in an underestimate of the EW compared to a method that utilizes spectral decomposition, such as PAHFIT (Smith et al, 2007b). Of the 28 sources we have in common with Wu et al. (2009), 12 of them had consistent $11.3\mu$m EW values (within a factor of 2), 6 had lower values than we obtained (which would be expected from the disagreements between the spline vs. decomposition methods mentioned above) and 10 had higher values, where for 6 of these, PAHFIT had obtained an EW value of zero, yet the spline method yielded a measurement. Comparing our results with Gallimore et al. (2010) gave better results, though a discrepancy did still exist: of the 23 sources in common, we obtained consistent EW
values (within a factor of 2) for 11 sources at 11.3\(\mu\)m and for 12 sources at 17\(\mu\)m. Though Gallimore used PAHFIT to measure these features, they modified the code to include more fine-structure lines, fit silicate emission features, and use the cold dust model from Ossenkopf et al. (1992); they also generated their own software to build spectral data cubes whereas we employed CUBISM. Such differences could account for the inconsistencies in our PAH EW measurements. Though the derived EWs are different from those reported by Wu et al. and Gallimore et al. for at least half the sources we have in common, our main conclusions based on PAH EWs (see Section 2.4.4 and Chapter 5) agree qualitatively with Wu et al. and Gallimore et al.: PAH features are associated with other star formation activity indicators (Gallimore et al. 2010, Wu et al. 2009) and the EWs are inversely correlated to the strength of the ionization field (Wu et al. 2009 where they use the IRAS colors to parametrize AGN strength).

In the discussion that follows, we divide the 12\(\mu\)m-sample into two classes, those with weak PAH emission ("PAH-weak" sources) and those with strong PAH emission ("PAH-strong" sources, galaxies with EW > 1 \(\mu\)m in either the 11.3 \(\mu\)m or 17\(\mu\)m band, with PAH EWs detected in both bands); the strong PAH emission is likely due to starburst activity in the host galaxy (see Section 2.4.4).

2.4 Diagnostics of Intrinsic AGN Luminosity

Our goal is to evaluate the relative efficacy of the five different proxies for the AGN intrinsic luminosity under consideration in this paper. We expect that these different proxies will not agree perfectly, due to the different physical mechanisms that produce and affect the emission features as well as biases resulting from sample selection, starburst contamination, statistical errors and in some cases, uncertain application of extinction corrections. To address this, we undertake two kinds of comparisons.

First, we will use our two Sy2 samples to inter-compare these proxies in a pair-wise
fashion and measure the amount of scatter in the corresponding flux ratios. Which proxies agree best with one another? Second, we will compare these pairs of flux ratios to the corresponding values for unobscured Type 1 AGN to test which proxies are more “isotropic,” i.e. suffer the least AGN-viewing-angle dependence.

Figures 2.1 - 2.10 show the histograms of a subset of ratios for the five proxies. In each plot, the solid black line represents both samples combined, the red dashed line and green dotted-dashed line delineate the 12µm sample (“PAH-weak” and “PAH-strong” sources respectively) and the cyan filled histogram reflects the [OIII]-sample. Adjacent to these histograms are the luminosity vs. luminosity plots, showing the correlation between these indicators: the cyan asterisks represent the [OIII] sample, the red diamonds (green triangles) depict the “PAH-weak” (“PAH-strong”) 12µm sources, and the dashed black line represents the best fit from multiple linear regression analysis (i.e. the REGRESS routine in IDL), where in the figure captions, ρ is the linear regression coefficient and P_{uncorr} is the probability that the two quantities are uncorrelated. Though the distance dependence in luminosity vs. luminosity plots enhances the correlation compared to flux vs. flux plots, we employed this method as the 12µm sample lies at a systematically lower redshift, and thus have higher flux values, than the [OIII] sample. One of our main goals is to examine the dispersion in the flux ratios, where this distance dependence cancels out. In §4.3, we test if these ratios are affected by luminosity.

Where available, the values for Sy1s are included in these plots. The results are summarized in Tables 2.8 and 2.9 which lists the mean and sigma of each ratio for the combined sample and the sub-samples separately. In the histograms and luminosity plots, the upper limits are plotted but not included in the analysis of the mean and sigma (except for the ratios involving the hard X-ray flux). Since only 12 of the 51 AGN were detected in hard X-rays, we have employed survival analysis to quantify the correlations among the proxies and to calculate the mean of the ratios. This approach takes the upper-limits into account (ASURV Rev 1.2, Isobe and Feigelson 1990; LaValley, Isobe and Feigelson 1992; for univariate problems using the Kaplan-Meier estimator, Feigelson and Nelson 1985; for bivariate problems, Isobe et al. 1986).
2.4.1 Inter-Comparison of Proxies

The isotropic luminosity diagnostics that agree best, and therefore may be least subject to the uncertainties and errors discussed above, are \( F_{[\text{OIII}]_{\text{obs}}} \), \( F_{[\text{OIV}]} \) and \( F_{\text{MIR}} \). A wider spread is present between the radio and hard X-ray fluxes compared with the optical and MIR values.

In all cases, a wider dispersion is present between all the flux ratios in the 12\( \mu \)m sample as compared to the [OIII] sample. Below, we examine whether such a scatter could be due to aperture effects, extinction corrections applied to the [OIII] flux, starburst contamination to the the MIR flux or if it represents a real difference between AGN selected on the basis of [OIII] flux versus MIR flux.

Since the 12\( \mu \)m Sy2s are typically more nearby than the [OIII]-selected galaxies, aperture effects can potentially play a significant role when comparing flux values by either missing NLR flux or obtaining too much host galaxy contamination. However, we find no evidence in our data for such an effect (see Appendix A). Another possible explanation for this wider dispersion is that the optical data for the 12\( \mu \)m sample are drawn from the literature, which can introduce scatter into the optical diagnostics as such data are not taken and reduced in a uniform matter. The most striking example of this is the comparison of the [OIV] flux with the observed and extinction corrected [OIII]-flux: de-reddening the [OIII]-flux widens the dispersion in the 12\( \mu \)m-sample (see Figure 2.1). This can be an artifact of using literature H\( \alpha \) and H\( \beta \) values and to a lesser extent can be due to large amounts of dust in the host galaxies of the 12\( \mu \)m sample as evidenced by the wide range of Balmer decrements. Goulding and Alexander (2009) note that galaxies that would not be identified optically as AGN (i.e. have a low “D” value, see Section 2.4.4) tend to have similar Balmer decrements yet higher \( F_{[\text{OIV}]/F_{[\text{OIII}], \text{obs}}} \) ratios than optically identified AGN. This result suggests that applying a reddening correction using the Balmer decrement still under-represents the intrinsic [OIII] flux. However, our 12\( \mu \)m sources with lower “D” values (<1.2) do not show systematically higher \( F_{[\text{OIV}]/F_{[\text{OIII}], \text{obs}}} \) ratios, indicating that “extra” extinction that Goulding and Alexander observe in their sources is not present in ours. As shown in Figure 2.11, the ratio of \( F_{[\text{OIV}]/F_{[\text{OIII}], \text{obs}}} \) increases with
Hα/Hβ, denoting that both quantities trace host galaxy extinction, though with wide scatter. Comparison with the locus of points for the [OIII] sample shows that the Balmer decrement is systematically higher for similar 12μm F_{[OIV]}/F_{[OIII],obs} values, suggesting that the the 12μm Balmer decrements are over-estimating the amount of dust present rather than under-estimating. This result indicates that the literature Balmer decrements, which are not analyzed in a systematic and homogeneous way, are introducing uncertainties that bias the results and do not better recover the truly intrinsic AGN luminosity.

However, this can not be the only cause of the greater scatter in the 12μm sample, since the ratio of MIR/[OIV] fluxes shows more scatter in the 12 μm sample (Figure 2.3), though these data were analyzed homogeneously. Could the presence of Sy2s in the 12μm sample that have significant contributions from starburst activity create the wider dispersion in these diagnostics? To address this issue, we isolated the “PAH-strong” sources, which have greater amounts of star formation activity (discussed in detail below). The distributions between the “PAH-strong” and “PAH-weak” sub-samples are similar, suggesting that starburst processes are not responsible for the wider dispersion. We also focused on sources with a limited “D” value, which as noted above indicates the relative contribution of AGN to starburst activity. Repeating the calculation of mean and standard deviations on the flux ratios for the 12μm sources with 1.2 ≤ D ≤ 1.7 did not result in a significant decrease (a factor of 2 or more) in the dispersion with the exception of log (F_{MIR}/F_{[OIII],obs}) (σ=0.42 dex), log (F_{[OIII],obs}/F_{8.4GHz}) (σ=0.56 dex) and log (F_{[OIII],corr}/F_{8.4GHz}) (σ=0.49 dex). For these first two ratios, this is largely due to the removal of the 3 outliers (F04385-0828, F08572+3914 and Arp 220) with systematically higher (lower) F_{MIR}/F_{[OIII],obs} (F_{[OIII],obs}/F_{8.4GHz}) values from the full sample. The dispersions for the other ratios were still systematically higher than the [OIII]-sample. We conclude that there is a real difference between the AGN selected on the basis of [OIII] emission-lines and MIR continuum.

We also compared our results with two other samples of Seyfert 2 galaxies: one a complete sample down to a flux limit of (1-3) ×10^{-11} erg cm^{-2} s^{-1} at 14 - 195 keV drawn from the 3 and 9 month Swift-BAT survey (Meléndez et al. 2008 and references
therein) and the other drawn from the revised Shapley-Ames catalog (Shapley & Ames 1932; Sandage & Tammann 1987), consisting of galaxies with $B_T \leq 13$ (Diamond-Stanic et al., 2009). Here we include those radio quiet Seyfert types 1.8 - 2 that have measured [OIII] and [OIV] fluxes, giving 12 and 56 Sy2s, respectively. The log of the ratios of [OIV] to [OIII],obs for both samples are higher than our combined sample, $0.60 \pm 0.74$ dex (Meléndez et al. 2008) and $0.57 \pm 0.67$ dex (Diamond-Stanic et al. 2009) vs. $0.09 \pm 0.41$ dex, but the differences are not statistically significant.

A wider dispersion is present in these comparison samples than the [OIII]-selected sample (as was the case for the 12$\mu$m sample). This may indicate that selection based on [OIII] leads to better agreement between between the [OIII] and [OIV] flux rather than selection based on other methods. This effect could be due to the [OIII]-bright sources having less extinction in the NLR than Sys selected in other ways.

As the samples in Weaver et al. (2010) and Winter et al. (2010) samples were selected based on their hard (14-195 keV) X-ray flux from the Swift-BAT 9 month (Winter et al., 2010) and Weaver et al., 2010) and 22 month (Weaver et al., 2010) catalog, we can compare our Sy2 X-ray flux ratios. Using the values in Winter et al. (2010), we find log ($F_{14-195keV}/F_{[OIII],obs}$) = $2.76 \pm 0.59$ dex and log ($F_{14-195keV}/F_{[OIII],corr}$) = $2.34 \pm 0.69$ dex for Sy2 galaxies. The log ($F_{14-195keV}/F_{[OIV]}$) ratio from Weaver et al. (2010) for Sy2s is $2.38 \pm 0.45$ dex. All three values are systematically higher than what we obtain for our samples of Sy2 galaxies by roughly an order of magnitude (see Table 2.9). This is depicted graphically in Figure 2.12. Employing survival analysis, we compared these ratios between the BAT-selected Sy2s and the [OIII] and 12$\mu$m samples separately and find that they differ significantly (i.e. $p < 0.05$, corresponding to the 2$\sigma$ level, that they are drawn from the same parent population), with the caveat that with only one [OIII] Sy2 detected by BAT, the comparison between BAT and [OIII] selected Sy2s may be less robust. These differences suggest that the samples selected in hard X-rays do not fairly sample the population of Type 2 AGN selected in the MIR and possibly the optical, however comparisons with BAT-selected Sy1s

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4We note that for the cases where the Winter et al. 2010 Balmer decrement was less than the assumed intrinsic value (3.1), we did not apply a reddening correction, but rather used the observed value, both here and in §4.2.
reveal mixed results (see Section 2.4.2).

### 2.4.2 Comparison with Sy1s

In order to determine if the proxies we are considering are affected by the orientation of the AGN, and to evaluate the extent to which they may be considered truly “isotropic,” we compared our Sy2 results with the corresponding Sy1 values, using data taken from the literature. The Sy1 MIR fluxes were calculated from the 14.7µm flux densities reported in Deo et al. (2009), where they analyzed a heterogeneous sample of Sy1 and Sy2 galaxies available in the Spitzer archive, ranging in redshift $0.002 < z < 0.82$. The radio flux values were derived from the high-resolution 8.4-GHz flux density values from Thean et al. (2000), which presented analysis of the extended 12µm sample.\(^5\) The hard X-ray data (14-195 keV) are drawn from Meléndez et al. (2008, sample selection described above), the 22-month Swift-BAT Catalog (Tueller et al., 2010) and Rigby et al. (2009, same parent sample as Diamond-Stanic et al. 2009, with X-ray data derived from the 22-month Swift-BAT Catalog, BeppoSAX (Dadina 2007) and Integral (Krivonos et al. 2007)). The comparison Sy1 [OIII] and [OIV] flux values are derived from Meléndez et al. (2008) and Tommasin et al. (2008, 2010), which presents high resolution Spitzer spectroscopy of the extended 12µm sample. As only Winter et al. (2010) quote Balmer decrements, we only have comparison Sy1 $F_{[OIII], corr}$ values for the samples selected from the BAT catalog (i.e. $F_{14–195keV}$ and $F_{[OIV]}$ from Weaver et al. 2010). We utilize both the Kolmogorov-Smirnov test (“K-S” test) and Kuiper’s test on the detected data points (excluding the three [OIV] and three radio upper limits in the 12µm data) to determine to which extent the flux ratios are significantly inconsistent between the Sy1 and Sy2 galaxies: a lower K-S and Kuiper “D” value indicates that these two populations are drawn from the same parent population, suggesting that such fluxes are independent of viewing angle. The Kuiper test is similar to the K-S test but with the following modification: the “D” statistic of the K-S test represents the maximum deviation between the cumu-

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\(^5\)The extended 12µm sample probes to a lower flux density limit than the original 12µm sample: 0.22 Jy vs. 0.30 Jy, giving a total of 118 detected Sys over the 59 detected in the original sample (Rush et al., 1993).
lative distribution functions (CDFs) of the two samples, whereas the “D” statistic in Kuiper’s test is the sum of the maximum and minimum deviations between the CDFs of the two samples, so that this statistic is as sensitive to the tails as to the median of the distribution. The results of the K-S test and Kuiper test agree in that they do not lead us to reject the null hypothesis that the two samples are drawn from the same parent population, with the exception of the $F_{[OIV]}/F_{[OIII]}^{\text{obs}}$ and $F_{MIR}/F_{[OIV]}$ ratios, where the tests lead to conflicting results. We note that two-sample tests work better for larger data sets, so the probabilities quoted in Table 2.10 should be interpreted as approximate.

The comparisons of the Sy2 and Sy1 samples are shown in Figures 2.1 through 2.10. In each, the dotted-dashed and (in the cases of more than one comparison sample) dashed line(s) on these plots indicate the mean values for the Sy1 diagnostic ratios and the correlations from linear regression we calculated from the literature values.

A mild disagreement between the average Sy1 and Sy2 $F_{[OIV]}/F_{[OIII]}^{\text{obs}}$ and $F_{MIR}/F_{[OIV]}$ ratios (up to a factor of $\sim 2$) are evident. We obtain mixed results as to the significance of this difference based on the statistical test used: according to the K-S test, the $F_{[OIV]}/F_{[OIII]}^{\text{obs}}$ and $F_{MIR}/F_{[OIV]}$ ratios for the Sy1 and Sy2 populations are statistically significantly different ($D=0.355$, $p=0.009$ and $D=0.415$, $p=0.006$, respectively), but not according to the Kuiper test ($D=0.364$, $p=0.065$ and $D=0.393$, $p=0.087$, respectively). We find similar disparate results when we run these tests on the $F_{[OIV]}/F_{[OIII]}^{\text{obs}}$ ratio for the detected points between the Sy1s and Sy2s in the Meléndez et al. (2008) and Diamond-Stanic et al (2009) samples, namely that the K-S test implies different parent populations ($p=0.005$ and $p=0.004$, respectively) but not the Kuiper test ($p=0.097$ and $p=0.126$, respectively). Meléndez et al. (2008) and Diamond-Stanic et al. (2009) (as well has Haas et al. 2005, who compared seven quasars with seven Fanaroff-Riley II (FRII) radio galaxies) have reported significant differences between the observed [OIII] and [OIV] flux between Sy1s (quasars for Haas et al. 2005) and Sy2s (FRIIs for Haas et al. 2005), with the type 2 sources having higher $F_{[OIV]}/F_{[OIII]}^{\text{obs}}$ ratios. These authors have attributed the diminution of [OIII] in type 2 AGN to extinction in the NLR. Baum et al. (2010) suggests that
such [OIII] obscuration results from the AGN torus: using the 12 µm sample, they find a correlation between the \( F_{[OIV]} / F_{[OIII],obs} \) ratio and the Sil 10µm feature, which probes torus obscuration.\(^6\) In type 1 Sy1s, this silicate feature is in emission, whereas Sy2s exhibit Sil absorption, making the Sil strength a probe of system orientation. The ratio of \( F_{[OIV]} \) to \( F_{[OIII],obs} \) increases with Sil absorption (parametrized by negative values of the Sil strength) which could suggest that the torus is extincting part of the [OIII] emission. Our results may confirm these previous studies as we find that Sy2s tend to have lower observed [OIII] emission as compared to Sy1s and this may be due to NLR extinction. We note, however, that such extinction affects the [OIII] line only up to a factor of 2 on average between our Sy2 and comparison Sy1 samples, albeit with a wide dispersion, and this difference between the two populations may not be significant.

The average log \( (F_{MIR}/F_{[OIII],obs}) \) ratio is consistent between Sy1s (2.56 ± 0.50 dex) and Sy2s (2.48 ± 0.68 dex), which could seemingly contradict the results cited above where NLR extinction causes attenuation of the [OIII] flux in Sy2s but not in Sy1s. The clumpy torus model of Nenkova et al. (2008) and smooth torus model of Pier & Krolik (1992) predicts a slight anisotropy in emission at 12µm depending on viewing angle: as the viewing angle increases from 0° (Sy1) to 90° (Sy2), the torus flux decreases by a factor of ~2. The effects of depressed MIR emission in Sy2s and enhanced MIR emission in Sy1s, assuming [OIII] is more extincted in the former than the latter, would therefore result in \( F_{MIR}/F_{[OIII],obs} \) ratios that are more consistent than \( F_{[OIV]}/F_{[OIII],obs} \), which is indeed what we observe. However, the average differences between \( F_{MIR}/F_{[OIII],obs} \) and \( F_{[OIV]}/F_{[OIII],obs} \) are within the scatter of these ratio values, and we are unable to rule this out as the main driver for the disagreement, rather than invoking anisotropies in torus emission.

The \( F_{MIR}/F_{[OIV]} \) diagnostic ratio shows the smallest dispersion for the combined sample and no evidence for luminosity bias (see Section 2.4.3) which may indicate that they are the most robust proxies for the intrinsic AGN luminosity in Type 2 AGN. Though the MIR flux is not corrected for starburst contamination (see Appendix B),

\(^6\)They define the Sil strength by the natural logarithm of the observed flux of the feature divided by the interpolated continuum flux at 10µm.
and the Sy2s in the 12µm sample are thought to harbor more star formation activity than Sy1s (e.g. Buchanan et al. 2006), we see no evidence that star formation activity is contributing significantly to the MIR emission. However, as noted above, the KS test does indicate that this diagnostic ratio is significantly different from Sy1s.

The different slopes between Sy1s and Sy2s in the luminosity plots of the radio data against other intrinsic AGN flux proxies (Figures 2.4, 2.5 and 2.6) suggest disagreements between these samples. However, the $F_{[OIV]}/F_{8.4GHz}$ and $F_{MIR}/F_{8.4GHz}$ flux ratios are consistent between Sy1 and Sy2 galaxies, indicating that the disparate slopes are perhaps influenced by scatter due to the wide range of radio loudness in AGN. Results of the KS test and Kuiper’s test (Table 2.10) also indicate that the differences in the radio flux ratios between Sy1s and Sy2s are not statistically significant. Diamond-Stanic et al. (2009) compared the 6 cm radio data between Sy1s and Sy2s and found that for the Sy2s with a measured X-ray column density, these two samples show no statistically significantly differences, though they find a higher probability that they are drawn from the same distribution (~68 - 78%) than we do (~55%). Meléndez et al. (2010) also found that the 8.4 GHz and [OIV] fluxes between Sy1 and Sy2 galaxies are not significantly different, though sources dominated by star formation (i.e. less than 50% of the [NeII] line attributable to AGN ionization) had statistically different $F_{[OIV]}/F_{8.4GHz}$ values than AGN dominated sources, indicating that radio emission may not accurately trace intrinsic AGN power. This latter result may agree qualitatively with our Figure 2.5, where the “PAH-strong” sources lie at or below the best-fit line between $L_{[OIV]}$ and $L_{8.4GHz}$.

The hard X-ray proxy performs much more poorly (Figures 2.7 - 2.10), based on both the wider dispersion in the diagnostic flux ratios and the larger disagreement between the Sy1 and Sy2 flux ratios. The mean hard X-ray emission (normalized by other isotropic indicators) in Sy2s tends to be about an order of magnitude weaker than in Sy1s, though this is driven largely by the 12µm sample as only one source was detected by BAT in the [OIII] sample. This disagreement agrees with the results of Rigby et al. (2008) and Weaver et al. (2010), where the X-ray flux was normalized by the [OIV] emission. Indeed, using survival analysis, we find that $F_{14-195keV}/F_{[OIV]}$ disagrees significantly between BAT-selected Sy1s and both the [OIII] and 12µm sub-
samples. Such a large disagreement is not found between the Sy1s and Sy2s in the Winter et al. (2010) sample (see Table 2.9), which is driven by the lower [OIII] flux observed in their Sy2s as compared to their Sy1s. The hard X-ray to [OIII] flux ratios, both observed and reddening corrected, do not differ significantly between the BAT-selected Sy1s and the [OIII]-selected Sy2s, but do for the 12 µm sample.\footnote{\textit{F}_{14-195\text{keV}}/\textit{F}_{[OIII],\text{obs}} has mixed results for the 12 µm sample: according to two of the tests (Logrank and Peto & Prentice Generalized Wilcoxon Test), the difference is significant though with other tests, the null hypothesis that the two samples are drawn from the same parent distribution can only be discarded at the \sim12\% confidence level.}

According to the Logrank and Peto & Prentice Generalized Wilcoxon tests, the hard X-ray flux normalized by the MIR flux differs significantly for both Sy2 subsamples and the BAT-selected Sy1s. Consistent with the results from Section 2.4.1, hard X-ray selected AGN do not represent the population of those selected in the MIR, and there may be some evidence that they do not fully sample the optically selected sources. Compton scattering may be responsible for weakening the observed hard X-ray emission in Sy2s, as suggested by Weaver et al. (2010), which indicates that the 14-195 keV emission is not truly isotropic.

## 2.4.3 Luminosity Dependence

As we have seen above, there is significant scatter in the flux ratios of the different proxies for AGN intrinsic luminosity. Here we examine the possibility that some of this scatter is caused by systematic differences that correlate with the accretion rate of the black hole (in units of the Eddington limit).

To perform this test, for any pair of luminosity proxies we parametrized $L_{AGN}/L_{Edd}$ by the square root of the product of the luminosities of the two proxies divided by the mass of the central black hole ($M_{BH}$, listed in Tables 2.1 and 2.2). Linear regression fits were performed, with the correlation coefficients and probability of uncorrelation listed in Table 2.11.

We find two statistically significant anti-correlations (Figure 2.13): $\textit{F}_{[OIV]}/\textit{F}_{[OIII],\text{obs}}$ and $\textit{F}_{MIR}/\textit{F}_{[OIII],\text{obs}}$. The anti-correlations are largely driven by those galaxies with a high Balmer decrement. When we exclude the 6 sources with H$\alpha$/H$\beta \geq 9$, which
may be those systems with the most NLR extinction, these anti-correlations are no longer statistically significant. This may indicate that the bolometric correction to the observed [OIII] luminosity might have a weak dependence on the Eddington ratio. However, the observed [OIII] luminosity, which partly parametrizes the Eddington ratio, does not as accurately trace intrinsic AGN flux for these more dust-obscured sources. If the Eddington ratio is defined as just $L_{OIV}/M_{BH}$ and $L_{MIR}/M_{BH}$ in these relationships, the anti-correlations are no longer significant. Hence, the weak trends in Figure 2.13 a) and b) is likely driven more by NLR extinction bias on the [OIII] flux rather than the accretion rate of the black hole.

2.4.4 Are [OIII] and [OIV] Biased by Star Formation?

In this section, we investigate whether the relative fraction of the AGN bolometric luminosity that emerges in [OIII] and [OIV] line emission is preferentially higher in galaxies with more star formation. This might be expected if the gas clouds in the NLR that are photoionized by the AGN and produce these lines are directly related to the gas clouds responsible for star-formation. If true, this would imply that AGN selected using [OIII] or [OIV] would be biased towards galaxies with higher star formation rates.

To test this, we have plotted the ratio of both $F_{[OIII],obs}$ and $F_{[OIV]}$ to $F_{MIR}$ versus the indicators of the relative importance of star-formation processes vs. AGN activity. One such diagnostic involves the use of the MIR polycyclic aromatic hydrocarbon (PAH) features. These have been shown to be correlated with star formation activity (e.g. Smith et al. 2007) and possibly anti-correlated with the presence of an AGN (O’Dowd et al. 2009; Voit 1992). We used the EW of the PAH features to assess the relative amount of starburst activity in the host galaxy (e.g. Genzel et al. 1998). Another empirical diagnostic of the relative contribution of the starburst in the MIR can be parametrized by the MIR spectral index: $\alpha_{20-30\mu m}$. Larger

\[ \alpha_{\lambda_1 - \lambda_2} = \log(f_{\lambda_1}/f_{\lambda_2})/\log(\lambda_1/\lambda_2) \]
values of $\alpha_{20-30\mu m}$ indicate the presence of cold dust from starburst activity (Deo et al. 2009 and references therein). The ratio of the MIR [OIV] (ionization potential 55 eV) to [NeII] 12.81 $\mu$m (ionization potential 21 eV) emission-lines probes the hardness of ionizing spectrum and hence the relative importance of the AGN and starburst. A larger ratio (~1) implies the dominance of AGN activity whereas a lower ratio (~0.02) is pure starburst activity (Genzel et al., 1998). The analogous diagnostic from optical spectra is the distance a galaxy spectrum lies from the locus of star forming galaxies in the Baldwin, Phillips & Televich BPT (1981, BPT) diagram

$$D = \sqrt{([NII]/H\alpha + 0.45)^2 + ([OIII]/H\beta + 0.5)^2},$$

Kauffmann et al. 2003). A larger “D” parameter indicates pure AGN activity while a smaller value implies a mixture of starburst and AGN processes in the host galaxy. Figure 2.14 illustrates the agreement between [OIV]/[NeII] and these other diagnostics of the ionization field hardness: as the ionization field becomes more dominated by the AGN relative to star formation, [OIV]/[NeII] increases while the PAH EWs and $\alpha_{20-30\mu m}$ decrease and D increases. In §5.1.4, we expand on this analysis to include star-forming galaxies, composite systems and Sy2s, testing the agreement of these diagnostics over a range of radiation field hardness.

We find no strong trends between the star formation indicators and [OIV] and [OIII] emission, as illustrated in Figures 2.15 and 2.16. We therefore conclude that there is no convincing evidence that host galaxies with a large star formation rate have preferentially higher relative luminosities of [OIII] and [OIV] at the luminosities represented in this sample, where the bolometric luminosity ($L_{bol}$) ranges from $L_{bol} \approx 10^9 - 8 \times 10^{11} \, L_{\odot}$, which is $\sim3\times10^{-5}$ to 0.5 of the Eddington luminosity ($L_{edd}$)\(^9\). Thus, these proxies of intrinsic AGN power are not biased by star formation activity at these Eddington ratios.

\(^9\)We estimated $L_{bol}$ by assuming the observed mid-infrared flux constitutes 20% of the bolometric flux (Spinoglio & Malkan, 1989).
2.5 Summary

We have taken an empirical approach in analyzing the agreement among the various indicators of isotropic AGN luminosity for two complete and homogeneously selected samples of Sy2s, one selected based on observed [OIII] flux and the other on MIR flux. The diagnostic ratios with the smallest spread are likely those where such biases from sample selection, starburst contamination, statistical errors, and scatter due to the various physical mechanisms that produce these emission features, are minimized. Such indicators, as well as those that agree the most with Sy1 relations, may be the most robust tracers of AGN activity. Our results on these indicators are summarized below.

- **Sample Selection** The optically selected sample, picked on the basis of high [OIII] flux, shows tighter correlations among these diagnostics than the MIR selected sample. We investigated whether the inclusion of active star forming galaxies in the 12µm sample introduced the spread in these ratios by dividing the sample into galaxies that have large amounts of starburst activity (“PAH-strong”) and those that do not (“PAH-weak”). The distribution of the diagnostic ratios for the two sub-samples are similar. Isolating the 12µm sources with a limited D range (1.2≤D≤1.7) also results in large scatter that is systematically higher than that observed in the [OIII] sample for all but three of the flux ratios. A similarly wide spread between $F_{[OIV]} / F_{[OIII],obs}$ is present in other samples (i.e. Meléndez et al. 2008 and Diamond-Stanic et al. 2009), indicating that sample selection based on [OIII] is primarily responsible for the tighter correlations we observe. This may be due to less extinction in the NLR region which would be expected in sources that have high observed [OIII] flux.

- **Extinction Correction** Applying an extinction correction to the [OIII] flux tightens the correlations with the other luminosity indicators for the [OIII]-selected sample, yet broadens the dispersion for the 12µm sample. It is not clear whether this difference is primarily due to the different sources of the emission-line data (homogeneous SDSS data for the [OIII] sample and heterogeneous data for the 12µm sample), or whether it simply points out the limitations of extinction corrections in very dusty AGN. Comparison of the optical vs. MIR properties of the most dusty AGN in the
SDSS suggest that the former effect is important (Wild et al. 2010).

- Agreement Among Sy2s The observed \([\text{OIII}], \text{[OIV]}\) and MIR luminosities agree the best in the combined Sy2 sample. \(F_{\text{MIR}}\) and \(F_{\text{[OIV]}}\) agree the best in comparison with the other indicators in the combined Sy2 sample, having the least scatter. The widest spread among the various proxies is seen in the radio emission. The X-ray data are dominated by upper limits, but also show a significantly larger dispersion than the optical and IR isotropic flux indicators.

- Comparison with Sy1s The mean ratio of the observed \([\text{OIII]}\) to the \([\text{OIV]}\) flux nd \([\text{OIV]}\) to MIR flux is lower in Sy2 than in Sy1s by a factor of 1.5-2, while the mean ratio of the observed \([\text{OIII]}\) flux to MIR is consistent between Sy2s and Sy1s. The former result, which represents a statistically significant difference between Sy1s and Sy2s according to the KS test but not Kuiper’s test, agrees with previous findings (e.g. Haas et al. 2005, Meléndez et al. 2008, Diamond-Stanic et al. 2009) and has been interpreted as extinction affecting \([\text{OIII]}\) in the NLR, or even torus obscuration attenuating the \([\text{OIII]}\) emission (Baum et al. 2010). However, the latter result cannot be simply explained by a larger amount of dust extinction of \([\text{OIII]}\) in the Sy2s, but it could be due to a slight anisotropy in the MIR emission as predicted by Pier & Krolik (1992) and Nenkova et al. (2008) where Sy1s could have up to a factor of two higher MIR flux as compared to Sy2s. The wide scatter in these ratios can also be responsible for the discrepancy between the \(F_{\text{[OIV]}}/F_{\text{[OIII]}},\text{obs}\) and \(F_{\text{MIR}}/F_{\text{[OIII]}},\text{obs}\) values, which may be the main driver for the mild disagreement rather than torus emission anisotropy. The \(F_{\text{[OIV]}}/F_{8.4\text{GHz}}\) and \(F_{\text{MIR}}/F_{8.4\text{GHz}}\) mean values are consistent between Sy1 and Sy2 galaxies (in agreement with Diamond-Stanic et al. 2009 and Meléndez et al. 2010 for the \([\text{OIV}]\) and radio comparison), though the slopes of the luminosity plots show disagreements and there is wide scatter which is expected due to the wide range of radio loudness observed in AGNs.

- Hard X-ray Selected Samples We find that the hard X-ray flux (relative to the \([\text{OIII}], \text{[OIV]}, \text{and MIR fluxes}) is suppressed by about an order-of-magnitude in MIR selected Sy2s compared to both Sy1s (consistent with Rigby et al. 2008) and to hard X-ray selected Type 2 AGN (Winter et al. 2010 and Weaver et al. 2010). The comparison with the \([\text{OIII]}\) sample is mixed, with statistically significant differences
between the Sy2s and Sy1s when the X-ray flux is normalized by the [OIV] and MIR flux, but not when normalized by the [OIII] flux. However, hard X-ray selected Sy2s differ significantly from [OIII]-selected Sy2s (though with only one [OIII] Sy2 detected by BAT, this analysis may be less robust than the 12µm comparison). These results indicate that hard X-ray emission (E > 10 keV) is anisotropic and hard X-ray selected samples are biased against the more heavily obscured type 2 AGN that are present in MIR and possibly [OIII] selected samples. As Weaver et al. (2010) note for sources detected in hard X-rays, Compton scattering could be responsible for the hard X-ray attenuation observed in Type 2 AGN as compared to Type 1. In more obscured sources, Compton scattering may be pushing them below the flux sensitivity of BAT.

We tested whether the [OIII] and [OIV] emission is stronger in galaxies with larger amounts of starburst activity. The ratios of the [OIII]/MIR and [OIV]/MIR fluxes show little if any evidence for a correlation with the relative amount of star formation. This lack of a relationship suggests that the [OIII] and [OIV] lines are not biased to be a preferentially higher fraction of the AGN bolometric luminosity in host galaxies with more star formation activity (more dense gas).
Table 2.1. [OIII] Sample

<table>
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$^1$Distances based on redshift, assuming a cosmology of $H_0 = 70$ km s$^{-1}$, $\Omega_M = 0.27$ and $\Omega_{\text{vac}} = 0.73$.

$^2$Masses based on velocity dispersion: $M_{BH} = 10^{8.13}(\sigma/200$ km s$^{-1})^{4.02}$ $M_\odot$ (Tremaine et al., 2002).
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$^1$Distances based on redshift, assuming a cosmology of $H_0 = 70$ km s$^{-1}$, $\Omega_M = 0.27$ and $\Omega_{\text{vac}} = 0.73$. Coordinates and redshift values from NED.

$^2$Masses based on velocity dispersion: $M_{BH} = 10^{8.13}(\sigma/200$ km s$^{-1})^{4.02} M_{\odot}$ (Tremaine et al., 2002), except for F08572+3915 which is based on photometry of the host galaxy (see V09 for details). The FWHM of the [OIII] line was used as a proxy for $\sigma$ for F04385-0828, F05189-2524 and TOLOLO 1238-364 (Wang & Zhang 2007, Greene & Ho 2005).

Table 2.3. Optical Emission Line Fluxes\(^1\) and Ratios for [OIII] Sample

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<th>([\text{[OIII]}]_{\text{corr}})</th>
<th>(\text{H}\alpha/\text{H}\beta)</th>
<th>([\text{[NII]}]/\text{H}\alpha)</th>
<th>([\text{[OIII]}]/\text{H}\beta)</th>
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Table 2.4. Optical Emission Line Fluxes and Ratios for 12µm Sample

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⁴ Fluxes in 12µm Sample
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$^1$Fluxes in $10^{-14}$ erg s$^{-1}$ cm$^{-2}$

$^2$Optical References:
Table 2.5. *Spitzer* Observation Summary

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\(^1\)The Program ID for the Sy2s in the [OIII] sample is 30773.

\(^2\)For low resolution spectral mapping observations.

\(^b\)Galaxies that had dedicated off-source high-resolution observations and were therefore background subtracted. See Section 3.2 for details.
Table 2.6. MIR Flux and PAH EW values for [OIII] Sample

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<th>[OIV]25.89µm</th>
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<th>EW</th>
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<td>10^{-11} erg s^{-1} cm^{-2}</td>
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<th>EW</th>
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<td>10^{-11} erg s^{-1} cm^{-2}</td>
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1Upper limits on flux correspond to 5σ upper limits.
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<th>EW 11.3μm</th>
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<td>8.17</td>
<td>0.135</td>
<td>0.117</td>
<td>0.49</td>
</tr>
<tr>
<td>NGC 1386&lt;sup&gt;1&lt;/sup&gt;</td>
<td>4.61±0.35</td>
<td>83.4±1.6</td>
<td>6.62</td>
<td>0.131</td>
<td>0.239</td>
<td>1.54</td>
</tr>
<tr>
<td>F04385-0828</td>
<td>4.33±0.16</td>
<td>6.88±0.83</td>
<td>10.6</td>
<td>0</td>
<td>0.131</td>
<td>1.14</td>
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<tr>
<td>NGC 1667</td>
<td>3.18±0.08</td>
<td>2.91±0.12</td>
<td>2.73</td>
<td>0.578</td>
<td>1.35</td>
<td>1.82</td>
</tr>
<tr>
<td>F05189-2524</td>
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<td>10.9</td>
<td>0</td>
<td>0.129</td>
<td>2.62</td>
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<tr>
<td>F08572+3915</td>
<td>2.60±0.25</td>
<td>&lt;5.7</td>
<td>7.44</td>
<td>0</td>
<td>1.85</td>
<td>3.61</td>
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<td>NGC 3982</td>
<td>3.01±0.09</td>
<td>3.48±0.23</td>
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<td>1.63</td>
<td>0.933</td>
<td>1.46</td>
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<tr>
<td>NGC 4388&lt;sup&gt;1&lt;/sup&gt;</td>
<td>24.8±0.4</td>
<td>264±1</td>
<td>6.64</td>
<td>0.083</td>
<td>0.187</td>
<td>1.32</td>
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<tr>
<td>NGC 4501</td>
<td>1.69±0.07</td>
<td>2.73±0.17</td>
<td>1.38</td>
<td>0.947</td>
<td>1.86</td>
<td>1.01</td>
</tr>
<tr>
<td>TOLOLO 1238-364</td>
<td>13.6±0.2</td>
<td>14.0±0.7</td>
<td>12.0</td>
<td>0.253</td>
<td>0.065</td>
<td>0.83</td>
</tr>
<tr>
<td>NGC 4968</td>
<td>7.84±0.15</td>
<td>26.5±0.4</td>
<td>7.90</td>
<td>0.174</td>
<td>0.105</td>
<td>0.22</td>
</tr>
</tbody>
</table>
Table 2.7 (cont’d)

<table>
<thead>
<tr>
<th>Galaxy</th>
<th>[NeII]12.81μm</th>
<th>[OIV]25.89μm</th>
<th>$F_{\text{MIR}}$</th>
<th>EW 11.3μm</th>
<th>EW 17μm</th>
<th>$\alpha_{20–30\mu m}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$10^{-14}$ erg s$^{-1}$ cm$^{-2}$</td>
<td>$10^{-11}$ erg s$^{-1}$ cm$^{-2}$</td>
<td></td>
<td>μm</td>
<td>μm</td>
<td></td>
</tr>
<tr>
<td>M-3-34-64</td>
<td>16.9±0.4</td>
<td>95.9±1.2</td>
<td>12.3</td>
<td>0.010</td>
<td>0.035</td>
<td>0.90</td>
</tr>
<tr>
<td>NGC 5135$^2$</td>
<td>31.5±0.8</td>
<td>60.8±1.1</td>
<td>4.34</td>
<td>0.387</td>
<td>0.322</td>
<td>2.49</td>
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<tr>
<td>NGC 5194</td>
<td>23.9±0.4</td>
<td>28.5±1.2</td>
<td>8.04</td>
<td>1.71</td>
<td>1.63</td>
<td>2.06</td>
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<tr>
<td>NGC 5347$^3$</td>
<td>2.28±0.09</td>
<td>6.70±0.56</td>
<td>4.12</td>
<td>0.086</td>
<td>0.060</td>
<td>0.55</td>
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<tr>
<td>Mrk 463</td>
<td>3.12±0.15</td>
<td>59.0±1.2</td>
<td>7.81</td>
<td>0</td>
<td>0.016</td>
<td>0.55</td>
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<tr>
<td>NGC 5506$^1$</td>
<td>21.0±0.5</td>
<td>220±2</td>
<td>17.3</td>
<td>0.048</td>
<td>0.257</td>
<td>1.39</td>
</tr>
<tr>
<td>NGC 5929</td>
<td>3.13±0.05</td>
<td>3.98±0.18</td>
<td>0.58</td>
<td>1.15</td>
<td>0.792</td>
<td>1.85</td>
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<tr>
<td>NGC 5953</td>
<td>17.0±0.3</td>
<td>16.5±0.5</td>
<td>4.13</td>
<td>2.28</td>
<td>1.82</td>
<td>2.63</td>
</tr>
<tr>
<td>Arp 220</td>
<td>20.6±0.2</td>
<td>&lt;24</td>
<td>8.47</td>
<td>0</td>
<td>5.51</td>
<td>5.85</td>
</tr>
<tr>
<td>NGC 6890</td>
<td>3.44±0.06</td>
<td>7.84±0.21</td>
<td>4.06</td>
<td>0.380</td>
<td>0.357</td>
<td>0.90</td>
</tr>
<tr>
<td>IC 5063</td>
<td>7.82±0.42</td>
<td>99.0±1.7</td>
<td>14.6</td>
<td>0.009</td>
<td>0.063</td>
<td>1.10</td>
</tr>
<tr>
<td>NGC 7130$^1$</td>
<td>22.4±0.5</td>
<td>26.3±1.1</td>
<td>4.63</td>
<td>0.138</td>
<td>0.113</td>
<td>2.53</td>
</tr>
<tr>
<td>NGC 7172</td>
<td>9.66±0.42</td>
<td>35.5±0.6</td>
<td>3.23</td>
<td>0.170</td>
<td>2.31</td>
<td>2.56</td>
</tr>
<tr>
<td>NGC 7582</td>
<td>76.5±1.3</td>
<td>87.9±1.4</td>
<td>5.11</td>
<td>1.51</td>
<td>0.275</td>
<td>2.70</td>
</tr>
<tr>
<td>NGC 7590</td>
<td>2.25±0.06</td>
<td>3.81±0.5</td>
<td>1.77</td>
<td>1.95</td>
<td>1.95</td>
<td>1.75</td>
</tr>
</tbody>
</table>
Table 2.7 (cont’d)

<table>
<thead>
<tr>
<th>Galaxy</th>
<th>[NeII]12.81(\mu m)</th>
<th>[OIV]25.89(\mu m)</th>
<th>F_{MIR}</th>
<th>EW 11.3(\mu m)</th>
<th>17(\mu m)</th>
<th>(\alpha_{20-30}\mu m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NGC 7674</td>
<td>7.06±0.15</td>
<td>38.3±1.1</td>
<td>11.6</td>
<td>0.012</td>
<td>0.103</td>
<td>0.79</td>
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</table>

1Program ID 30572 only for F_{MIR}.
2Program ID 00086 only for F_{MIR}.
3Program IDs 30572 and 00086 averaged together for F_{MIR}.
Table 2.8. Diagnostic Ratios: Optical & Infrared

<table>
<thead>
<tr>
<th>Diagnostic Ratio(^1)</th>
<th>Sample</th>
<th>Mean</th>
<th>σ</th>
</tr>
</thead>
<tbody>
<tr>
<td>(F_{[OIII],corr}/F_{[OIII],obs})</td>
<td>Both (51 Sy2s)</td>
<td>0.73</td>
<td>0.52</td>
</tr>
<tr>
<td></td>
<td>[OIII]-only (20 Sy2s)</td>
<td>0.34</td>
<td>0.22</td>
</tr>
<tr>
<td></td>
<td>12μm-only (31 Sy2s)</td>
<td>0.97</td>
<td>0.51</td>
</tr>
<tr>
<td></td>
<td>Sy2s (Winter et al. 2010, 24)</td>
<td>0.43</td>
<td>0.49</td>
</tr>
<tr>
<td></td>
<td>Sy1s (Winter et al. 2010, 29)</td>
<td>0.28</td>
<td>0.48</td>
</tr>
<tr>
<td>(F_{[OIV]}/F_{[OIII],corr})</td>
<td>Both (48 Sy2s)</td>
<td>-0.58</td>
<td>0.48</td>
</tr>
<tr>
<td></td>
<td>[OIII]-only (20 Sy2s)</td>
<td>-0.26</td>
<td>0.24</td>
</tr>
<tr>
<td></td>
<td>12μm-only (28 Sy2s)</td>
<td>-0.81</td>
<td>0.48</td>
</tr>
<tr>
<td></td>
<td>Sy2s(^2)(8)</td>
<td>-0.38</td>
<td>0.56</td>
</tr>
<tr>
<td></td>
<td>Sy1s(^2)(10)</td>
<td>-0.90</td>
<td>0.58</td>
</tr>
<tr>
<td>(F_{[OIV]}/F_{[OIII],obs})</td>
<td>Both (48 Sy2s)</td>
<td>0.09</td>
<td>0.41</td>
</tr>
<tr>
<td></td>
<td>[OIII]-only (20 Sy2s)</td>
<td>0.09</td>
<td>0.29</td>
</tr>
<tr>
<td></td>
<td>12μm-only (28 Sy2s)</td>
<td>0.10</td>
<td>0.48</td>
</tr>
<tr>
<td></td>
<td>Sy2s (Meléndez et al. 2008, 12)</td>
<td>0.60</td>
<td>0.74</td>
</tr>
<tr>
<td></td>
<td>Sy2s (Diamond-Stanic et al. 2009, 56)</td>
<td>0.57</td>
<td>0.67</td>
</tr>
<tr>
<td></td>
<td>Sy1s (Meléndez et al. 2008, 18)</td>
<td>-0.21</td>
<td>0.42</td>
</tr>
<tr>
<td></td>
<td>Sy1s (Diamond-Stanic et al. 2009, 16)</td>
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<td>0.53</td>
</tr>
<tr>
<td>(F_{MIR}/F_{[OIII],corr})</td>
<td>Both (49 Sy2s)</td>
<td>1.76</td>
<td>0.59</td>
</tr>
<tr>
<td></td>
<td>[OIII]-only (20 Sy2s)</td>
<td>1.89</td>
<td>0.27</td>
</tr>
<tr>
<td></td>
<td>12μm-only (29 Sy2s)</td>
<td>1.68</td>
<td>0.72</td>
</tr>
<tr>
<td>(F_{MIR}/F_{[OIII],obs})</td>
<td>Both (49 Sy2s)</td>
<td>2.48</td>
<td>0.68</td>
</tr>
<tr>
<td></td>
<td>[OIII]-only (20 Sy2s)</td>
<td>2.23</td>
<td>0.38</td>
</tr>
<tr>
<td></td>
<td>12μm-only (29 Sy2s)</td>
<td>2.64</td>
<td>0.80</td>
</tr>
<tr>
<td></td>
<td>Sy1s(^3)(12)</td>
<td>2.56</td>
<td>0.50</td>
</tr>
<tr>
<td>(F_{MIR}/F_{[OIV]})</td>
<td>Both (46 Sy2s)</td>
<td>2.29</td>
<td>0.40</td>
</tr>
<tr>
<td>Diagnostic Ratio¹</td>
<td>Sample</td>
<td>Mean</td>
<td>σ</td>
</tr>
<tr>
<td>-------------------</td>
<td>----------------------</td>
<td>------</td>
<td>----</td>
</tr>
<tr>
<td></td>
<td></td>
<td>dex</td>
<td>dex</td>
</tr>
<tr>
<td>[OIII]-only (20 Sy2s)</td>
<td>2.15 0.26</td>
<td></td>
<td></td>
</tr>
<tr>
<td>12µm-only (26 Sy2s)</td>
<td>2.41 0.45</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sy1s⁴(24)</td>
<td>2.59 0.38</td>
<td></td>
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</tr>
</tbody>
</table>

¹**Ratios in log space**

²Sy1 and Sy2 [OIII] values from Winter et al. (2010) and [OIV] values from Weaver et al. (2010)

³Sy1 MIR values from Deo et al. (2009) and [OIII] values from Meléndez et al. (2008)

⁴Sy1 MIR values from Deo et al. (2009) and [OIV] values from Tommasin et al. (2010) & Meléndez et al. (2008)
Table 2.9. Diagnostic Ratios: Optical & Infrared vs Radio & X-ray²

<table>
<thead>
<tr>
<th>Diagnostic Ratio¹</th>
<th>Sample</th>
<th>Mean</th>
<th>σ</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>dex</td>
<td>dex</td>
</tr>
<tr>
<td>( F_{[\text{OIII}],\text{corr}} / F_{8.4\text{GHz}} )</td>
<td>12( \mu )m-only (26 Sy2s)</td>
<td>3.56</td>
<td>0.87</td>
</tr>
<tr>
<td>( F_{[\text{OIII}],\text{obs}} / F_{8.4\text{GHz}} )</td>
<td>12( \mu )m-only (26 Sy2s)</td>
<td>2.53</td>
<td>0.99</td>
</tr>
<tr>
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<td>Sy1s (12)</td>
<td>2.94</td>
<td>0.93</td>
</tr>
<tr>
<td>( F_{[\text{OIV}] / F_{8.4\text{GHz}} )</td>
<td>12( \mu )m-only (23 Sy2s)</td>
<td>2.83</td>
<td>0.64</td>
</tr>
<tr>
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<td>Sy1s (25)</td>
<td>2.84</td>
<td>0.90</td>
</tr>
<tr>
<td>( F_{\text{MIR}} / F_{8.4\text{GHz}} )</td>
<td>12( \mu )m-only (25 Sy2s)</td>
<td>5.17</td>
<td>0.66</td>
</tr>
<tr>
<td></td>
<td>Sy1s (22)</td>
<td>5.41</td>
<td>0.78</td>
</tr>
<tr>
<td>( F_{14-195\text{keV}} / F_{[\text{OIII}],\text{corr}} )</td>
<td>Both (51 Sy2s)</td>
<td>0.50</td>
<td>...</td>
</tr>
<tr>
<td></td>
<td>[OIII]-only (20 Sy2s)</td>
<td>1.79</td>
<td>...</td>
</tr>
<tr>
<td></td>
<td>12( \mu )m-only (31 Sy2s)</td>
<td>0.48</td>
<td>...</td>
</tr>
<tr>
<td></td>
<td>Sy2s (Winter et al. 2010, 24)</td>
<td>2.30</td>
<td>0.68</td>
</tr>
<tr>
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<td>Sy1s (Winter et al. 2010, 29)</td>
<td>1.74</td>
<td>0.54</td>
</tr>
<tr>
<td>( F_{14-195\text{keV}} / F_{[\text{OIII}],\text{obs}} )</td>
<td>Both (51 Sy2s)</td>
<td>1.48</td>
<td>...</td>
</tr>
<tr>
<td></td>
<td>[OIII]-only (20 Sy2s)</td>
<td>2.37</td>
<td>...</td>
</tr>
<tr>
<td></td>
<td>12( \mu )m-only (31 Sy2s)</td>
<td>1.53</td>
<td>...</td>
</tr>
<tr>
<td></td>
<td>Sy2s (Winter et al. 2010, 24)</td>
<td>2.73</td>
<td>0.57</td>
</tr>
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<td>Sy1s (Winter et al. 2010, 29)</td>
<td>2.02</td>
<td>0.54</td>
</tr>
<tr>
<td>( F_{14-195\text{keV}} / F_{[\text{OIV}] )</td>
<td>Both (48 Sy2s)</td>
<td>1.51</td>
<td>...</td>
</tr>
<tr>
<td></td>
<td>[OIII]-only (20 Sy2s)</td>
<td>2.13</td>
<td>...</td>
</tr>
<tr>
<td></td>
<td>12( \mu )m-only (28 Sy2s)</td>
<td>1.53</td>
<td>...</td>
</tr>
<tr>
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<td>Sy2s (Weaver et al. 2010, 33)</td>
<td>2.30</td>
<td>0.47</td>
</tr>
<tr>
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<td>Sy1s (Weaver et al. 2010, 37)</td>
<td>2.60</td>
<td>0.47</td>
</tr>
<tr>
<td></td>
<td>Sy1s (Rigby et al. 2009, 17)</td>
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<td>0.39</td>
</tr>
<tr>
<td>( F_{14-195\text{keV}} / F_{\text{MIR}} )</td>
<td>Both (49 Sy2s)</td>
<td>-0.75</td>
<td>...</td>
</tr>
<tr>
<td></td>
<td>[OIII]-only (20 Sy2s)</td>
<td>-0.11</td>
<td>...</td>
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</table>
Table 2.9 (cont’d)

<table>
<thead>
<tr>
<th>Diagnostic Ratio$^1$</th>
<th>Sample</th>
<th>Mean</th>
<th>σ</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>12μm-only (29 Sy2s)</td>
<td>-0.73</td>
<td>...</td>
</tr>
<tr>
<td></td>
<td>Sy1 (21)</td>
<td>-0.28</td>
<td>0.26</td>
</tr>
<tr>
<td>$F_{14–195keV}/F_{8.4GHz}$</td>
<td>12μm-only (26 Sy2s)</td>
<td>4.27</td>
<td>...</td>
</tr>
<tr>
<td></td>
<td>Sy1s (21)</td>
<td>5.30</td>
<td>0.61</td>
</tr>
</tbody>
</table>

$^1$Ratios in log space

$^2$Mean of Sy2 X-ray flux ratios calculated using survival analysis (Kaplan-Meier estimator) to include upper limits. The KM-estimator requires at least 2 detections, so one of the [OIII]-sample upper limits was converted to a detection which biases the mean for this sub-sample.
Table 2.10. Results of Two Sample Tests between Sy1s and Sy2s

<table>
<thead>
<tr>
<th>Diagnostic Ratio</th>
<th>Kuiper Test</th>
<th>KS Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>( F_{[OIV]}/F_{[OIII],obs} )</td>
<td>( N_{eff}^{1} )</td>
<td>D</td>
</tr>
<tr>
<td>19.9</td>
<td>0.364</td>
<td>0.065</td>
</tr>
<tr>
<td>( F_{MIR}/F_{[OIII],obs} )</td>
<td>8.49</td>
<td>0.304</td>
</tr>
<tr>
<td>( F_{MIR}/F_{[OIV]} )</td>
<td>15.8</td>
<td>0.393</td>
</tr>
<tr>
<td>( F_{[OIII],obs}/F_{8.4GHz} )</td>
<td>8.21</td>
<td>0.385</td>
</tr>
<tr>
<td>( F_{[OIV]}/F_{8.4GHz} )</td>
<td>12.0</td>
<td>0.318</td>
</tr>
<tr>
<td>( F_{MIR}/F_{8.4GHz} )</td>
<td>11.7</td>
<td>0.327</td>
</tr>
</tbody>
</table>

\(^{1}N_{eff} = n_{1} \times n_{2}/(n_{1} + n_{2})\) where \( n_{1} \) and \( n_{2} \) are the number of data points in each sample.
Table 2.11. Correlation of Diagnostic Ratios with Eddington Parameters

<table>
<thead>
<tr>
<th>Diagnostic Ratio</th>
<th>$\rho$</th>
<th>$P_{uncorr}$</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Optical &amp; Infrared</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$F_{OIII,corr}/F_{OIII,obs}$</td>
<td>-0.224</td>
<td>0.115</td>
</tr>
<tr>
<td>$F_{OIV}/F_{OIII,corr}$</td>
<td>-0.100</td>
<td>0.500</td>
</tr>
<tr>
<td>$F_{OIV}/F_{OIII,obs}$</td>
<td>-0.315</td>
<td>0.029</td>
</tr>
<tr>
<td>$F_{MIR}/F_{OIII,corr}$</td>
<td>-0.251</td>
<td>0.082</td>
</tr>
<tr>
<td>$F_{MIR}/F_{OIII,obs}$</td>
<td>-0.417</td>
<td>0.003</td>
</tr>
<tr>
<td>$F_{MIR}/F_{OIV}$</td>
<td>-0.266</td>
<td>0.074</td>
</tr>
<tr>
<td><strong>Radio and X-ray$^1$</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$F_{OIII,corr}/F_{8.4GHz}$</td>
<td>0.008</td>
<td>0.967</td>
</tr>
<tr>
<td>$F_{OIII,obs}/F_{8.4GHz}$</td>
<td>0.142</td>
<td>0.491</td>
</tr>
<tr>
<td>$F_{OIV}/F_{8.4GHz}$</td>
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<td>0.352</td>
</tr>
<tr>
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<td>-0.381</td>
<td>0.061</td>
</tr>
<tr>
<td>$F_{14-195keV}/F_{OIII,corr}$</td>
<td>...</td>
<td>0.329</td>
</tr>
<tr>
<td>$F_{14-195keV}/F_{OIII,obs}$</td>
<td>...</td>
<td>0.194</td>
</tr>
<tr>
<td>$F_{14-195keV}/F_{OIV}$</td>
<td>...</td>
<td>0.933</td>
</tr>
<tr>
<td>$F_{14-195keV}/F_{MIR}$</td>
<td>...</td>
<td>0.666</td>
</tr>
<tr>
<td>$F_{14-195keV}/F_{8.4GHz}$</td>
<td>...</td>
<td>0.283</td>
</tr>
</tbody>
</table>

$^1$X-ray correlations computed using Cox Hazard Model in ASURV software package.
Figure 2.1 a) Distribution of \( \log \left( \frac{F_{\text{OIV}}}{F_{\text{OIII},\text{corr}}} \right) \). Black solid line shows the combined sample, filled cyan histogram depicts the [OIII]-sample, and red (green) dashed histogram are the weak PAH (strong PAH) 12\( \mu \)m sources. b) \( \log (L_{\text{OIV}}) \) vs \( \log (L_{\text{OIII},\text{corr}}) \); black dashed line represents best-fit from linear regression with \( \rho = 0.839 \) giving \( P_{\text{uncorr}} = 9.82 \times 10^{-14} \) (slope = 0.85 \pm 0.08 dex with intercept at 5.49 dex). Cyan asterisks represent the [OIII] sample and red diamonds (green triangles) depict the weak PAH (strong PAH) 12\( \mu \)m Sy2s. The blue dotted-dashed line in a) and b) reflect the values for Sy1s, with \( F_{\text{OIII},\text{corr}} \) from Winter et al. (2010) and \( F_{\text{OIV}} \) from Weaver et al. (2010). c) Distribution of \( \log \left( \frac{F_{\text{OIV}}}{F_{\text{OIII},\text{obs}}} \right) \). d) \( \log (L_{\text{OIV}}) \) vs \( \log (L_{\text{OIII},\text{obs}}) \); black dashed line represents best-fit from linear regression with \( \rho = 0.886 \) giving \( P_{\text{uncorr}} = 5.83 \times 10^{-17} \) (slope = 0.88 \pm 0.07 dex with intercept at 5.08 dex). The purple dashed line and blue dot-dashed line represent the Sy1 values from Diamond-Stanic et al. (2009) and Meléndez et al. (2008) samples, respectively.
Figure 2.2 a) Distribution of \( \log(\frac{F_{\text{MIR}}}{F_{\text{[OIII]}}}) \). b) \( \log(L_{\text{MIR}}) \) vs \( \log(L_{\text{[OIII]}}) \); \( \rho = 0.709 \) giving \( P_{\text{uncorr}} = 1.35 \times 10^{-9} \) (slope = 0.71 ± 0.09 dex with intercept at 13.9 dex). c) Distribution of \( \log(\frac{F_{\text{MIR}}}{F_{\text{[OIII]}}}) \). d) \( \log(L_{\text{MIR}}) \) vs \( \log(L_{\text{[OIII]}}) \); \( \rho = 0.676 \) giving \( P_{\text{uncorr}} = 9.87 \times 10^{-8} \) (slope = 0.60 ± 0.10 dex with intercept at 18.8 dex). The blue dashed-dotted line represents the Sy1 values, with \( F_{\text{MIR}} \) from Deo et al. (2009) and \( F_{\text{[OIII]}} \) from Meléndez et al. (2008). Color and linestyle coding same as Figure 2.1.
Figure 2.3 Left: Distribution of \( \log \left( \frac{F_{\text{MIR}}}{F_{\text{[OIV]}}} \right) \). Right: \( \log (L_{\text{MIR}}) \) vs \( \log (L_{\text{[OIV]}}) \); \( \rho = 0.879 \) giving \( P_{\text{uncorr}} = 9.80 \times 10^{-16} \) (slope = 0.80 ± 0.07 dex with intercept at 10.4 dex). The blue dashed-dotted line represents the Sy1 values, with \( F_{\text{MIR}} \) from Deo et al. (2009) and \( F_{\text{[OIV]}} \) from Tommasin et al. (2010) and Meléndez et al. (2008). The relationship between \( L_{\text{MIR}} \) and \( L_{\text{[OIV]}} \) is nearly identical for Sy1s and Sy2s. Color and linestyle coding same as Figure 2.1.
Figure 2.4 a) Distribution of $\log \left( \frac{F_{\text{[OIII]}}}{F_{\text{8.4GHz}}} \right)$. b) $\log (L_{\text{[OIII]}})$ vs $\log (L_{\text{8.4GHz}})$; $\rho=0.667$ giving $P_{\text{uncorr}}=2.00 \times 10^{-4}$ (slope = $0.57 \pm 0.13$ dex with intercept at 20.1 dex). c) Distribution of $\log \left( \frac{F_{\text{[OIII]}}}{F_{\text{8.4GHz}}} \right)$. d) $\log (L_{\text{[OIII]}})$ vs $\log (L_{\text{8.4GHz}})$; $\rho=0.57$ giving $P_{\text{uncorr}}=0.003$ (slope = $0.49 \pm 0.14$ dex with intercept at 22.1 dex). The blue dashed-dotted line represents the Sy1 values, with the radio data from Thean et al. (2000) and $F_{\text{[OIII]}}$ from Diamond-Stanic et al. (2009) and Meléndez et al. (2008). Color and linestyle coding same as Figure 2.1.
Figure 2.5 Left: Distribution of log (F_{OIV}/F_{8.4GHz}). Right: Log (L_{OIV}) vs log (L_{8.4GHz}); ρ=0.805 giving P_{uncorr}=3.52×10^{-6} (slope = 0.63 ± 0.10 dex with intercept at 16.9 dex). The blue dashed-dotted line represents the Sy1 values, with the radio data from Thean et al. (2000) and F_{OIV} from Diamond-Stanic et al. (2009) and Meléndez et al. (2008). Color and linestyle coding same as Figure 2.1.

Figure 2.6 Left: Distribution of log (F_{MIR}/F_{8.4GHz}). Right: Log (L_{MIR}) vs log (L_{8.4GHz}); ρ=0.827 giving P_{uncorr}=3.53×10^{-7} (slope = 0.62 ± 0.09 dex with intercept at 19.8 dex). The blue dashed-dotted line represents the Sy1 values, with the radio data from Thean et al. (2000) and F_{MIR} from Deo et al. (2009). Color and linestyle coding same as Figure 2.1.
Figure 2.7 a) Distribution of log \( \frac{F_{14-195\text{keV}}}{F_{[\text{OIII}],\text{corr}}} \). b) Log \( L_{14-195\text{keV}} \) vs log \( L_{[\text{OIII}],\text{corr}} \) with dashed line from survival analysis; \( P_{\text{uncorr}}=0.0075 \) (slope = 0.50 ± 0.18 dex with intercept at 21.5 dex). c) Distribution of log \( \frac{F_{14-195\text{keV}}}{F_{[\text{OIII}],\text{obs}}} \). d) Log \( L_{14-195\text{keV}} \) vs log \( L_{[\text{OIII}],\text{obs}} \) with dashed line from survival analysis; \( P_{\text{uncorr}}=0.0028 \) (slope = 0.53 ± 0.18 dex with intercept at 20.7 dex). In both luminosity vs. luminosity plots, the blue dotted-dashed line represents the Sy1 values from the Winter et al. sample (2010). Color and linestyle coding same as Figure 2.1.
Figure 2.8 Left: Distribution of log (F_{14−195 keV}/F_{[OIV]}). Right: Log (L_{14−195 keV}) vs log (L_{[OIV]}) with dashed line from survival analysis; correlation probability \( \sim 99.97\% \) (slope = 0.77 ± 0.18 dex with intercept at 11.1 dex). The blue dotted-dashed and purple dashed lines represent the Sy1 values from Weaver et al. (2010) and Rigby et al. (2009), respectively. Color and linestyle coding same as Figure 2.1.

Figure 2.9 Left: Distribution of log (F_{14−195 keV}/F_{MIR}). Right: Log (L_{14−195 keV}) vs log (L_{MIR}) with dashed line from survival analysis; P_{uncorr}=0.0040 (slope = 0.67 ± 0.19 dex with intercept at 13.5 dex). Blue dotted-dashed line represents the Sy1 values, with F_{14−195 keV} from Meléndez et al. (2008) and Tueller et al. (2009) and F_{MIR} from Deo et al. (2009). Color and linestyle coding same as Figure 2.1.
Figure 2.10 Left: Distribution of log ($F_{14-195\text{keV}}/F_{8.4\text{GHz}}$). Right: Log ($L_{14-195\text{keV}}$) vs log ($L_{8.4\text{GHz}}$) with dashed line from survival analysis; correlation probability $\sim 99.4\%$ (slope = $0.47 \pm 0.16$ dex with intercept at 24.6 dex). The blue dotted-dashed line represent the Sy1 values, with $F_{14-195\text{keV}}$ from Meléndez et al. (2008) and Tueller et al. (2009) and $F_{8.4\text{GHz}}$ from Thean et al. (2000). Color and linestyle coding same as Figure 2.1.
Figure 2.11 Log ($F_{[OIV]} / F_{[OIII],obs}$) vs $H\alpha / H\beta$. The green triangles are the 12$\mu$m sources with $D < 1.2$, the red diamonds are the 12$\mu$m sources with $D \geq 1.2$ and the cyan asterisks represent the [OIII] sample.
Figure 2.12 Comparison of 14-195 keV flux ratios between BAT selected Sy2s and IR and optically selected Sy2s. In all 3 plots, the solid black line (arrows) represents the combined [OIII] and 12µm sample with detected (upper limits) 14-195 keV emission and the dotted-dashed blue line represents the BAT selected Sy2s from Winter et al. (2010, panels a and b) and Weaver et al. (2010, panel c). The vertical black line reflects the mean values for our combined [OIII] and 12µm sample (from Survival Analysis) and the vertical dashed blue line delineates the mean for the Sy2 samples from Winter et al. (2010, panels a and b) and Weaver et al. (2010, panel c). In all cases, the BAT selected Sy2s have systematically higher hard X-ray emission when normalized by other intrinsic AGN proxies as compared to the optical and IR selected Sy2s, with the mean values differing by almost an order of magnitude or more.
Figure 2.13 Flux ratios vs. $L_{AGN}/L_{Edd}$. The cyan asterisks represent the [OIII] sample, the red diamonds the “PAH-weak” 12µm sub-sample and the green triangles the “PAH-strong” 12 µm sub-sample.
Figure 2.14 $F_{[OIV]}/F_{[NeII]}$ vs. other diagnostics of ionization field hardness: a) PAH EW at 11.3 µm, b) PAH EW at 17 µm, c) $\alpha_{20-30\mu m}$, d) optical D parameter. The trends illustrate that these diagnostics agree. As the ionization field becomes more dominated by the AGN relative to star formation, $[OIV]/[NeII]$ increases while the PAH EWs and $\alpha_{20-30\mu m}$ decrease and D increases. The color coding is the same as in Figure 2.13.
Figure 2.15 a) Log ($F_{\text{OIV}}/F_{\text{MIR}}$) vs log (PAH EW 11.3µm). b) Log ($F_{\text{OIV}}/F_{\text{MIR}}$) vs log (PAH EW 17µm). c) Log ($F_{\text{OIV}}/F_{\text{MIR}}$) vs $\alpha_{20-30\mu m}$. d) Log ($F_{\text{OIV}}/F_{\text{MIR}}$) vs D. No strong trends are apparent. The color coding is the same as in Figure 2.13.
Figure 2.16 a) Log ($F_{\text{[OIII,obs]}}/F_{\text{MIR}}$) vs log (PAH EW 11.3\(\mu\)m). b) Log ($F_{\text{[OIII,obs]}}/F_{\text{MIR}}$) vs log (PAH EW 17\(\mu\)m). c) Log ($F_{\text{[OIII,obs]}}/F_{\text{MIR}}$) vs $\alpha_{20-30\,\mu\text{m}}$. d) Log ($F_{\text{[OIII,obs]}}/F_{\text{MIR}}$) vs D. No strong trends are apparent. The color coding is the same as in Figure 2.13.
Chapter 3

X-ray Observations of Homogeneous Samples of Seyfert 2 Galaxies: Data Reduction

The amount of AGN obscuration can be revealed by 2-10 keV X-ray analysis. Compton-thick AGN are weak 2-10 keV X-ray emitters due to the combined effects of photo-electric absorption and Compton scattering, which can scatter photons out of the line of sight or to lower energies where the photons are then absorbed by the obscuring medium. Hence, selecting AGN samples based on intrinsic AGN flux proxies, which are ideally unaffected by the amount of toroidal obscuration present, is therefore necessary to uncover Compton-thick AGN.

We investigate the toroidal obscuration of the two homogeneous samples of Sy2s presented in Chapter 2, which were selected on parameters that trace the intrinsic AGN luminosity. Of the 20 [OIII]-selected Sy2s, 2 had archival XMM-Newton observations and we were awarded XMM-Newton time for another 15 sources. Archival Chandra and XMM-Newton data exist for 28 of the 31 12µm sources. Though both original samples are complete, since X-ray data only exists for 17/20 and 28/31 sources from the [OIII] and 12µm samples respectively, our resultant sample for X-ray analysis is nearly complete.

The Chandra and/or XMM-Newton spectra of these Sy2s were fit in a homoge-
neous and systematic manner using XSpec, an X-ray spectral fitting software. However, column densities derived from spectral fitting in the 2-10 keV band are highly model dependent and thus may not always reflect the intrinsic toroidal absorption, especially when simple models are used. Other diagnostics, which are more model independent, are therefore necessary to identify potentially Compton-thick sources. As the 2-10 keV X-ray emission is suppressed in absorbed sources, the ratio of this emission to intrinsic flux indicators can probe the amount of obscuration. In Compton-thick sources, the ratio of the 2-10 keV X-ray flux \( F_{2-10keV} \) to \( F_{\text{intrinsic}} \) is about an order of magnitude or lower than what is observed in unobscured sources (e.g. Bassani et al. 1999, Cappi et al. 2006, Panessa et al. 2006, Meléndez et al. 2008).

X-ray spectral signatures, most notably the equivalent width (EW) of the neutral Fe K\( \alpha \) line at 6.4 keV, can also aid in uncovering heavily obscured sources. As the EW is measured against a suppressed continuum, it rises with increasing column density, reaching values of several hundred eV to over 1 keV in Compton-thick sources (e.g. Levenson et al. 2002). In this chapter, we present the X-ray spectral fitting techniques from which we derive observed 2-10 keV fluxes and where applicable, Fe K\( \alpha \) EWs or upper limits. The results are discussed in Chapter 4.

### 3.1 Data Reduction Overview

For the [OIII] sample, we were awarded XMM-Newton time to observe 15 members of the 20 from this sample for a nominal 23 ks per target before filtering. Two additional targets from this sample were previously observed with XMM-Newton and were added: Mrk 609 (PI: Aschenbach) and 2MASX J12183945+4706275 (PI: Page), bringing the sample total to 17. Twenty-eight of the 31 Sy2s from the 12\( \mu \)m sample had available archival Chandra and XMM-Newton observations, which we utilized for this analysis.

The X-ray data were reduced using XAssist (Ptak & Griffiths, 2003), which runs the Science Analysis System (SAS) tasks to filter the raw data, generate light curves, clean the data for flaring, and extract spectra and associated response files (\textit{rmfs} and
arfs) for user-defined sources. Table 3.1 and 3.2 lists the ObsIDs and net exposure times after filtering for the [OIII] and 12µm samples respectively.

Most spectra (3/17 [OIII] sources, 18/26 12µm sources) had an adequate number of detected photons to be grouped by a minimum of >5 counts per bin (and in a majority of these cases, >10-15 counts/bin) without loss of spectral information and were thus analyzed with $\chi^2$. The remaining sources were analyzed with the Cash statistic (C-stat, Cash 1979) and binned by 2-3 counts as XSpec handles slightly binned spectra better than unbinned when using C-stat (Teng et al., 2005); these sources are marked in Tables 3.3 and 3.5.

### 3.1.1 [OIII] Sample

Flaring in the XMM-Newton observations of 2MASX J10181928+3722419, 2MASX J11110693+0228477, and NGC 5695 were significant, so we applied minimal background filtering. One target, 2MASX J12183945+4706275, fell on the chip gap in the PN detector, so we analyzed only the MOS1 and MOS2 data for this source.

### 3.1.2 12µm Sample

Twenty-five out of 28 sources were detected at the 3σ level or greater in the 0.5 - 10 keV band. One (NGC5193) was detected in the soft band (0.5 - 2 keV) and we were thus able to fit this part of the spectrum. We obtained upper 2 - 10 keV flux limits on this source and the two undetected sources (F08572+3915 and NGC 7590), discussed in detail below.

### 3.2 Fitting Multiple Spectra

Multiple observations for each source, as well as the spectra from the three XMM-Newton detectors (PN, MOS1 and MOS2), were fit simultaneously with a constant multiplicative factor which was allowed to vary by ~20% to account for calibration differences among detectors/observations. The remaining model parameters were
initially tied together, with the residuals inspected to check for inconsistencies among observations.

\section{3.2.1 12\textmu m Sample}

Many of the 12\textmu m Sy2s had multiple archival X-ray observations. Spectral differences among observations can be due to source variability or, in the case of comparing \textit{Chandra} and \textit{XMM-Newton} data, instrument resolution. Differences among multiple \textit{XMM-Newton} observations of the same source are interpreted as variability, and were present in 4/28 sources (NGC 4388, NGC 5506, NGC 7172 and NGC 7582).

Nine Sy2s had both \textit{Chandra} and \textit{XMM-Newton} archival data, with 8/9 having flux and/or spectral discrepancies between observations; only NGC 424 had consistent \textit{Chandra} and \textit{XMM-Newton} data. As \textit{Chandra} has higher spatial resolution than \textit{XMM-Newton}, it better isolates the central AGN. Differences in the spectra between the two observatories could thus be due to source variability, or extended emission from the host galaxy (e.g. X-ray binaries, thermal emission from hot gas, etc.) that \textit{XMM-Newton} can not resolve from the AGN emission. To test if such differences were due to variability or host galaxy contamination, we extracted the \textit{Chandra} source region to have the same size as the \textit{XMM-Newton} region, \textasciitilde20. If the best fit parameters and flux were consistent between the two datasets with the matched aperture extraction areas, we concluded that extended emission is likely contaminating the \textit{XMM-Newton} observation. If a discrepancy still existed, we interpreted this as source variability between observations.

Five sources showed evidence of contamination from extended emission within the \textit{XMM-Newton} aperture, i.e. matched aperture extraction between the \textit{Chandra} and \textit{XMM-Newton} observations resulted in consistent model parameters and flux: NGC 1386, F05189-2524, NGC 3982, NGC 4501 and Mrk 463. For 3 of these sources (NGC 1386, F05189-2524 and Mrk 463), the best-fit parameters with the default \textit{Chandra} extraction region were consistent with the \textit{XMM-Newton} spectra, with the exception of the constant multiplicative factor which was lower in the \textit{Chandra} observations (\textasciitilde40 – 70\% of \textit{XMM-Newton}). We therefore fit the \textit{XMM-Newton} and \textit{Chandra}
spectra simultaneously to constrain the *Chandra* parameters. However, we report the flux from the *Chandra* observations only in Table 3.8, as this isolates the central AGN. The spectra from the default *Chandra* extraction areas for the other two sources (NGC 3982 and NGC 4501) did not have consistent model parameters with the *XMM-Newton* spectra, likely due to X-ray binaries in the host galaxy affecting the spectral shape in the *XMM-Newton* data, so we therefore fit the *Chandra* spectra from the default extraction area independently and report these parameters in Table 3.5.

Three Sy2s were variable between the two observatories: NGC 4388, Arp 220 and NGC 7582. Arp 220 was fit simultaneously between the *Chandra* and *XMM-Newton* observations with only the absorption component fit independently for the *Chandra* spectrum. NGC 4388 and NGC 7582 exhibited spectral variation between the *Chandra* and *XMM-Newton* observations and were therefore fit independently. We list the best fit parameters for the default *Chandra* extraction spectra and the *XMM-Newton* spectra separately in Table 3.5 for these two sources.

### 3.3 Spectral Fitting

We used simple absorbed power law models to fit the spectra for the detected sources, which may not accurately represent the complex geometry of these systems. However, our main goal is to apply a systematic and homogeneous analysis of the spectra to derive an observed X-ray flux, and where possible, EW of the Fe Kα line. More extensive X-ray modeling of many of the 12µm Sy2s have been investigated in detail in the literature (e.g. see Brightman & Nandra 2010 for more detailed X-ray modeling of the extended 12µm sample) and we do not intend to replicate previously published work. In Appendix C, we discuss individual sources, compare our derived parameters with those quoted in the literature and comment on the impact more complex models have on such parameters. We find that in 18/23 sources, we recover consistent (within 1σ) observed X-ray fluxes and Fe Kα EW values as more complex models. This work also represents the first analysis of the [OIII] sample and of a handful of datasets for the 12µm sample (i.e. *Chandra* spectrum of IC 5063, *XMM-Newton*...
In many cases, a single absorbed power law model failed to accommodate the data. A second power law component at higher energies was necessary, as evident by both the shape of the spectrum and the high $\chi^2$ value for a single power law fit. These targets were fit with a double absorbed power law (i.e. $\text{phabs}_1 \ast (\text{pow}_1 + \text{phabs}_2 \ast \text{pow}_2)$). The two power law indices ($\Gamma$) were tied together and the normalizations and absorption components were fit independently. Such a model represents a partial covering geometry with the first power law denoting the soft scattered and/or reflected AGN continuum and the second component describing the absorbed transmitted emission. We required a lower limit on the first absorption component ($N_{H,1}$) to be equal to the Galactic absorption. In some cases, the best-fit absorption was equal to the Galactic $N_H$ and we subsequently froze $N_{H,1}$ to the Galactic value for these sources. The best-fit parameters from these fits are listed in Tables 3.3 and 3.5, along with their corresponding $\chi^2$ values. The double power law fit passes the F-test at almost or better than the 3$\sigma$ confidence level for all targets to which it was applied, indicating that this model more accurately represents the data. Though applying the F-test to certain astrophysical tests is inappropriate (e.g. Protassov et al. 2002), the high probabilities derived indicate that the more complex models are likely statistically robust. This second power law component indicates that we are observing scattered and/or reflected AGN emission from these sources. We included a Gaussian component to model the Fe K$\alpha$ emission when this feature was present (see below).

Levenson et al. (2004; 2005) and Guainazzi et al. (2005) showed that soft thermal emission from hot gas associated with a starburst is commonly found in Seyfert galaxies. Here we simply accommodate the possible presence of a starburst by fitting each of the targets with a thermal component (APEC in XSpec) added to the aforementioned absorbed single or double powerlaw model. The metal abundances were initially fixed to solar, allowing only the plasma temperature and normalization to be fit. The fit parameters from the powerlaw plus thermal model are listed in Tables 3.4 and 3.5.
We list the observed 2-10 keV X-ray flux and luminosity from these best-fit models in Tables 3.7 and 3.8. For the cases where addition of the APEC model improved the fit, we excluded this component when deriving the X-ray flux. For the 12µm sample, the flux was averaged among multiple observations when these observations were consistent. For variable sources, the flux is listed independently for each observation. For Arp 220, only the absorption varied between the XMM-Newton and Chandra observations, which had a negligible impact on the flux. We therefore averaged the XMM-Newton and Chandra fluxes for this source. We note that NGC 7582 has a higher observed Chandra flux, compared to the XMM-Newton fluxes, despite the smaller Chandra spectral extraction area; aperture effects could contribute to the lower Chandra flux (compared with XMM-Newton) for NGC 4388.

3.3.1 [OIII] Sample

Six targets best fit by a single absorbed power law (Mrk 0609, CGCG 064-017, 2MASX J10181928+3722419, CGCG 242-028, 2MASX J13463217+6423247 and NGC 5695). In six cases (Mrk 0609, IC 0486, 2MASX J08244333+2959238, 2MASX J11110693+0228477, CGCG 242-028 and 2MASX J12183945+4706275), the best-fit absorption was the same as the Galactic absorption, so we froze this parameter to the Galactic value for these spectral fits; for 2MASX J13463217+6423247, the spectral fit was best constrained by freezing absorption to the Galactic value and the photon index to 1.8.

We were able to fit the metal abundances for 2 of the sources: NGC 0291 and CGCG 242-028. For 4 of the targets (Mrk 0609, 2MASX J10181928+3722419, CGCG 242-028, and Mrk 1457), addition of the thermal component significantly improved the results at greater than the 3σ level according to the F-test. We note that inclusion of this model component causes the power law index to decrease and to fall within the more commonly observed range for Mrk 1457 and 2MASX J11570483+5249036; though Γ increases for 2MASX J10181928+3722419, the lower end of the 90% confidence level for this parameter now falls within the typical range observed in Seyferts (0.5 < Γ < 2.3, Cappi et al. 2006). However, the power law indices remained too
steep for 2MASX J08035923+2345201 and SBS 1133+572 (4.94$^{+0.86}_{-0.95}$ and 3.11$^{+0.43}_{-0.35}$, respectively) and allowing the two photon indices to be fit independently caused more unphysical results: a negative $\Gamma_2$ for 2MASX J08035923+2345201 and a much steeper $\Gamma_2$ for SBS 1133+572. Hence we froze $\Gamma_2$ at 1.8 for these sources.

The [OIII] spectra with the best-fit models are shown in Figures 3.1, 3.2 and 3.3.

### 3.3.2 12$\mu$m Sample

For 16 of the 25 12$\mu$m Sy2s, addition of the APEC component improved the fit at greater than the 3$\sigma$ level over the best-fit single or double power law model, according to the f-test.\(^1\) We were only able to obtain an upper limit on $N_{H,1}$ for three sources (Mrk 463, NGC 6890 and NGC 7130), as the lower error bound pegged at the Galactic absorption; the upper 90% limit is thus listed in Table 3.5. We also quote the 90% upper limit on kT for the six cases where the lower error on the temperature pegged at the limit of 0.1 keV (F05189-2524, NGC 3982, the Chandra observation of NGC 4388, NGC 4968, NGC 5347 and the Chandra observation of NGC 7582). In addition to Gaussian components to accommodate the Fe Kα feature when present (see below), we included Gaussian components for other emission features in NGC 1068 and NGC 7582 (see Appendix C). In Table 3.6, we list the best-fit parameters for the absorbed single/double power law fit for NGC 5953 and the 9 sources which according to the f-test, are not statistically significantly improved ($\geq 3\sigma$) by adding the APEC component and are therefore better described by the simpler single/double power law model (NGC 424, the Chandra observation of NGC 4388, NGC 4968, NGC 5135, NGC 5347, NGC 6890, IC 5063, the Chandra observation of NGC 7582 and NGC 7674).

In Figure 3.4, we plot the 12$\mu$m X-ray spectra with the best-fit models. As many sources have multiple observations, we plot only one spectrum per observation, generally using the PN spectrum for XMM-Newton observations unless the MOS spectrum had better signal-to-noise. Though we report the flux of the Chandra observations only for NGC 1386, F05189-2524 and Mrk 463, we plot both the XMM-Newton and

\(^1\)Due to the marginal soft detection of NGC 5953, we did not fit this source with APEC.
Chandra spectra to illustrate how the XMM-Newton spectra helped to constrain the fit.

3.3.2.1 Pileup

Bright X-ray sources can be susceptible to pileup which occurs when a CCD records two or more photons as a single event during the frame integration time. To test if this phenomenon affected our bright sources, we examined the pattern and observed distribution plots from the SAS task epatplot for XMM-Newton observations and the output of PIMMS\(^2\) for Chandra observations. In a handful of XMM-Newton observations (i.e. NGC 1068, NGC 5506 and NGC 7172), one to two of the detectors exhibited evidence of pileup, but at least one of the detectors did not. The “piled” spectra were therefore disregarded from the fit without loss of information as we obtained one to two non-piled spectra per observation (see Appendix C for details).

As PIMMS uses simple models to test for the presence of pileup (e.g. single absorbed power laws whereas most of our sources needed a second power law component), we fit the Chandra spectra with evidence of pileup (i.e. IC 5063 and NGC 7582) in Sherpa, using the jdpileup model and best-fit continuum model (with a Gaussian at the Fe K\(\alpha\) energy if necessary), to better constrain the pileup percentage. However, we utilized the pileup model in XSpec (with \(\alpha\), the “grade migration” parameter, as the only free parameter) along with the best-fit models to derive the 2 - 10 keV flux and Fe K\(\alpha\) EW, where the pileup component was removed before calculating these quantities. We note that the Sherpa and XSpec fits using their respective pileup models give consistent best-fit parameters and observed fluxes.

3.3.2.2 Upper Limits

Three sources were not detected within the 2 - 10 keV range: F08572+3915, NGC 5953 and NGC 7590. NGC 5953 was detected in the soft band (0.5 - 2 keV) and was therefore fit with an absorbed power law model. It was necessary to freeze the absorption to properly model the photon index. As the soft component generally

\(^2\)http://cxc.harvard.edu/toolkit/pimms.jsp
results from scattered/reflected AGN emission, the absorption attenuating this component results from obscuration along the line of sight rather than intrinsic toroidal absorption. In many cases in this study, such absorption is on the order of Galactic $N_H$ or marginally higher, so we froze $N_H$ to the Galactic value. From this fit in the soft band, we extrapolated an upper limit on the 2 - 10 keV flux.

F08572+3915 and NGC 7590 were not detected over the background in their ∼15 ks Chandra and ∼10 ks XMM-Newton observations, respectively. We therefore used a Bayesian approach to estimate an upper limit on the flux based on the total number of counts within the spectral extraction region and an assumed spectral shape for the AGN. We used a region size of ∼2" for F08572+3915 and ∼7.5" for NGC 7590 (though XMM-Newton has lower resolution and the extraction region is generally ∼20", we constrained this region to a smaller size to exclude contamination from a nearby ultraluminous X-ray source (Colbert & Ptak, 2002)). For NGC 7590, we coadded the MOS spectra together using the ftool addspec. We used the total detected and background counts from these spectra to calculate a one-sided 3σ (i.e. 99.9% confidence level) upper limit on the number of source counts. We then obtained an upper limit on the count rate by dividing this source count by the exposure time of the observation. Using an absorbed power law model, which included Galactic absorption, Compton-thick absorption ($N_H = 1.5 \times 10^{24}$ cm$^{-2}$, which is a conservative estimate as neither source was detected in X-rays) at the redshift of the source and a photon index of 1.8, we calculated the 2-10 keV flux that corresponds to the 3σ upper limit on the count rate. These upper limits are listed in Table 3.8. We note that applying this method to NGC 5953 results in a higher X-ray flux upper limit than extrapolating the spectral fit of the soft emission to higher energies, $\sim 2 \times 10^{-13}$ erg s$^{-1}$ cm$^{-2}$ vs $\sim 5 \times 10^{-14}$ erg s$^{-1}$ cm$^{-2}$. We choose the latter value since this is based on the spectral information we have for this source.
3.4 Fe Kα Detection

As noted above, we used a Gaussian component to model the neutral Fe Kα emission. In many cases, this feature was evident when fitting the 0.5 - 8 keV spectrum. For the sources where this line was not visible, we tested for its presence using the ZGAUSS model, freezing the energy at 6.4 keV and the width at 0.01 keV and inputting the galaxy’s redshift. From this fit, we can derive either a detection or upper limit on the neutral Fe Kα flux and possibly EW.

We tested the significance of the Fe Kα EW detections by running simulations based on the power law(s) only component(s) of the local fit, 1000 spectra for each Fe Kα detection. We fit these simulated spectra with a Gaussian (or ZGAUSS) component to estimate the null hypothesis distribution of line normalizations. Then the percentage of times that the observed line normalization exceeded the simulated line normalizations gives the statistical significance of the line.

3.4.1 [OIII] Sample

We detected the Fe Kα emission-line in nine of the [OIII] sources. For five cases with the highest signal-to-noise (IC 0486, 2MASX J08244333+2959238, CGCG 064-017, 2MASX J12384342+0927362 and CGCG 218-007) we were able to measure the energy and, for 4 of these, the width of the Kα line while the other 4 detected sources were fit with ZGAUSS. The simulation results indicate that the chance of detecting the Fe Kα line at or above the observed value due to random variations is less than 1% for IC 0486, 2MASX J08244333+2959238, CGCG 064-017, Mrk 1457, 2MASX J11570483+5249036, 2MASX J12384342+0927362 and CGCG 218-007; less than 6% for Mrk 0609, and less than 14% for 2MASX J12183945+4706275. Data-to-model ratio plots for the 5 cases with the highest signal to noise are shown in Figure 3.5, where the spectra were fit without the line component; the presence of residuals at

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3We performed rigorous error analysis on a sub-set of these simulated spectra and found no statistical significant change in the Fe Kα detection when new global minimizations were found.

4For the 5 cases with fitted Fe Kα line energy, the fitted energy is consistent with the rest-frame Fe Kα energy, 6.4 keV.
the Fe Kα energy indicate that this line is present. For the 8 undetected targets, we were only able to obtain 3-σ upper limits on the flux. The measurements for all 17 sources are listed in Table 3.9, where the Fe Kα luminosities and EWs are the observed values.

As this work represents the first X-ray analysis of these sources, we investigated the Fe Kα emission in more detail. The 5 targets for which we were able to measure the energy of the Fe Kα line were also fit with a diskline model (Fabian et al., 1989) which applies to Fe Kα emission resulting from reflection of photons off the accretion disk. The results are listed in Table 3.10. The inclination angle was constrained for 3 targets (IC 0486, 2MASX J08244333+2959238, and 2MASX J12384342+0927362), indicating that these lines are likely Doppler broadened. The EWs derived from the diskline model are listed in Table 3.10. However, this model does not provide an improved fit over the use of a Gaussian component to model the Fe Kα line and we therefore use the results from the Gaussian fits in the following analysis.

3.4.2 12µm Sample

For the 12µm sources that had both XMM-Newton and Chandra observations and had evidence of extended emission in the XMM-Newton field of view (i.e. NGC 1386, F05189-2524, NGC 3982, NGC 4501 and Mrk 463), we used only the Chandra spectrum to model the Fe Kα emission to isolate the AGN contribution.

To better constrain the EW of the neutral Fe Kα line, we also fit the local continuum, from 3-4 keV to 8 keV, with a power law or double absorbed power law with an absorption component attenuating the second power law (when the spectral shape required this extra model). We then added a Gaussian or ZGAUSS component to this local continuum fit. The results of the global and local continuum fits to the neutral Fe Kα line are listed in Table 3.11. In some cases (e.g. NGC 424, NGC 1386), the local fit better constrains the underlying continuum and therefore leads to a more reliable value for the EW. We use the EWs from the local fits in the subsequent analysis.
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</tr>
<tr>
<td>IC 0486(^1)</td>
<td>0.03</td>
<td>1.25(^{+0.07}_{-0.06})</td>
<td>1.08(^{+0.09}_{-0.08}) =(\Gamma_1)</td>
<td>495.9 (448)</td>
<td>758.1 (449)</td>
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<tr>
<td>2MASX J08035923+2345201</td>
<td>0.28(^{+0.17}_{-0.23})</td>
<td>4.66(^{+2.63}_{-1.70})</td>
<td>67.0(^{+30.0}_{-30.4}) =(\Gamma_1)</td>
<td>28.4 (42)</td>
<td>41.4 (44)</td>
<td></td>
</tr>
<tr>
<td>2MASX J08244333+2959238 (^1)</td>
<td>0.03</td>
<td>2.72(^{+0.12}_{-0.11})</td>
<td>22.9(^{+2.3}_{-1.7}) =(\Gamma_1)</td>
<td>227.1 (165)</td>
<td>924 (169)</td>
<td></td>
</tr>
<tr>
<td>CGCG 064-017</td>
<td>0.77(^{+0.05}_{-0.06})</td>
<td>1.88(^{+0.08}_{-0.08})</td>
<td></td>
<td></td>
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<td>205.7 (267)</td>
</tr>
<tr>
<td>2MASX J10181928+3722419(^2)</td>
<td>0.01</td>
<td>3.17(^{+0.38}_{-0.33})</td>
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<td></td>
<td>72.9 (63)</td>
</tr>
<tr>
<td>2MASX J11110693+0228477(^1)</td>
<td>0.04</td>
<td>1.97(^{+0.25}_{-0.25})</td>
<td>5.75(^{+1.76}_{-1.76}) =(\Gamma_1)</td>
<td>58.6 (40)</td>
<td>111.9 (42)</td>
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</tr>
<tr>
<td>SBS 1133+572</td>
<td>0.07(^{+0.07}_{-0.05})</td>
<td>3.30(^{+0.54}_{-0.45})</td>
<td>61.2(^{+66.8}_{-28.3}) =(\Gamma_1)</td>
<td>40.8 (50)</td>
<td>57.4 (52)</td>
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</tr>
<tr>
<td>Mrk 1457</td>
<td>0.11(^{+0.09}_{-0.04})</td>
<td>3.36(^{+1.09}_{-0.82})</td>
<td>32.1(^{+6.5}_{-4.9}) =(\Gamma_1)</td>
<td>52.7 (37)</td>
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<tr>
<td>2MASX J11570483+5249036</td>
<td>0.06(^{+0.05}_{-0.05})</td>
<td>3.10(^{+0.51}_{-0.41})</td>
<td>127(^{+38}_{-42}) =(\Gamma_1)</td>
<td>98.4 (57)</td>
<td>159.1 (59)</td>
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<tr>
<td>2MASX J12183945+4706275(^1)</td>
<td>0.02</td>
<td>2.87(^{+0.38}_{-0.43})</td>
<td>89.6(^{+51.4}_{-38.3}) =(\Gamma_1)</td>
<td>21.1 (21)</td>
<td>54.5 (23)</td>
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</tr>
<tr>
<td>2MASX J12384342+0927362</td>
<td>0.03(^{+0.05}_{-0.01})</td>
<td>2.60(^{+0.38}_{-0.23})</td>
<td>33.8(^{+3.8}_{-3.2}) =(\Gamma_1)</td>
<td>179.6 (124)</td>
<td>777.3 (126)</td>
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</tr>
<tr>
<td>CGCG 218-007</td>
<td>0.06(^{+0.34}_{-0.04})</td>
<td>2.74(^{+2.40}_{-0.67})</td>
<td>44.5(^{+12.5}_{-10.3}) =(\Gamma_1)</td>
<td>57.6 (64)</td>
<td>140.6 (68)</td>
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</tr>
<tr>
<td>NGC 5695</td>
<td>0.06(^{+0.24}_{-0.05})</td>
<td>3.01(^{+2.16}_{-0.70})</td>
<td></td>
<td></td>
<td></td>
<td>79.7(64)</td>
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</table>

**Target**

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<th>(\Gamma_1)</th>
<th>(N_H) (10(^{22}) cm(^{-2}))</th>
<th>(\Gamma_2)</th>
<th>c-stat</th>
<th>c-stat 1pow</th>
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<td>(DOF)</td>
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Table 3.3 (cont’d)

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<th>Galaxy</th>
<th>$N_{H,1}$</th>
<th>$\Gamma_1$</th>
<th>$N_{H,2}$</th>
<th>$\Gamma_2$</th>
<th>$\chi^2$</th>
<th>$\chi^2$ 1pow</th>
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<td></td>
<td>$10^{22}$ cm$^{-2}$</td>
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<td>(DOF)</td>
<td>(DOF)</td>
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<tr>
<td>NGC 0291</td>
<td>0.09$^{+0.05}_{-0.09}$</td>
<td>2.98$^{+1.35}_{-0.87}$</td>
<td>64.9$^{+51.1}_{-34.4}$</td>
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<td>57.5 (43)</td>
</tr>
<tr>
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<td>113.2 (93)</td>
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<tr>
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<td>1.8</td>
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</tbody>
</table>

$^1$Best fit absorption same as Galactic absorption.

$^2$Absorption frozen at Galactic value to fit $\Gamma$ at a physical value.

$^3$$\Gamma$ frozen at 1.8 and absorption frozen at Galactic value to constrain spectral fit.
Table 3.4. [OIII] Sample: Parameters for Thermal + Powerlaw Fits

<table>
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<tr>
<th>Galaxy</th>
<th>$N_{H,1}$</th>
<th>kT$^1$</th>
<th>abund</th>
<th>$\Gamma_1$</th>
<th>$N_{H,2}$</th>
<th>$\Gamma_2$</th>
<th>$\chi^2$ (DOF)</th>
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</thead>
<tbody>
<tr>
<td>Mrk 0609$^2$</td>
<td>0.04</td>
<td>0.27$^{+0.05}_{-0.04}$</td>
<td>1</td>
<td>1.77$^{+0.05}_{-0.04}$</td>
<td></td>
<td></td>
<td>159.7 (203)</td>
</tr>
<tr>
<td>IC 0486</td>
<td>0.06$^{+0.09}_{-0.03}$</td>
<td>$&lt;0.17$</td>
<td>1</td>
<td>1.22$^{+0.08}_{-0.07}$</td>
<td>1.0$^{+0.1}_{-0.1}$</td>
<td>=\Gamma_1</td>
<td>489.2 (445)</td>
</tr>
<tr>
<td>2MASX J08035923+2345201</td>
<td>0.53$^{+0.15}_{-0.37}$</td>
<td>$&lt;0.12$</td>
<td>1</td>
<td>5.16$^{+0.99}_{-3.70}$</td>
<td>19.7$^{+16.4}_{-17.3}$</td>
<td>1.8</td>
<td>23.9 (40)</td>
</tr>
<tr>
<td>2MASX J08244333+2959238$^2$</td>
<td>0.03</td>
<td>0.18$^{+0.04}_{-0.05}$</td>
<td>1</td>
<td>2.49$^{+0.18}_{-0.19}$</td>
<td>22.1$^{+2.3}_{-1.9}$</td>
<td>=\Gamma_1</td>
<td>214.9 (163)</td>
</tr>
<tr>
<td>CGCG 064-017</td>
<td>0.80$^{+0.07}_{-0.07}$</td>
<td>-</td>
<td>1</td>
<td>1.90$^{+0.10}_{-0.09}$</td>
<td></td>
<td></td>
<td>204.4 (265)</td>
</tr>
<tr>
<td>2MASX J10181928+3722419</td>
<td>0.12$^{+0.26}_{-0.11}$</td>
<td>$&lt;0.20$</td>
<td>1</td>
<td>3.41$^{+2.35}_{-1.31}$</td>
<td></td>
<td></td>
<td>51.1 (60)</td>
</tr>
<tr>
<td>2MASX J11110693+0228477</td>
<td>0.06$^{+0.09}_{-0.02}$</td>
<td>0.22$^{+0.07}_{-0.06}$</td>
<td>1</td>
<td>1.72$^{+0.86}_{-0.65}$</td>
<td>5.2$^{+1.8}_{-1.3}$</td>
<td>=\Gamma_1</td>
<td>54.3(37)</td>
</tr>
<tr>
<td>SBS 1133+572</td>
<td>0.03$^{+0.08}_{-0.02}$</td>
<td>0.83$^{+0.23}_{-0.20}$</td>
<td>1</td>
<td>3.06$^{+0.38}_{-0.30}$</td>
<td>37.9$^{+49.1}_{-21.3}$</td>
<td>1.8</td>
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</tr>
<tr>
<td>Mrk 1457</td>
<td>0.53$^{+0.14}_{-0.12}$</td>
<td>0.14$^{+0.03}_{-0.03}$</td>
<td>1</td>
<td>1.64$^{+0.68}_{-1.00}$</td>
<td>27.6$^{+10.3}_{-7.0}$</td>
<td>=\Gamma_1</td>
<td>35.3(35)</td>
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<tr>
<td>2MASX J11570483+5249036</td>
<td>0.05$^{+0.07}_{-0.03}$</td>
<td>0.26$^{+0.05}_{-0.03}$</td>
<td>1</td>
<td>2.69$^{+0.51}_{-0.38}$</td>
<td>123$^{+54}_{-44}$</td>
<td>=\Gamma_1</td>
<td>79.5(55)</td>
</tr>
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<td>2MASX J12183945+4706275$^2$</td>
<td>0.02</td>
<td>$&lt;0.24$</td>
<td>1</td>
<td>1.96$^{+0.70}_{-0.86}$</td>
<td>90.3$^{+62.7}_{-36.8}$</td>
<td>=\Gamma_1</td>
<td>15.0 (19)</td>
</tr>
<tr>
<td>2MASX J12384342+0927362</td>
<td>0.03$^{+0.06}_{-0.02}$</td>
<td>$&lt;0.22$</td>
<td>1</td>
<td>2.37$^{+0.45}_{-0.28}$</td>
<td>32.6$^{+1.1}_{-1.2}$</td>
<td>=\Gamma_1</td>
<td>167.6 (122)</td>
</tr>
<tr>
<td>CGCG 218-007</td>
<td>0.02$^{+0.18}_{-0.01}$</td>
<td>-</td>
<td>1</td>
<td>2.55$^{+1.64}_{-0.51}$</td>
<td>43.7$^{+4.7}_{-7.6}$</td>
<td>=\Gamma_1</td>
<td>56.0 (62)</td>
</tr>
<tr>
<td>NGC 5695$^2$</td>
<td>0.01</td>
<td>0.25$^{+0.74}_{-0.13}$</td>
<td>1</td>
<td>2.41$^{+0.60}_{-0.39}$</td>
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<td>75.8 (63)</td>
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Target

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<th>$N_H$</th>
<th>kT</th>
<th>abund</th>
<th>$\Gamma_1$</th>
<th>$N_H$</th>
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<td></td>
<td>$10^{22}$ cm$^{-2}$</td>
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<td>Galaxy</td>
<td>$N_{H,1}$/$10^{22}$ cm$^{-2}$</td>
<td>$kT^1$/keV</td>
<td>abund</td>
<td>$\Gamma_1$</td>
<td>$N_{H,2}$/$10^{22}$ cm$^{-2}$</td>
<td>$\Gamma_2$</td>
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<td>------------------------</td>
<td>------------------------------</td>
<td>------------</td>
<td>---------</td>
<td>-----------</td>
<td>-------------------------------</td>
<td>------------</td>
</tr>
<tr>
<td>NGC 0291</td>
<td>$0.10^{+0.26}_{-0.06}$</td>
<td>$0.20^{+0.13}_{-0.07}$</td>
<td>$&lt;2.8$</td>
<td>$2.60^{+0.36}_{-0.34}$</td>
<td>$67.4^{+46.6}_{-39.3}$</td>
<td>$=\Gamma_1$</td>
</tr>
<tr>
<td>CGCG 242-028</td>
<td>$0.68^{+0.70}_{-0.50}$</td>
<td>$&lt;0.12$</td>
<td>$&lt;0.16$</td>
<td>$0.21^{+0.39}_{-0.39}$</td>
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</tr>
<tr>
<td>2MASX J13463217+6423247$^3$</td>
<td>$0.42^{+0.22}_{-0.40}$</td>
<td>$&lt;0.13$</td>
<td>1</td>
<td>1.8</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$^1$“-” denotes unconstrained parameter.

$^2$Best fit absorption is same as Galactic absorption.

$^3$\(\Gamma\) frozen to 1.8 to constrain spectral fit.
### Table 3.5. 12µm Sample: APEC model parameters (solar abundance)

<table>
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<tr>
<th>Galaxy</th>
<th>(N_{H,1})</th>
<th>kT</th>
<th>(\Gamma)</th>
<th>(N_{H,2})</th>
<th>(\chi^2)</th>
<th>(\chi^2) 2pow</th>
<th>(\chi^2) 1pow</th>
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</thead>
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<td>keV</td>
<td></td>
<td>10(^{22}) cm(^{-2})</td>
<td>DOF</td>
<td>DOF</td>
<td>DOF</td>
</tr>
<tr>
<td>NGC 0424(^2)</td>
<td>0.05(^{+0.04}_{-0.03})</td>
<td>0.82(^{+0.18}_{-0.17})</td>
<td>2.85(^{+0.32}_{-0.28})</td>
<td>16.8(^{+5.8}_{-3.5})</td>
<td>269.5 (171)</td>
<td>273.8 (173)</td>
<td>846.4 (178)</td>
</tr>
<tr>
<td>NGC 1068</td>
<td>0.31(^{+0.03}_{-0.03})</td>
<td>0.61(^{+0.01}_{-0.01})</td>
<td>2.02(^{+0.59}_{-0.45})</td>
<td>9.33(^{+1.77}_{-2.68})</td>
<td>450.4 (247)</td>
<td>1013 (249)</td>
<td>6634 (269)</td>
</tr>
<tr>
<td>NGC 1144(^1)</td>
<td>0.06</td>
<td>0.37(^{+0.29}_{-0.06})</td>
<td>1.91(^{+0.37}_{-0.24})</td>
<td>47.0(^{+3.5}_{-3.2})</td>
<td>174.7 (149)</td>
<td>216.8 (151)</td>
<td>1347 (156)</td>
</tr>
<tr>
<td>NGC 1320</td>
<td>0.07(^{+0.03}_{-0.02})</td>
<td>0.78(^{+0.07}_{-0.07})</td>
<td>3.30(^{+0.22}_{-0.19})</td>
<td>43.5(^{+81.5}_{-12.3})</td>
<td>269.1 (170)</td>
<td>311.2 (172)</td>
<td>639.9 (177)</td>
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<tr>
<td>NGC 1386</td>
<td>0.04(^{+0.03}_{-0.02})</td>
<td>0.66(^{+0.04}_{-0.03})</td>
<td>2.97(^{+0.27}_{-0.22})</td>
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<td>2.18(^{+0.34}_{-0.37})</td>
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<td>49.8 (38)</td>
<td>...</td>
<td>82.3 (39)</td>
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<td>6.75(^{+0.40}_{-0.41})</td>
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<td>NGC 3982(^3,6)</td>
<td>0.53(^{+0.11}_{-0.16})</td>
<td>&lt;0.12</td>
<td>0.57(^{+1.14}_{-0.90})</td>
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<td>21.7 (16)</td>
<td>...</td>
<td>45.7 (18)</td>
</tr>
<tr>
<td>NGC 4388 (Chandra)</td>
<td>1.47(^{+0.49}_{-0.53})</td>
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<td>0.92(^{+0.27}_{-0.45})</td>
<td>29.2(^{+3.1}_{-4.3})</td>
<td>110.6 (92)</td>
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<td>58.9 (40)</td>
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<td>51.0 (77)</td>
<td>...</td>
<td>72.6 (78)</td>
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<tr>
<td>NGC 4968(^6)</td>
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<td>&lt;0.13</td>
<td>1.50(^{+0.41}_{-0.31})</td>
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<td>343.0 (267)</td>
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<td>337.8 (270)</td>
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<td>0.79(^{+0.02}_{-0.02})</td>
<td>2.68(^{+0.10}_{-0.09})</td>
<td>46.7(^{+1.6}_{-1.6})</td>
<td>847.5 (493)</td>
<td>1660 (495)</td>
<td>8590 (500)</td>
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<td>( \text{keV} )</td>
<td>( \Gamma )</td>
<td>( N_{H,2} )</td>
<td>( \chi^2 )</td>
<td>( \chi^2 )</td>
<td>( \chi^2 )</td>
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<td>( 10^{22} ) cm(^{-2} )</td>
<td>DOF</td>
<td>2pow DOF</td>
<td>1pow DOF</td>
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<td>2.78(^{+0.14}_{-0.12} )</td>
<td>104(^{+81}_{-70} )</td>
<td>194.8 (132)</td>
<td>200.8 (134)</td>
<td>317.8 (138)</td>
</tr>
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<td>0.65(^{+0.05}_{-0.04} )</td>
<td>2.20(^{+0.16}_{-0.17} )</td>
<td>90.1(^{+62.9}_{-43.1} )</td>
<td>274.0 (231)</td>
<td>445.2 (232)</td>
<td>944.9 (237)</td>
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<td>&lt;0.24</td>
<td>1.19(^{+0.24}_{-0.26} )</td>
<td>63.6(^{+37.4}_{-25.7} )</td>
<td>31.8 (22)</td>
<td>36.9 (24)</td>
<td>78.4 (26)</td>
</tr>
<tr>
<td>Mrk 463</td>
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<td>0.73(^{+0.03}_{-0.04} )</td>
<td>2.02(^{+0.27}_{-0.12} )</td>
<td>26.5(^{+4.9}_{-4.6} )</td>
<td>334.2 (263)</td>
<td>600.3 (268)</td>
<td>1505 (270)</td>
</tr>
<tr>
<td>NGC 5506(^7 )</td>
<td>0.11(^{+0.01}_{-0.01} )</td>
<td>0.77(^{+0.04}_{-0.05} )</td>
<td>1.71(^{+0.01}_{-0.01} )</td>
<td>2.68(^{+0.03}_{-0.03} )</td>
<td>2720 (2385)</td>
<td>2781 (2387)</td>
<td>15637 (2389)</td>
</tr>
<tr>
<td>NGC 5506(^8 )</td>
<td>0.13(^{+0.01}_{-0.01} )</td>
<td>0.85(^{+0.10}_{-0.03} )</td>
<td>1.77(^{+0.01}_{-0.0} )</td>
<td>2.80(^{+0.01}_{-0.02} )</td>
<td>4171 (3143)</td>
<td>4299 (3145)</td>
<td>31991 (3147)</td>
</tr>
<tr>
<td>Arp 220 (XMM)(^{1,4} )</td>
<td>0.04</td>
<td>0.82(^{+0.05}_{-0.05} )</td>
<td>1.27(^{+0.15}_{-0.15} )</td>
<td>...</td>
<td>146.0 (145)</td>
<td>...</td>
<td>248.4 (147)</td>
</tr>
<tr>
<td>Arp 220 (Chandra)</td>
<td>0.47(^{+0.07}_{-0.06} )</td>
<td>&quot;</td>
<td>&quot;</td>
<td>...</td>
<td>&quot;</td>
<td>...</td>
<td>&quot;</td>
</tr>
<tr>
<td>NGC 6890(^6 )</td>
<td>&lt;0.10</td>
<td>0.78(^{+0.24}_{-0.19} )</td>
<td>3.28(^{+0.88}_{-0.74} )</td>
<td>27.4(^{+18.4}_{-11.3} )</td>
<td>164.0 (148)</td>
<td>171.3 (150)</td>
<td>197.4 (152)</td>
</tr>
<tr>
<td>IC 5063(^9 )</td>
<td>0.64(^{+0.26}_{-0.43} )</td>
<td>0.43(^{+0.17}_{-0.22} )</td>
<td>1.39(^{+0.41}_{-0.26} )</td>
<td>19.6(^{+2.3}_{-2.4} )</td>
<td>131.0 (116)</td>
<td>135.6 (119)</td>
<td>452.5 (120)</td>
</tr>
<tr>
<td>NGC 7130(^6 )</td>
<td>&lt;0.08</td>
<td>0.76(^{+0.04}_{-0.04} )</td>
<td>2.41(^{+0.27}_{-0.26} )</td>
<td>64.1(^{+58.9}_{-23.3} )</td>
<td>220.7 (199)</td>
<td>381.8 (201)</td>
<td>563.9 (206)</td>
</tr>
<tr>
<td>NGC 7172(^{1,5} )</td>
<td>0.02</td>
<td>0.26(^{+0.03}_{-0.02} )</td>
<td>1.55(^{+0.03}_{-0.01} )</td>
<td>7.74(^{+0.09}_{-0.08} )</td>
<td>2330 (1748)</td>
<td>2530 (1750)</td>
<td>5379 (1751)</td>
</tr>
<tr>
<td>NGC 7582 (XMM)(^{1,5} )</td>
<td>0.01</td>
<td>0.71(^{+0.01}_{-0.01} )</td>
<td>1.95(^{+0.03}_{-0.02} )</td>
<td>26.0(^{+1.5}_{-1.5} )</td>
<td>1586 (886)</td>
<td>4044 (903)</td>
<td>15004 (910)</td>
</tr>
<tr>
<td>NGC 7582 (Chandra)(^5 )</td>
<td>1.24(^{+0.07}_{-0.10} )</td>
<td>&lt;0.11</td>
<td>1.80(^{+0.42}_{-0.04} )</td>
<td>19.8(^{+2.3}_{-2.0} )</td>
<td>104.9 (81)</td>
<td>117.5 (83)</td>
<td>305.2 (85)</td>
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</table>
Table 3.5 (cont’d)

<table>
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<tr>
<th>Galaxy</th>
<th>$N_{H,1}$ $10^{22}$ cm$^{-2}$</th>
<th>kT keV</th>
<th>$N_{H,2}$ $10^{22}$ cm$^{-2}$</th>
<th>$\chi^2$</th>
<th>$\chi^2$ 2pow</th>
<th>$\chi^2$ 1pow</th>
<th>DOF</th>
<th>DOF</th>
<th>DOF</th>
</tr>
</thead>
<tbody>
<tr>
<td>NGC 7674$^1$</td>
<td>0.04</td>
<td>0.70$^{+0.13}_{-0.09}$</td>
<td>2.92$^{+0.16}_{-0.15}$</td>
<td>34.7$^{+10.3}_{-7.3}$</td>
<td>112.9 (72)</td>
<td>129.6 (74)</td>
<td>342.4 (75)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1Best-fit $N_H$ was same as Galactic value and therefore frozen at this value.

2Best-fit parameters between Chandra and XMM-Newton observations are consistent.

3Best-fit parameters between Chandra and XMM-Newton observations differ due to presence of extended emission in XMM field of view. Parameters for the Chandra observation, which isolates the point source, are listed.

4Best-fit parameters between Chandra and XMM-Newton observations differ due to variability.

5Second power law component normalizations fit independently between the two XMM-Newton observations.

6Used c-stat.


8XMM-Newton observations from Jan 9, 2002; Aug 7, 2004; Jul 27, 2008 and Jan 2, 2009.

9Used pileup model.
<table>
<thead>
<tr>
<th>Galaxy</th>
<th>$N_{H,1}$ ($\times 10^{22}$ cm$^{-2}$)</th>
<th>$\Gamma$</th>
<th>$N_{H,2}$ ($\times 10^{22}$ cm$^{-2}$)</th>
<th>$\chi^2$</th>
<th>DOF</th>
</tr>
</thead>
<tbody>
<tr>
<td>NGC 0424</td>
<td>$0.07^{+0.03}_{-0.03}$</td>
<td>$2.97^{+0.27}_{-0.26}$</td>
<td>$16.9^{+6.0}_{-3.0}$</td>
<td>273.8</td>
<td>(173)</td>
</tr>
<tr>
<td>NGC 4388 (Chandra)</td>
<td>$0.22^{+0.24}_{-0.15}$</td>
<td>$0.38^{+0.39}_{-0.36}$</td>
<td>$23.3^{+3.5}_{-3.1}$</td>
<td>121.7</td>
<td>(94)</td>
</tr>
<tr>
<td>NGC 4968$^{1,2}$</td>
<td>0.08</td>
<td>$1.94^{+0.14}_{-0.13}$</td>
<td>...</td>
<td>337.8</td>
<td>(270)</td>
</tr>
<tr>
<td>NGC 5135$^1$</td>
<td>0.05</td>
<td>$2.75^{+0.11}_{-0.10}$</td>
<td>$118^{+82}_{-60}$</td>
<td>200.8</td>
<td>(134)</td>
</tr>
<tr>
<td>NGC 5347$^1$</td>
<td>0.02</td>
<td>$1.41^{+0.24}_{-0.22}$</td>
<td>$56.2^{+31.9}_{-22.9}$</td>
<td>36.9</td>
<td>(24)</td>
</tr>
<tr>
<td>NGC 5953$^{1,2}$</td>
<td>0.03</td>
<td>$2.10^{+0.63}_{-0.65}$</td>
<td>...</td>
<td>39.9</td>
<td>(21)</td>
</tr>
<tr>
<td>NGC 6890$^2$</td>
<td>$0.21^{+0.11}_{-0.09}$</td>
<td>$3.86^{+0.75}_{-0.64}$</td>
<td>$18.9^{+16.5}_{-11.0}$</td>
<td>171.3</td>
<td>(150)</td>
</tr>
<tr>
<td>IC 5063$^{1,3}$</td>
<td>0.06</td>
<td>$1.48^{+0.26}_{-0.25}$</td>
<td>$20.5^{+1.4}_{-1.4}$</td>
<td>135.6</td>
<td>(119)</td>
</tr>
<tr>
<td>NGC 7582 (Chandra)$^3$</td>
<td>$&lt;0.23$</td>
<td>$1.63^{+0.50}_{-0.40}$</td>
<td>$18.8^{+2.9}_{-2.1}$</td>
<td>117.5</td>
<td>(83)</td>
</tr>
<tr>
<td>NGC 7674$^1$</td>
<td>0.04</td>
<td>$2.86^{+0.12}_{-0.11}$</td>
<td>$36.9^{+12.4}_{-7.7}$</td>
<td>129.6</td>
<td>(74)</td>
</tr>
</tbody>
</table>

$^1$Best-fit $N_H$ was same as Galactic value and therefore frozen at this value.

$^2$Used c-stat.

$^3$Used pileup model.
<table>
<thead>
<tr>
<th>Galaxy</th>
<th>$F_{2-10\text{keV}}$ (10$^{-13}$ erg/s/cm$^2$)</th>
<th>$\log L_{2-10\text{keV}}$ (erg s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NGC 0291</td>
<td>1.26$^{+13.9}_{-1.06}$</td>
<td>41.0$^{+1.0}_{-0.8}$</td>
</tr>
<tr>
<td>Mrk 0609</td>
<td>15.3$^{+15.3}_{-7.64}$</td>
<td>42.6$^{+0.3}_{-0.3}$</td>
</tr>
<tr>
<td>IC 0486</td>
<td>49.0$^{+49.0}_{-24.4}$</td>
<td>42.9$^{+0.3}_{-0.3}$</td>
</tr>
<tr>
<td>2MASX J08035923+2345201</td>
<td>0.27$^{+0.58}_{-0.21}$</td>
<td>40.7$^{+0.5}_{-0.7}$</td>
</tr>
<tr>
<td>2MASX J08244333+2959238</td>
<td>9.09$^{+9.09}_{-4.53}$</td>
<td>42.1$^{+0.3}_{-0.3}$</td>
</tr>
<tr>
<td>CGCG 064-017</td>
<td>12.2$^{+12.2}_{-6.07}$</td>
<td>42.5$^{+0.3}_{-0.3}$</td>
</tr>
<tr>
<td>2MASX J10181928+372419</td>
<td>0.03$^{+0.03}_{-0.01}$</td>
<td>40.2$^{+0.3}_{-0.3}$</td>
</tr>
<tr>
<td>2MASX J11110693+0228477</td>
<td>1.15$^{+1.73}_{-0.57}$</td>
<td>41.5$^{+0.4}_{-0.3}$</td>
</tr>
<tr>
<td>CGCG 242-028</td>
<td>1.44$^{+1.43}_{-0.72}$</td>
<td>41.3$^{+0.3}_{-0.3}$</td>
</tr>
<tr>
<td>SBS 1133+572</td>
<td>0.66$^{+1.98}_{-0.45}$</td>
<td>41.6$^{+0.6}_{-0.5}$</td>
</tr>
<tr>
<td>Mrk 1457</td>
<td>2.87$^{+6.29}_{-1.73}$</td>
<td>42.2$^{+0.5}_{-0.4}$</td>
</tr>
<tr>
<td>2MASX J11570483+5249036</td>
<td>1.08$^{+1.64}_{-0.74}$</td>
<td>41.5$^{+0.4}_{-0.5}$</td>
</tr>
<tr>
<td>2MASX J12183945+4706275</td>
<td>1.46$^{+2.20}_{-1.09}$</td>
<td>42.5$^{+0.4}_{-0.6}$</td>
</tr>
<tr>
<td>2MASX J12384342+0927362</td>
<td>9.52$^{+9.52}_{-4.75}$</td>
<td>43.2$^{+0.3}_{-0.3}$</td>
</tr>
<tr>
<td>CGCG 218-007</td>
<td>7.77$^{+7.77}_{-5.31}$</td>
<td>42.1$^{+0.3}_{-0.5}$</td>
</tr>
<tr>
<td>2MASX J13463217+6423247</td>
<td>0.16$^{+0.16}_{-0.08}$</td>
<td>40.3$^{+0.3}_{-0.3}$</td>
</tr>
<tr>
<td>NGC 5695</td>
<td>0.09$^{+0.14}_{-0.05}$</td>
<td>39.6$^{+0.4}_{-0.3}$</td>
</tr>
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</table>
Table 3.8. 12\(\mu\)m Sample: 2 - 10 keV X-ray Flux and Luminosity Values

<table>
<thead>
<tr>
<th>Galaxy</th>
<th>(F_{2-10keV}) (10^{-13}) erg/s/cm(^2)</th>
<th>Log (L_{2-10keV}) erg/s</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>NGC 0424</td>
<td>(11.5^{+6.4}_{-3.7})</td>
<td>(41.56^{+0.19}_{-0.17})</td>
<td></td>
</tr>
<tr>
<td>NGC 1068</td>
<td>(54.2^{+310}_{-32.0})</td>
<td>(41.27^{+0.48}_{-0.39})</td>
<td></td>
</tr>
<tr>
<td>NGC 1144</td>
<td>(33.4^{+36.6}_{-12.9})</td>
<td>(42.77^{+0.32}_{-0.21})</td>
<td></td>
</tr>
<tr>
<td>NGC 1320</td>
<td>(3.84^{+2.83}_{-1.39})</td>
<td>(40.83^{+0.24}_{-0.20})</td>
<td></td>
</tr>
<tr>
<td>NGC 1386</td>
<td>(1.55^{+0.42}_{-0.50})</td>
<td>(39.48^{+0.10}_{-0.17})</td>
<td>Chandra observation</td>
</tr>
<tr>
<td>NGC 1667</td>
<td>(0.43^{+0.11}_{-0.11})</td>
<td>(40.33^{+0.10}_{-0.13})</td>
<td></td>
</tr>
<tr>
<td>F05189-2524</td>
<td>(23.5^{+5.5}_{-4.9})</td>
<td>(43.00^{+0.09}_{-0.10})</td>
<td>Chandra observations</td>
</tr>
<tr>
<td>F08572+3915</td>
<td>&lt;1.26</td>
<td>&lt;42.02</td>
<td></td>
</tr>
<tr>
<td>NGC 3982</td>
<td>(0.56^{+1.28}_{-0.39})</td>
<td>(39.28^{+0.52}_{-0.52})</td>
<td>Chandra observation</td>
</tr>
<tr>
<td>NGC 4388</td>
<td>(74.6^{+88.5}_{-38.5})</td>
<td>(42.01^{+0.34}_{-0.32})</td>
<td>Chandra observation</td>
</tr>
<tr>
<td></td>
<td>(86.9^{+28.6}_{-17.7})</td>
<td>(42.08^{+0.12}_{-0.10})</td>
<td>XMM Jul 2002 observation</td>
</tr>
<tr>
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<td>(244^{+76}_{-47})</td>
<td>(42.53^{+0.12}_{-0.09})</td>
<td>XMM Dec 2002 observation</td>
</tr>
<tr>
<td>NGC 4501</td>
<td>(1.07^{+0.73}_{-0.51})</td>
<td>(40.17^{+0.23}_{-0.28})</td>
<td>Chandra observation</td>
</tr>
<tr>
<td>TOLOLO 1238-364</td>
<td>(1.21^{+0.31}_{-0.26})</td>
<td>(40.50^{+0.10}_{-0.11})</td>
<td></td>
</tr>
<tr>
<td>NGC 4968</td>
<td>(2.08^{+0.26}_{-0.26})</td>
<td>(40.65^{+0.05}_{-0.06})</td>
<td></td>
</tr>
<tr>
<td>M-3-34-64</td>
<td>(32.5^{+3.1}_{-3.1})</td>
<td>(42.31^{+0.04}_{-0.04})</td>
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<tr>
<td>NGC 5135</td>
<td>(2.31^{+0.98}_{-1.68})</td>
<td>(40.99^{+0.15}_{-0.56})</td>
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<tr>
<td>Galaxy</td>
<td>$F_{2-10\text{keV}}$ (10^{-13} \text{erg/s/cm}^2)</td>
<td>$\log L_{2-10\text{keV}}$ (\text{erg/s})</td>
<td>Comments</td>
</tr>
<tr>
<td>-----------</td>
<td>-----------------------------------------------</td>
<td>------------------------------------------</td>
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<tr>
<td>NGC 5953</td>
<td>$&lt;0.51$</td>
<td>$&lt;39.73$</td>
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</tr>
<tr>
<td>Arp 220</td>
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<td>$40.88^{+0.07}_{-0.07}$</td>
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<td>$1.20^{+4.01}_{-0.88}$</td>
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<tr>
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<td>$42.55^{+0.19}_{-0.19}$</td>
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<tr>
<td>NGC 7130</td>
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<td>$41.06^{+0.30}_{-0.30}$</td>
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<td>$517^{+43}_{-40}$</td>
<td>$42.96^{+0.03}_{-0.03}$</td>
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<td>$234^{+1.0}_{-1.8}$</td>
<td>$42.61^{+0.30}_{-0.03}$</td>
<td>2002 &amp; 2004 observations</td>
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<tr>
<td>NGC 7582</td>
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<td>$41.05^{+0.03}_{-0.04}$</td>
<td>2005 XMM observation</td>
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<td>$38.6^{+3.0}_{-3.1}$</td>
<td>$41.32^{+0.03}_{-0.04}$</td>
<td>2001 XMM observation</td>
</tr>
<tr>
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<td>$164^{+263}_{-87}$</td>
<td>$41.95^{+0.42}_{-0.33}$</td>
<td>Chandra observations</td>
</tr>
<tr>
<td>NGC 7590</td>
<td>$&lt;2.72$</td>
<td>$&lt;40.17$</td>
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</tr>
<tr>
<td>NGC 7674</td>
<td>$5.71^{+3.05}_{-1.69}$</td>
<td>$42.03^{+0.19}_{-0.15}$</td>
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</tr>
<tr>
<td>Galaxy</td>
<td>Energy(^2)</td>
<td>(\sigma)</td>
<td>EW(^3)</td>
</tr>
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<td>------------------------</td>
<td>--------------</td>
<td>------------</td>
<td>---------</td>
</tr>
<tr>
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<td>6.28 keV</td>
<td>0.01 keV</td>
<td>&lt;3.4</td>
</tr>
<tr>
<td>Mrk 0609</td>
<td>6.19 keV</td>
<td>0.01 keV</td>
<td>0.22(^{+0.15}_{-0.15})</td>
</tr>
<tr>
<td>IC 0486(^4)</td>
<td>6.26(^{+0.03}_{-0.03})</td>
<td>&lt;0.09 keV</td>
<td>0.19(^{+0.26}_{-0.05})</td>
</tr>
<tr>
<td>2MASX J08035923+2345201</td>
<td>6.22 keV</td>
<td>0.01 keV</td>
<td>&lt;1.5</td>
</tr>
<tr>
<td>2MASX J08244333+2959238(^4)</td>
<td>6.26(^{+0.24}_{-0.10})</td>
<td>0.27(^{+0.33}_{-0.10})</td>
<td>0.77(^{+0.74}_{-0.24})</td>
</tr>
<tr>
<td>CGCG 064-017(^4)</td>
<td>6.19(^{+0.25}_{-0.09})</td>
<td>- keV</td>
<td>0.18(^{+0.09}_{-0.09})</td>
</tr>
<tr>
<td>2MASX J10181928+3722419</td>
<td>6.10 keV</td>
<td>0.01 keV</td>
<td>-</td>
</tr>
<tr>
<td>2MASX J11110693+0228477</td>
<td>6.18 keV</td>
<td>0.01 keV</td>
<td>&lt;0.89</td>
</tr>
<tr>
<td>CGCG 242-028</td>
<td>6.24 keV</td>
<td>0.01 keV</td>
<td>&lt;1.8</td>
</tr>
<tr>
<td>SBS 1133+572</td>
<td>6.09 keV</td>
<td>0.01 keV</td>
<td>&lt;1.0</td>
</tr>
<tr>
<td>Mrk 1457</td>
<td>6.15 keV</td>
<td>0.01 keV</td>
<td>1.03(^{+0.44}_{-0.44})</td>
</tr>
<tr>
<td>2MASX J11570483+5249036</td>
<td>6.18 keV</td>
<td>0.01 keV</td>
<td>2.18(^{+0.66}_{-0.71})</td>
</tr>
<tr>
<td>2MASX J12183945+4706275</td>
<td>5.85 keV</td>
<td>0.01 keV</td>
<td>1.11(^{+0.66}_{-0.67})</td>
</tr>
<tr>
<td>2MASX J12384342+0927362(^4)</td>
<td>5.90(^{+0.33}_{-0.03})</td>
<td>&lt;0.09 keV</td>
<td>0.17(^{+0.07}_{-0.06})</td>
</tr>
<tr>
<td>CGCG 218-007(^4)</td>
<td>6.18(^{+0.30}_{-0.12})</td>
<td>0.23(^{+0.28}_{-0.15})</td>
<td>0.76(^{+0.89}_{-0.43})</td>
</tr>
</tbody>
</table>
### Table 3.9 (cont’d)

<table>
<thead>
<tr>
<th>Galaxy</th>
<th>Energy $^2$ (keV)</th>
<th>$\sigma$ (keV)</th>
<th>EW $^3$ (keV)</th>
<th>Flux $^{10^{-14} \text{ erg cm}^{-2} \text{ s}^{-1}}$</th>
<th>log L$_{\text{FeK}\alpha}$ (ergs s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2MASX J13463217+6423247</td>
<td>6.25</td>
<td>0.01</td>
<td>-</td>
<td>&lt;7.1</td>
<td>&lt;40.96</td>
</tr>
<tr>
<td>NGC 5695</td>
<td>6.31</td>
<td>0.01</td>
<td>-</td>
<td>&lt;5.4</td>
<td>&lt;40.36</td>
</tr>
</tbody>
</table>

$^1$Upper limits on EW, flux and luminosity are 3$\sigma$ upper limits; upper limits on $\sigma$ are 90% upper limits.

$^2$Energy in observed frame.

$^3$“-” denotes unconstrained parameter.

$^4$Targets with the highest signal-to-noise for the Fe K$\alpha$ line detection.
Table 3.10.  [OIII] Sample: Double Powerlaw + Diskline Model Parameters\(^1\)

<table>
<thead>
<tr>
<th>Target</th>
<th>(N_{H,1}) (10^{22}) cm(^{-2})</th>
<th>(N_{H,2}) (10^{22}) cm(^{-2})</th>
<th>(\Gamma_2)</th>
<th>Energy</th>
<th>Inclination(^2)</th>
<th>EW keV</th>
<th>(\chi^2) (DOF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>IC 0486(^3)</td>
<td>0.03</td>
<td>1.29(^{+0.06}_{-0.07})</td>
<td>1.11(^{+0.07}_{-0.08})</td>
<td>6.33(^{+0.03}_{-0.03})</td>
<td>&lt;15</td>
<td>0.25(^{+0.05}_{-0.08})</td>
<td>501.4 (448)</td>
</tr>
<tr>
<td>2MASX J08244333+2959238(^3)</td>
<td>0.03</td>
<td>2.74(^{+0.07}_{-0.07})</td>
<td>22.0(^{+1.6}_{-1.6})</td>
<td>6.23(^{+0.08}_{-0.07})</td>
<td>36.2(^{+23.4}_{-9.1})</td>
<td>0.97(^{+0.37}_{-0.21})</td>
<td>224.3 (165)</td>
</tr>
<tr>
<td>CGCG 064-017</td>
<td>0.77(^{+0.06}_{-0.06})</td>
<td>1.88(^{+0.10}_{-0.08})</td>
<td>6.27(^{+0.03}_{-0.19})</td>
<td>-</td>
<td>0.20(^{+0.09}_{-0.09})</td>
<td>206.5 (267)</td>
<td></td>
</tr>
<tr>
<td>2MASX J12384342+0927362</td>
<td>0.07(^{+0.06}_{-0.05})</td>
<td>2.97(^{+0.47}_{-0.39})</td>
<td>29.1(^{+4.0}_{-3.2})</td>
<td>6.13(^{+0.07}_{-0.07})</td>
<td>&gt; 62.1</td>
<td>1.22(^{+0.35}_{-0.38})</td>
<td>177.7 (124)</td>
</tr>
<tr>
<td>CGCG 218-007</td>
<td>0.08(^{+0.34}_{-0.06})</td>
<td>2.89(^{+2.42}_{-0.83})</td>
<td>42.8(^{+14.2}_{-11.5})</td>
<td>6.17(^{+0.15}_{-0.13})</td>
<td>-</td>
<td>1.08(^{+0.86}_{-0.62})</td>
<td>58.1 (64)</td>
</tr>
</tbody>
</table>

\(^1\)The diskline model does not provide a statistically significant improvement over the use of a Gaussian component.

In the cases of a double power law fit, \(\Gamma_2=\$\Gamma_1\) and is not listed separately here.

\(^2\)“-“ denotes unconstrained parameter.

\(^3\)Best-fit absorption same as Galactic absorption.
### Table 3.11. $12\mu$m Sample: Fe Kα Flux and EW

<table>
<thead>
<tr>
<th>Galaxy</th>
<th>Global Fit</th>
<th></th>
<th>Local Fit</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Energy</td>
<td>σ</td>
<td>EW</td>
<td>Energy</td>
</tr>
<tr>
<td></td>
<td>keV</td>
<td>km/s</td>
<td></td>
<td>keV</td>
</tr>
<tr>
<td>NGC 0424$^2$</td>
<td>6.45$^{+0.07}_{-0.07}$</td>
<td>0.42$^{+0.17}_{-0.11}$</td>
<td>4.22$^{+0.88}_{-0.97}$</td>
<td>3.95$^{+0.83}_{-0.91}$</td>
</tr>
<tr>
<td>NGC 1068$^2$</td>
<td>6.40$^{+0.00}_{-0.01}$</td>
<td>&lt;0.03</td>
<td>0.65$^{+0.05}_{-0.05}$</td>
<td>5.52$^{+0.41}_{-0.40}$</td>
</tr>
<tr>
<td>NGC 1144$^3$</td>
<td>6.24$^{+0.02}_{-0.02}$</td>
<td>&lt;0.07</td>
<td>0.26$^{+0.06}_{-0.06}$</td>
<td>1.99$^{+0.49}_{-0.44}$</td>
</tr>
<tr>
<td>NGC 1320$^2$</td>
<td>6.37$^{+0.02}_{-0.03}$</td>
<td>0.06$^{+0.03}_{-0.03}$</td>
<td>3.50$^{+0.49}_{-0.47}$</td>
<td>1.55$^{+0.22}_{-0.21}$</td>
</tr>
<tr>
<td>NGC 1386 (Chandra)$^2$</td>
<td>6.39$^{+0.02}_{-0.03}$</td>
<td>&lt;0.05</td>
<td>3.43$^{+1.39}_{-1.39}$</td>
<td>0.51$^{+0.21}_{-0.21}$</td>
</tr>
<tr>
<td>NGC 1667$^{5,6}$</td>
<td>6.31</td>
<td>0.01</td>
<td>-</td>
<td>0.16$^{+0.10}_{-0.10}$</td>
</tr>
<tr>
<td>F05189-25212 (Chandra)$^6$</td>
<td>6.14</td>
<td>0.01</td>
<td>0.09$^{+0.09}_{-0.08}$</td>
<td>0.28$^{+0.27}_{-0.24}$</td>
</tr>
<tr>
<td>NGC 3982 (Chandra)$^6$</td>
<td>6.37</td>
<td>0.01</td>
<td>-</td>
<td>0.31$^{+0.41}_{-0.22}$</td>
</tr>
<tr>
<td>NGC 4388 (Chandra)$^2$</td>
<td>6.34$^{+0.02}_{-0.03}$</td>
<td>&lt;0.09</td>
<td>0.31$^{+0.08}_{-0.08}$</td>
<td>4.03$^{+1.06}_{-1.05}$</td>
</tr>
<tr>
<td>NGC 4388 (XMM Jul 2002)$^2$</td>
<td>6.37$^{+0.01}_{-0.01}$</td>
<td>&lt;0.09</td>
<td>0.46$^{+0.08}_{-0.08}$</td>
<td>7.05$^{+1.19}_{-1.16}$</td>
</tr>
<tr>
<td>NGC 4388 (XMM Dec 2002)$^2$</td>
<td>6.06$^{+0.02}_{-0.02}$</td>
<td>0.20$^{+0.03}_{-0.03}$</td>
<td>9.20$^{+1.24}_{-1.21}$</td>
<td>6.37$^{+0.01}_{-0.01}$</td>
</tr>
<tr>
<td>NGC 4501 (Chandra)$^6$</td>
<td>6.35</td>
<td>0.01</td>
<td>&lt;2.28</td>
<td>&lt;0.29</td>
</tr>
<tr>
<td>TOLOLO 1238-364$^3$</td>
<td>6.30$^{+0.29}_{-0.23}$</td>
<td>0.39$^{+0.34}_{-0.28}$</td>
<td>-</td>
<td>0.70$^{+0.38}_{-0.30}$</td>
</tr>
<tr>
<td>NGC 4968$^2$</td>
<td>6.38$^{+0.08}_{-0.03}$</td>
<td>0.13$^{+0.16}_{-0.05}$</td>
<td>-</td>
<td>0.95$^{+0.23}_{-0.20}$</td>
</tr>
<tr>
<td>M-3-34-64$^4$</td>
<td>6.30$^{+0.02}_{-0.01}$</td>
<td>&lt;0.08</td>
<td>0.17$^{+0.04}_{-0.03}$</td>
<td>1.27$^{+0.32}_{-0.21}$</td>
</tr>
<tr>
<td>Galaxy</td>
<td>Energy (keV)</td>
<td>$\sigma$</td>
<td>EW (keV)</td>
<td>Flux$^1$</td>
</tr>
<tr>
<td>------------------------------</td>
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</tr>
<tr>
<td>NGC 5135$^2$</td>
<td>6.34$^{+0.04}_{-0.04}$</td>
<td>&lt;0.12</td>
<td>1.18$^{+0.56}_{-0.45}$</td>
<td>0.46$^{+0.22}_{-0.18}$</td>
</tr>
<tr>
<td>NGC 5194$^2$</td>
<td>6.39$^{+0.02}_{-0.01}$</td>
<td>&lt;0.04</td>
<td>3.05$^{+0.82}_{-0.65}$</td>
<td>0.40$^{+0.11}_{-0.08}$</td>
</tr>
<tr>
<td>NGC 5347$^{2,6}$</td>
<td>6.35</td>
<td>0.01</td>
<td>1.04$^{+0.49}_{-0.45}$</td>
<td>0.37$^{+0.17}_{-0.16}$</td>
</tr>
<tr>
<td>Mrk 463 (Chandra)$^{3,6}$</td>
<td>6.10</td>
<td>0.01</td>
<td>&lt;0.38</td>
<td>&lt;0.27</td>
</tr>
<tr>
<td>NGC 5506 (2001 Feb 2)$^2$</td>
<td>6.38$^{+0.01}_{-0.01}$</td>
<td>0.09$^{+0.02}_{-0.01}$</td>
<td>0.11$^{+0.01}_{-0.01}$</td>
<td>8.02$^{+0.69}_{-0.68}$</td>
</tr>
<tr>
<td>NGC 5506 (2004 Jul 11)$^2$</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
</tr>
<tr>
<td>NGC 5506 (2004 Jul 14)$^2$</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
</tr>
<tr>
<td>NGC 5506 (2004 Jul 22)$^2$</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
</tr>
<tr>
<td>NGC 5506 (2002 Jan 9)$^2$</td>
<td>6.45$^{+0.01}_{-0.01}$</td>
<td>0.13$^{+0.02}_{-0.01}$</td>
<td>0.10$^{+0.01}_{-0.01}$</td>
<td>10.3$^{+0.8}_{-0.7}$</td>
</tr>
<tr>
<td>NGC 5506 (2004 Aug 7)$^2$</td>
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<td>&quot;</td>
<td>&quot;</td>
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</tr>
<tr>
<td>NGC 5506 (2008 Jul 27)$^2$</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
</tr>
<tr>
<td>NGC 5506 (2009 Jan 2)$^2$</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
</tr>
<tr>
<td>Galaxy</td>
<td>Global Fit</td>
<td>Local Fit</td>
<td></td>
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<tr>
<td>------------------------</td>
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<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Energy (keV)</td>
<td>σ (keV)</td>
<td>EW (keV)</td>
<td>Flux(^1)</td>
</tr>
<tr>
<td>Arp 220(^6)</td>
<td>6.29</td>
<td>0.01</td>
<td>&lt;0.66</td>
<td>&lt;0.09</td>
</tr>
<tr>
<td>NGC 6890(^5,6)</td>
<td>6.35</td>
<td>0.01</td>
<td>1.21(^{+1.46}_{-1.01})</td>
<td>0.15(^{+0.18}_{-0.13})</td>
</tr>
<tr>
<td>IC 5063(^3,6)</td>
<td>6.33</td>
<td>0.01</td>
<td>0.05(^{+0.04}_{-0.04})</td>
<td>1.14(^{+0.96}_{-0.94})</td>
</tr>
<tr>
<td>NGC 7130(^3)</td>
<td>6.30(^{+0.04}_{-0.04})</td>
<td>&lt;0.09</td>
<td>0.70(^{+0.39}_{-0.31})</td>
<td>0.20(^{+0.11}_{-0.09})</td>
</tr>
<tr>
<td>NGC 7172 (2007)(^2)</td>
<td>6.33(^{+0.02}_{-0.01})</td>
<td>&lt;0.06</td>
<td>0.05(^{+0.01}_{-0.01})</td>
<td>3.10(^{+0.56}_{-0.48})</td>
</tr>
<tr>
<td>NGC 7172 (2004)(^2)</td>
<td>6.38(^{+0.01}_{-0.01})</td>
<td>0.09(^{+0.02}_{-0.02})</td>
<td>0.12(^{+0.01}_{-0.01})</td>
<td>4.11(^{+0.49}_{-0.49})</td>
</tr>
<tr>
<td>NGC 7172 (2002)(^2)</td>
<td>6.37(^{+0.03}_{-0.04})</td>
<td>0.14(^{+0.06}_{-0.04})</td>
<td>0.14(^{+0.03}_{-0.03})</td>
<td>4.88(^{+1.17}_{-0.91})</td>
</tr>
<tr>
<td>NGC 7582 (XMM 2005)(^2)</td>
<td>6.37(^{+0.01}_{-0.01})</td>
<td>&lt;0.04</td>
<td>0.41(^{+0.03}_{-0.03})</td>
<td>1.97(^{+0.16}_{-0.16})</td>
</tr>
<tr>
<td>NGC 7582 (XMM 2001)(^2)</td>
<td>6.37(^{+0.02}_{-0.01})</td>
<td>0.11(^{+0.03}_{-0.02})</td>
<td>0.62(^{+0.08}_{-0.07})</td>
<td>3.93(^{+0.52}_{-0.45})</td>
</tr>
<tr>
<td>NGC 7582 (Chandra)(^2,6)</td>
<td>6.37</td>
<td>0.01</td>
<td>0.18(^{+0.10}_{-0.07})</td>
<td>4.37(^{+2.31}_{-1.62})</td>
</tr>
</tbody>
</table>
Table 3.11 (cont’d)

<table>
<thead>
<tr>
<th>Galaxy</th>
<th>Global Fit</th>
<th>Local Fit</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Energy</td>
<td>σ</td>
</tr>
<tr>
<td></td>
<td>keV</td>
<td>keV</td>
</tr>
<tr>
<td>NGC 7674(^2,6)</td>
<td>6.22</td>
<td>0.01</td>
</tr>
</tbody>
</table>

\(^1\)Flux in units of \(10^{-13}\) erg s\(^{-1}\) cm\(^{-2}\). Line energies are reported in observed frame. Upper limits on parameters refer to the 90% confidence level whereas upper limits on the EW and flux signify 3\(\sigma\) error bars. “-” denotes unconstrained parameter.

\(^2\)Fe K\(\alpha\) line detected at greater than the 3\(\sigma\) level.

\(^3\)Fe K\(\alpha\) line detected at greater than the 2.5\(\sigma\) level.

\(^4\)Fe K\(\alpha\) line detected at greater than the 2\(\sigma\) level.

\(^5\)Fe K\(\alpha\) line detected at greater than the 1.5\(\sigma\) level.

\(^6\)XSpec model ZGAUSS used, with E frozen at 6.4 keV (rest-frame) and \(\sigma\) frozen at 0.01 keV.
Figure 3.1 Best-fit X-ray spectra for the first 6 [OIII] sources. The black line indicates the PN spectra and the red and green lines denote the MOS1 and MOS2 spectra respectively.
Figure 3.2 Best-fit X-ray spectra for the next 6 [OIII] sources. The color coding is the same as Figure 3.1.
Figure 3.3 Best-fit X-ray spectra for the remaining [OIII] sources. The color coding is the same as Figures 1 and 2, with the exception of 1218+4706 (2MASX J12183945+4706275) where the black and red lines indicate the MOS1 and MOS2 spectra respectively.
(a) Black - XMM PN spectrum, red - Chandra spectrum

(b) Black - XMM MOS2 spectrum from Jul 29, 2000 observation, red - XMM MOS2 spectrum from July 30, 2000 observation

(c) XMM PN spectrum.

(d) XMM PN spectrum.

(e) Black - XMM PN spectrum, red - Chandra spectrum.

(f) XMM PN spectrum.
(g) Black - XMM PN spectrum, red - Chandra spectrum from 2001 observation, green - Chandra spectrum from 2002 observation.

(h) Black - Chandra spectrum.

(i) Black - XMM PN spectrum from December 2002 observation, red - XMM PN spectrum from July 2002 observation.

(j) Chandra spectrum.

(k) Chandra spectrum.

(l) Chandra spectrum.
(m) Black - XMM PN spectrum from 2001 observation, red - XMM PN spectrum from 2004 observation.

(o) Chandra spectrum.

(p) Black - Chandra spectrum from 2000 observation, red - Chandra spectrum from 2001 observation, green - Chandra spectrum from 2003 observation.

(q) Chandra spectrum.

(r) Black - XMM PN spectrum, red - Chandra spectrum.
(s) Black - XMM PN spectrum from Jul 11, 2004 observation, red - XMM PN spectrum from Feb 2, 2001 observation, green - XMM PN spectrum from Jul 14, 2004 observation, blue - XMM PN spectrum from Jul 22, 2004 observation.

(u) Chandra spectrum.

(v) Black - XMM PN spectrum from 2002 observation, red - XMM PN spectrum from 2003 observation, green - XMM MOS1 spectrum from Jan 2005 observation, blue - Chandra spectrum.

(w) XMM PN spectrum.

(x) Chandra spectrum.
Figure 3.4 X-ray spectra with best-fit models for 12µm sample.
Figure 3.5 Data-to-model ratio plots of [OIII] sources where the Fe Kα line was detected at high significance for the 5 targets with the highest signal-to-noise ratio. In these plots, the spectra were fit with the best-fit model (double absorbed power law for 0800+2636, 0824+2959, 1238+0927 and 1323+4318 and single absorbed power law for 0959+1259) without the Gaussian component added. The residuals at the Fe Kα energy indicate that this line is present.
Chapter 4

X-ray Observations of Homogeneous Samples of Seyfert 2 Galaxies - Results

With the observed X-ray flux and Fe Kα EW constrained, we can determine the distribution of the amount of 2-10 keV attenuation associated with the obscuring torus. As both the 12µm and [OIII] sample were selected on intrinsic AGN properties, such a percentage might represent an unbiased estimate for the global AGN population. We also explore if the fitted column densities agree with the proxies we use for AGN obscuration: if the emission is seen primarily via scattering and/or reflection, do the fitted $N_H$ values recover the intrinsic absorption? The obscuration flux diagnostics and Fe Kα EWs also provide clues as to the obscuration geometry in these sources. We compare host galaxy and AGN properties with Compton-thick diagnostics to determine if sources with heavy absorption trace a unique populations from their less obscured counterparts. Finally, as higher energy (>10 keV) observations are necessary to confirm a source as Compton-thick, we comment on the detectability of these Sy2s by NuSTAR, an upcoming hard X-ray mission.
4.0.3 Obscuration Diagnostics

As fitted column densities are model dependent and could be unreliable, we use other proxies to investigate the amount of toroidal absorption in these systems, including the ratio of the observed X-ray flux to the inherent AGN flux. We consider three diagnostics for intrinsic AGN power ($F_{\text{intrinsic}}$): the $\text{[OIII]} \lambda 5007\AA$ line, the $\text{[OIV]} 25.89 \mu m$ line and the mid-infrared (MIR) continuum. As these proxies are to first-order unaffected by the obscuring medium (see Chapter 2), whereas the 2-10 keV X-ray flux is attenuated due to absorption and possibly Compton-scattering, the ratio of the X-ray flux to these tracers of intrinsic AGN power can probe the amount of obscuration present and has been used extensively in previous studies (e.g. Bassani et al. 1999, Heckman et al. 2005, Cappi et al. 2006, Panessa et al. 2006, Meléndez et al. 2008). We list the values of these obscuration diagnostic flux ratios in Tables 4.1 and 4.2 for the $\text{[OIII]}$ and 12$\mu m$ samples, respectively. There are, however, several limitations to using the $\text{[OIII]}$ and MIR fluxes in tracing the intrinsic AGN flux: the $\text{[OIII]}$ flux could be heavily affected by dust in the host galaxy and star formation processes can contaminate the MIR flux. In Chapter 2, we noted that applying the standard $R=3.1$ reddening correction utilizing the Balmer decrement introduced errors that did not better recover the intrinsic $\text{[OIII]}$ emission for the 12$\mu m$ sample, likely due to uncertainties in the H$\beta$ measurements from the literature. Due to uncertainties in correcting the $\text{[OIII]}$ and MIR fluxes for contamination, we use the observed parameters, with the caveat that these may not accurately probe intrinsic AGN emission for some sources. We discuss the implications of such biases below.

We plot the distributions of $F_{2-10\text{keV}}/F_{\text{[OIII]}\text{obs}}$, $F_{2-10\text{keV}}/F_{\text{[OIV]}}$ and $F_{2-10\text{keV}}/F_{\text{MIR}}$ in Figure 4.1 where the red dashed histogram represents the $\text{[OIII]}$-sample, the dark blue histogram denotes the non-variable 12$\mu m$ sources and the cyan histogram reflects the variable 12$\mu m$ sources, using the average X-ray flux among the multiple observations for each source. A wide range of values is evident in all three plots. We compared our values with Sy1 sources, with the average flux ratio and spread delineated by the grey shaded regions in Figure 4.1. The Sy1 comparison samples are culled from: a) Heckman et al. (2005) (heterogeneous $\text{[OIII]}$-bright sample, log
(<F_{2−10keV}/F_{OIII,\text{obs}}>) = 1.59±0.49 dex), b) Diamond-Stanic et al. (2009) (drawn from the revised Shapley-Ames catalog, log (<F_{2−10keV}/F_{OIV}> ) = 1.92±0.60 dex ) and c) Gandhi et al. (2009) (where F_{MIR} is calculated at 12.3\mu m with VISIR (Lagage et al., 2004) observations of Sys selected from Lutz et al. (2004) and those with existing or planned hard (14-195 keV) X-ray observations, log (<F_{2−10keV}/F_{MIR}>) = -0.34±0.30 dex). We note that Gandhi et al. (2009) report absorption-corrected X-ray luminosity whereas the other Sy1 comparison samples utilize the observed luminosity. This correction shifts the F_{2−10keV}/F_{MIR} Sy1 ratios to higher values, though such a correction could be expected to be minimal for type 1 AGN which are thought to be largely unobscured. Also, not correcting [OIII] flux for reddening and MIR flux for starburst contamination could possibly result in obscuration diagnostic ratios that are larger or smaller respectively, and though this affects several individual galaxies with large amounts of dust and/or greater star formation activity, no such systematic trends for the sample as a whole are evident. Yaqoob and Murphy (2011) have demonstrated that the ratio of F_{2−10keV}/F_{MIR} is more sensitive to the X-ray spectral slope and covering factor of the putative torus, rather than column density, indicating that a low ratio does not necessarily imply a Compton-thick source. However, despite these potential biases, we find all three obscuration diagnostics to agree: the majority of Sy2s have ratios an order of magnitude or lower than their Sy1 counterparts, which may indicate Compton-thick absorption.

This trend is further illustrated by Figure 4.2, which plots the observed X-ray luminosity as a function of intrinsic AGN luminosity proxies, with the best-fit relationship for Sy1s overplotted. Here, the red triangles represent the [OIII]-sample, the blue diamonds denote the non-variable 12\mu m sources and the cyan diamonds reflect the variable 12\mu m sources, with the individual X-ray fluxes (see Table 3.8) plotted for each variable source and connected by a solid line. The relationship for the Sy1 sources were calculated by multiple linear regression (i.e. REGRESS routine in IDL) for the Heckman et al. (2005) and Diamond-Stanic et al. (2009) samples; for the MIR relationship, we utilized the best-fit parameters from Gandhi et al. (2009) for their Sy1 subsample. The majority of Sy2s lie well below the relations for Sy1s, demonstrating that these type 2 AGN have weaker observed X-ray emission.
As the X-ray and optical and IR observations were not carried out simultaneously, it is possible that variability in the source could be responsible for the disagreements between the X-ray flux and intrinsic flux proxies. Such a scenario can be realized if the X-ray observations are made after the central source has “shut-off” (postulated to explain the discrepancy between the Type 1 optical spectrum yet reprocessing-dominated X-ray spectrum for NGC 4051, see Matt et al. (2003) and references therein), or the converse, where optical observations are made during a sedentary state and X-ray observations catch the source in active state (e.g. Guainazzi et al. (2005)). Though we can not rule out variability as contributing to the discrepancy between the X-ray luminosity and intrinsic AGN luminosity proxies for any individual source, such an effect can not be responsible for the overall trend in this sample. Variability in Sy1 samples contributes to the dispersion in $L_{2-10\text{keV}}/L_{\text{isotropic}}$ ratios, yet they exhibit systematically higher X-ray luminosity (normalized by intrinsic AGN power) than Sy2s (Figures 4.1 and 4.2). This is confirmed by two-sample tests where we employed survival analysis (ASURV Rev 1.2, Isobe and Feigelson 1990; LaValley, Isobe and Feigelson 1992; Feigelson and Nelson 1985 for univariate problems) to account for upper limits in the X-ray flux. The Sy1 and Sy2 obscuration diagnostic ratios differ at a statistically significant level ($\leq 1\times10^{-4}$ probability that they are drawn from the same parent population), which would not be expected if variability was the main driver for the discrepancy between intrinsic AGN flux and observed X-ray flux.

We have demonstrated that the majority of Sy2s in our samples are under-luminous in X-ray emission as compared to Sy1s, but is this trend due to obscuration or inherent X-ray weakness? The EW of the neutral Fe Kα line can differentiate between these two possibilities and is thus another obscuration diagnostic. In heavily obscured sources, the AGN continuum is suppressed, whereas the Fe Kα line is viewed in reflection, leading to a large Fe Kα EW (several hundred eV to several keV, e.g. Ghisellini et al. 1994, Levenson et al. 2002). In Figure 4.3, Fe Kα EW is plotted as a function of obscuration diagnostic ratios. A clear anti-correlation is present which is statistically significant according to survival analysis (Isobe et al. 1986 for bivariate problems): we obtain Spearman’s $\rho$ values of -0.648, -0.650 and -0.653 for Fe Kα
EW vs. $F_{2-10\text{keV}}/F_{\text{[OIII]}\text{,obs}}$, $F_{2-10\text{keV}}/F_{\text{[OIV]}}$ and $F_{2-10\text{keV}}/F_{\text{MIR}}$, respectively. These best-fit correlations are overplotted for each relation in Figure 4.3. The decrease of observed X-ray flux, normalized by intrinsic AGN flux, with increasing Fe Kα EW indicates that obscuration is responsible for attenuating X-ray emission in these Sy2s. These results are consistent with the three-dimensional diagnostic diagram of Bassani et al. 1999 which shows a correlation between Fe Kα EW and column density which anti-correlates with $F_{2-10\text{keV}}/F_{\text{[OIII]}\text{,corr}}$ (where $F_{\text{[OIII]}\text{,corr}}$ is the reddening corrected [OIII] flux).

Not only do a majority of this combined Sy2 sample exhibit trademarks of Compton-thick obscuration (an order of magnitude lower $F_{2-10\text{keV}}/F_{\text{isotropic}}$ ratios than Sy1s and large Fe Kα EW values), but a wide range of these diagnostic values are evident. No clear separation exists between Compton-thick and Compton-thin sub-populations. Also, though the diagnostic flux ratios generally point to the same sources as having Compton-thick obscuration, not all three ratios agree for a handful of sources (e.g. F05189-2524, NGC 5347, Arp 220, NGC 4388 and NGC 7582): some ratios indicate a Compton-thin source whereas others suggest Compton-thick. As the various intrinsic AGN indicators exhibit some scatter in inter-comparisons (see Chapter 2), a spread in $F_{2-10\text{keV}}/F_{\text{isotropic}}$ values is expected. For F05189-2524, NGC 5347 and Arp 220, this discrepancy could be due to dust in the host galaxy affecting the [OIII] line, as mentioned above and/or large amounts of dust in the host galaxy boosting the MIR flux. The 2005 XMM-Newton observation of NGC 7582 has a $F_{2-10\text{keV}}/F_{\text{[OIII]}\text{,obs}}$ value marginally higher than the nominal Compton-thick/Compton-thin boundary, so the three flux ratio diagnostics may be considered to agree. However, the biases discussed previously in the observed [OIII] flux and MIR flux can not account for the disagreement of the diagnostic flux ratios in the Chandra and July XMM-Newton observations of NGC 4388 and the 2001 XMM-Newton observation of NGC 7582, where $F_{2-10\text{keV}}/F_{\text{[OIV]}}$ point to the sources being Compton-thick at these stages, but the other ratios suggest a Compton-thin nature. Similarly, an Fe Kα EW of 1 keV is often cited as the nominal boundary for a Compton-thick source based on observations (e.g. Bassani et al. 1999, Comastri 2004, Levenson et al. 2006), yet NGC 1068, the archetype for a Compton-thick Sy2 (Matt et al., 1997), has a measured
EW of $0.60^{+0.05}_{-0.05}$ keV (in agreement with Pounds & Vaughan 2006 but not Matt et al. 2004, see Appendix C). Hence, though the diagnostics presented here can help in uncovering the possible Compton-thick nature of a type 2 AGN, nominal boundaries should be considered approximate, especially since a continuum of both diagnostic flux ratios and Fe Kα EWs are present.

4.0.4 Implications for the Local AGN Population

As both sub-samples were selected based on intrinsic AGN proxies and the majority is likely Compton-thick, this implies that heavily obscured sources could constitute most of the local Sy2 population. X-ray surveys in the 2-10 keV range, biased against these Compton-thick type 2 AGNs, would thus miss a significant portion of the population. Indeed, Heckman et al. 2005 find that the luminosity function (which parametrizes the number of sources per luminosity per volume) for X-ray selected AGN is lower than the luminosity function for optically ([OIII]) selected sources. However, recent work (Trouille & Barger 2010, Georgantopoulos & Akylas 2010) leads to the opposite conclusion, namely agreement between [OIII] and X-ray luminosity functions. As Georgantopoulos & Akylas (2010) point out, though the luminosity functions are similar, the selection techniques tend to find different objects, with [OIII]-selection favoring the X-ray weak sources. Hence, the number of sources per volume per luminosity may be comparable, but any one selection technique does not sample the full population. For instance, Yan et al. (2011) found that only 22% of their 288 optically selected AGNs are detected in the 200 ks Chandra Extended Groth Strip survey, and they attribute the non-detection of the majority of the remaining sources to heavy toroidal obscuration. Conversely, X-ray selection can identify AGN that are categorized as star-forming galaxies by optical emission line diagnostics. Yan et al. (2011) note that about 20% of the X-ray sources identified as star-forming galaxies from optical emission lines have X-ray emission in excess of that explicable by star-formation, indicating the presence of an AGN. This finding is similar to the results of Trouille & Barger 2010 who find that at least 20% of X-ray selected AGN in their sample are identified as star-forming according to optical di-
agnostics. Perhaps such competing biases work in concert to produce similar [OIII] and X-ray luminosity functions.

4.0.5 Investigating Obscuration Geometry

4.0.5.1 Fitted Column Densities

Here, we explore the relationship between obscuration diagnostics and the column densities ($N_H$) derived from spectral fitting. In Figure 4.4, we plot the fitted column densities as a function of $F_{2-10\text{keV}}/F_{\text{isotropic}}$ and Fe Kα EW; as the [OIV] line is the least affected by the host galaxy contamination mentioned above, we use $F_{[\text{OIV}]}$ as $F_{\text{isotropic}}$. With the exception of several sources, the fitted $N_H$ values approximately trace the degree of absorption implied by the obscuration diagnostics. However, a handful of sources lay several orders of magnitude below this trend, and are labeled in Figure 4.4. This result is consistent with the findings of Cappi et al. (2006), where several Sy2s have fitted $N_H$ values an order of magnitude below that suggested by $F_{2-10\text{keV}}/F_{\text{OIII}},_{\text{obs}}$. Both $F_{2-10\text{keV}}/F_{\text{isotropic}}$ and the Fe Kα EW diagnostics point to the same sources as being anomalous, with sources missing from the Fe Kα plot due to having an unconstrained EW or upper limit on the EW. All of these sources required only a single power law model (with a thermal component in many cases) to adequately fit the spectrum. The low observed X-ray fluxes and high Fe Kα EW values indicate that the emission is primarily seen in scattering and/or reflection, rather than transmission through the obscuring medium. Hence such fitted $N_H$ values are likely associated with the line of sight absorption to the scattered/reflected component, suggesting that simple models of a foreground screen extinguishing the central source do not always recover the intrinsic absorption.

Partial covering models, parametrized in this work by a double absorbed power law with the two photon indices tied together, can also misrepresent the inherent column density. For example, such a model fairly fit the spectra for NGC 1068 ($\chi^2=450.4$ with 247 degrees of freedom), yet the best fit $N_H$ was $\sim9 \times 10^{22}$ cm$^{-2}$ whereas the lower limit on this column density from higher energy observations is $10^{25}$ cm$^{-2}$ (Matt et
Though a partial covering model could more realistically represent the geometry of the system, assuming a certain percentage of transmitted light through the obscur ing medium with the rest scattered into the line of sight, it could be subject to the same limitations discussed above for single absorbed power law models.

Published $N_H$ distributions could potentially be biased, skewed to lower values, though checks based on obscuration diagnostics can help mitigate this problem. For example, Akylas et al. (2006) analyzed the X-ray spectra for 359 sources from XMM-Newton and the Chandra Deep Field - South (CDFS), deriving intrinsic column densities from fitted $N_H$ values though adopting a column density of $5 \times 10^{24} \text{ cm}^{-2}$ for the cases where $\Gamma < 1$, a signature of Compton-thick obscuration. However, as Cappi et al. (2006) note, this criterion could indicate a Compton-thick source while the Fe Kα EW and flux diagnostics suggest Compton-thin (e.g. NGC 4138 and NGC 4258) or vice versa (e.g. NGC 3079). Tozzi et al. (2006) use a reflection model (PEXRAV in XSpec) for Compton-thick sources in the CDFS, which are defined as those AGN with a better fit statistic using PEXRAV than an absorbed power law model. However, as Murphy & Yaqoob point out (2009), such a model describes reflection off of an accretion disk, which is not physically relevant for the putative torus obscuration. Derived $N_H$ values could then potentially be suspect for some sources. Other diagnostics are therefore crucial in checking the reliability of fitted $N_H$ values. For example, Krumpe et al. (2008) find the ratio of X-ray to optical flux, as well as the non-detection of an Fe Kα line in the stacked spectrum of 14 type II QSOs (AGN with intrinsic $L_{2-10\text{keV}} \geq 10^{44} \text{ erg/s}$), to verify their distribution of moderately absorbed, but not Compton-thick, column densities.

### 4.0.5.2 Variable Sources

It is intriguing to note that all X-ray variable sources in this study are on the high end of the obscuration flux diagnostics (see Figures 4.1 and 4.2). These high $F_{2-10\text{keV}}/F_{\text{isotropic}}$ flux ratios may indicate that the X-ray emission from the central source is seen directly. However, the high Fe Kα EW for the Chandra and July 2002 observations of NGC 4388 ($0.29^{+0.11}_{-0.08} \text{ keV}$ and $0.62^{+0.10}_{-0.10} \text{ keV}$, respectively) and for the
\textit{XMM-Newton} observations of NGC 7582 (0.58^{+0.04}_{-0.04} \text{ keV} \text{ and } 0.31^{+0.05}_{-0.05} \text{ keV}) are higher than predicted for transmission-dominated spectra, where the EW with respect to the primary transmitted emission is \textless 0.18 \text{ keV} (Matt, 2002). Piconcelli et al. (2007) propose a double absorption geometry to account for the variability in NGC 7582: a “thick” absorber which attenuates just the central source, attributed to the putative torus, and a “thin” absorber which enshrouds the primary and reflected emission and is located externally to the torus. They postulate that this inner, “thick” absorber is inhomogeneous, accounting for the observed X-ray variability. A similar scenario may be present for NGC 4388 and be responsible for both sources switching from transmitted-dominated to reflection-dominated states (or vice versa). The Fe Kα EWs for the two other variable sources, NGC 5506 and NGC 7172, as well as the flux ratio diagnostics are consistent with Compton-thin sources, implying the central source is consistently viewed directly.

4.0.6 Are Compton-Thick Sources Unique?

Here we investigate whether Compton-thick sources differ from their Compton-thin counterparts in terms of host galaxy and AGN properties. In particular, we examined whether systematic differences exist in intrinsic AGN power, Eddington ratio (\textit{L}_{\text{bolometric}}/\textit{L}_{\text{Eddington}}), central black hole mass (\textit{M}_{\text{BH}}), the AGN contribution to the ionization field, and the relative amount of star formation to AGN activity. The results are summarized in Figures 4.5 through 4.10 and in Table 4.3, where we utilized survival analysis to calculate Spearman \( \rho \) values and the associated probabilities that the obscuration diagnostics are uncorrelated with host galaxy properties: \( P<0.05 \) indicates that the quantities are significantly correlated (\( \geq 2\sigma \) level). The values of the relevant host galaxy parameters used in this analysis are presented in Chapter 2.

To test whether Compton-thick sources have unique AGN properties, we searched for correlations between toroidal obscuration and intrinsic AGN luminosity, accretion rate and central black hole mass (\textit{M}_{\text{BH}}). As discussed previously, the [OIV] 25.89\( \mu \)m line serves as a robust proxy of intrinsic AGN flux as it is mainly ionized by the central engine and not affected by host galaxy reddening as the [OIII] line is (e.g.
Meléndez et al. 2008, Diamond-Stanic et al. 2009, Rigby et al 2009). We therefore utilize $L_{[OIV]}$ as $L_{\text{isotopic}}$ in Figures 4.5 and 4.6 and Table 4.3. According to survival analysis, a marginal statistically significant correlation exists between $L_{\text{isotopic}}$ and $F_{2-10\text{keV}}/F_{\text{MIR}}$. Figure 4.5, however, shows this dependency to be weak with a wide scatter, especially considering the error bars which can not be accommodated in the survival analysis calculation. We find no correlations between implied column density and accretion rate (using $L_{[OIV]}/M_{BH}$ as a proxy for the Eddington ratio) and $M_{BH}$ (Figures 4.6 and 4.7); survival analysis does indicate a weak significant relationship between Eddington parameter and $F_{2-10\text{keV}}/F_{\text{MIR}}$, but this is likely driven by the dependence on $L_{[OIV]}$. As the weak correlation between luminosity and obscuration is tenuous at best, we conclude that Compton-thick sources do not have systematically different AGN properties from their less obscured counterparts.

Could there be a relation between the obscuration shrouding the central engine and the large amounts of dust and gas necessary for starburst activity? As Levenson et al. (2004, 2005) point out, NGC 5135 and NGC 7130 (both members of the 12$\mu$m sample) are starburst galaxies that likely harbor Compton-thick AGN. The combined [OIII] and 12$\mu$m samples provide us an opportunity to test if such a relation is generic. We use infrared quantities to illuminate the relative importance of starburst versus AGN activity: $F_{[OIV]}/F_{[Ne\text{II}]}$, which probes the hardness of the ionization field as $F_{[OIV]}$ is largely ionized by the AGN whereas [NeII] 12.8$\mu$m is excited by star formation processes; the EW of the 17 $\mu$m polycyclic aromatic hydrocarbon (PAH) feature (Genzel et al., 1998), which includes the emission features between 16.4-17.9 $\mu$m; and the MIR spectral index $\alpha_{20-30\mu m}$ (Deo et al., 2009). A higher value of $F_{[OIV]}/F_{[Ne\text{II}]}$ indicates the dominance of AGN activity whereas larger PAH EW at 17$\mu$m and $\alpha_{20-30\mu m}$ values denote higher levels of starburst activity. As Figures 4.8 - 4.10 and Table 4.3 illustrate, a correlation between column density and hardness of incident ionization field/star formation activity do not exist. These results suggest that the gas responsible for starburst processes likely originates in regions of the galaxy not

1. $\alpha_{\lambda_1-\lambda_2} = \log(f_{\lambda_1}/f_{\lambda_2})/\log(\lambda_1/\lambda_2)$

2. We note that we only have these data for 27 of the 28 12$\mu$m sources presented in this work as NGC 1068 had saturated low-resolution Spitzer data. We were therefore unable to obtain a PAH 17 $\mu$m EW value or $\alpha_{20-30\mu m}$ value for this source.
associated with the putative torus, and similarly that gas from the interstellar medium does not contribute significantly to toroidal AGN obscuration in hard (2-10 keV) X-rays.

4.0.7 NuSTAR: Detection at Higher Energies

In order to confirm a source as Compton-thick, observations at higher energies (>10 keV) are necessary. The spectral characteristic of heavily obscured AGN is the so-called “Compton-hump”, a peak in the spectrum between 20-30 keV which is caused by the competing effects of absorption on the low-energy end and Compton down-scattering on the high energy range. The Nuclear Spectroscopic Telescope Array (NuSTAR), to be launched in 2012, is sensitive in the 5 - 80 keV band, and could thus confirm our obscured candidates as Compton-thick sources, if they are detected.

To test if these sources would be detectable by NuSTAR, we simulated higher energy spectra, using the XSpec command _fakeit_, based on the best-fit model and the associated response and background files provided by the NuSTAR team. For the three non-detections in the 12µm sample, we simulated spectra using a model that takes into account Compton scattering assuming a spheroidal obscuration geometry (PLCABS in XSpec), with $N_H = 10^{24}$ cm$^{-2}$, $\Gamma=1.8$ and the maximum number of scatterings set to 5; the normalization was adjusted such that model 2-10 keV flux equaled the upper limits we calculated via Bayesian analysis. Using the simulated observed source and background count rate, we estimated the exposure time necessary for a source to be detected at the 5σ level over the background. We find that all but five sources from the 12µm sample (NGC 1386, NGC 1667, Tololo 1238-364, NGC 4968 and NGC 6890) and four from the [OIII]-sample (2MASX 08035923+2345201, 2MASX J10181928+3722419, 2MASX J13463217+6423247 and NGC 5695) will be detected with exposure times less than 100 ks (see Appendix D). However, though our simulations indicate the three non-detected 2-10 keV sources will be observable by NuSTAR, this is an optimistic estimate, and should be treated with caution.

As noted in Chapter 2, the majority of these Sy2s are undetected by the Swift BAT Surveys, indicating that these sources are heavily absorbed. However, as NuSTAR
probes to a much deeper flux level in a million second observation than the BAT surveys ($\sim 2 \times 10^{-14}$ erg s$^{-1}$ cm$^{-2}$ vs. the limiting BAT flux of $\sim 3.1 \times 10^{-11}$ erg s$^{-1}$ cm$^{-2}$), the majority of these heavily obscured sources will likely be detected if observed by NuSTAR.

4.1 Summary

We have analyzed archival Chandra and XMM-Newton observations for two nearly complete homogeneous samples of Sy2 galaxies: one selected from the SDSS on the basis of observed [OIII] flux and a MIR sample from the original IRAS 12μm sample. The combined sample provided us with 45 Sy2s with existing Chandra and/or XMM-Newton data. Of these, three were not detected above the background (F08572+3915, NGC 5953 and NGC 7590) and four exhibited evidence of variability among multiple X-ray observations (NGC 4388, NGC 5506, NGC 7172 and NGC 7582).

We probed the amount of absorption present in these sources by comparing the 2-10 keV X-ray flux with optical and MIR proxies of intrinsic AGN power ($F_{\text{intrinsic}}$: the fluxes of the [OIII] $\lambda$ 5007 Å and [OIV] 25.89 μm emission lines and the MIR continuum flux at 13.5 μm) and by investigating X-ray spectral signatures of obscuration (i.e. Fe Kα EW). We compared such obscuration diagnostics with fitted column densities and explored the implications of these diagnostics on the AGN geometry. We also investigated whether a connection exists between the column density of the obscuring medium and host galaxy characteristics. Our results are summarized as follows:

1. The majority of the combined sample has $F_{\text{2-10keV}}/F_{\text{intrinsic}}$ values an order of magnitude or lower than the mean values for Sy1s. The statistically significant anti-correlation between $F_{\text{2-10keV}}/F_{\text{intrinsic}}$ and Fe Kα EW indicates that these lower diagnostic flux ratios are due to obscuration rather than inherent X-ray weakness in Sy2s. Thus a majority of these sources are potentially Compton-thick, consistent with the results of previous studies (e.g. Risaliti 1999).

2. A wide range of obscuration diagnostic values are present, indicating a continuum of column densities and/or inclination angles, rather than a clear seg-
regation into Compton-thick and Compton-thin sub-populations. Though the
diagnostics do generally point to the same sources as likely heavily absorbed,
disagreement does exist for a handful of Sy2s. Such a discrepancy is to be
expected based on the various biases affecting the observed intrinsic flux prox-
ies and the inherent spread in such isotropic flux indicators. Hence, nominal
Compton-thick boundaries should be considered approximate.

3. Though recent work (Georgantopoulos & Akylas (2010), Trouille & Barger
(2010)) shows the luminosity functions for X-ray selected and [OIII]-selected
AGN to be consistent, the various selection techniques favor differ classes of
objects. Heavily obscured sources, present in optically selected samples, are
missing from 2-10 keV X-ray samples. Sample selection based on intrinsic flux
proxies are therefore necessary to include the Compton-thick population, es-
pecially since highly absorbed sources constitute the majority of our homoge-
neously selected samples.

4. Though fitted column densities generally tend to trace the absorption implied
by obscuration diagnostics, several glaring inconsistencies are present. Such
discrepancies are most extreme when the hard X-ray spectrum is best fit by a
single absorbed power law, implying that the simple geometry of a foreground
screen attenuating the central source does not recover the intrinsic absorption.
This could result from scattering and/or reflected emission dominating over
the transmitted continuum, where the fitted column density reflects line of
sight absorption rather than the obscuration enshrouding the AGN. Such a
result indicates that published \( N_H \) distributions derived from single absorbed
power law models can be similarly biased, systematically under-representing the
intrinsic column density of type 2 AGN. Other diagnostics are therefore crucial
in checking the validity of fitted column densities.

5. The X-ray variable Sy2s populate the less obscured range of the flux ratio
obscuration diagnostics. Two of these sources (NGC 4388 and NGC 7582) do
show evidence of switching to a reflection-dominated state, as indicated by the
change in the Fe Kα EWs. As Piconcelli et al. (2007) suggest, this change could reflect an inhomogeneous thick absorber covering the central source, with a thin absorber attenuating both the reflected and transmitted emission. The other two variable sources (NGC 5506 and NGC 7172) show signs of Compton-thin absorption, suggesting that the central source is viewed directly.

6. We do not find compelling evidence that Compton-thick sources have unique AGN properties (intrinsic AGN luminosity, accretion rate and central black hole mass) or the relative amount of ionization due to the central engine compared to star formation processes ($F_{[OIV]}/F_{[NeII]}$, EW of the 17µm PAH feature, $\alpha_{20-30\mu m}$) and AGN absorption. Though several starburst galaxies do seem to host Compton-thick AGN (e.g. Levenson et al. 2004, 2005), such a relation is not present globally. Hence, we conclude that the gas responsible for star formation processes is not associated with the toroidal obscuration hiding the central engine.

7. Based on simulated high-energy (10-40 keV) spectra using the best-fit modeling of the 2-10 keV spectra, we estimate that the majority of this sample (36 out of 45) will be detected if observed by NuSTAR. The more heavily obscured sources which have not been detected by BAT surveys could likely be identified by NuSTAR as this future mission will probe to lower flux levels ($\sim2 \times 10^{-14}$ erg s$^{-1}$ cm$^{-2}$ vs. $\sim 3.1 \times 10^{-11}$ erg s$^{-1}$ cm$^{-2}$). These observations would confirm whether the heavily absorbed sources are indeed Compton-thick.
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<td>Log(\frac{F_{2-10\text{keV}}}{F_{\text{[OIV]}}})</td>
<td>Log(\frac{F_{2-10\text{keV}}}{F_{\text{MIR}}})</td>
</tr>
<tr>
<td>-----------</td>
<td>------------------------------------------------</td>
<td>------------------------------------------------</td>
<td>------------------------------------------------</td>
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Table 4.3. Correlation of AGN Properties and Star Formation Activity with Obscuration Diagnostics

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<tr>
<th></th>
<th>$\rho$</th>
<th>$P^1$</th>
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<tr>
<td>$L_{[OIV]}$ vs.</td>
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<tr>
<td>$F_{2-10keV}/F_{[OIII],obs}$</td>
<td>0.218</td>
<td>0.112</td>
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<tr>
<td>$F_{2-10keV}/F_{[OIV]}$</td>
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<tr>
<td>$L_{[OIV]}/M_{BH}$ vs.</td>
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<td>$M_{BH}$ vs.</td>
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<tr>
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<td>0.807</td>
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<td>PAW EW 17 $\mu$m vs.</td>
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<tr>
<td>$F_{2-10keV}/F_{MIR}$</td>
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<tr>
<td>Fe K$\alpha$ EW</td>
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<td>0.213</td>
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Table 4.3 (cont’d)

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<th>$\alpha_{20-30 \mu m}$ vs.</th>
<th>$\rho$</th>
<th>$P^1$</th>
</tr>
</thead>
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<tr>
<td>$F_{2-10 \text{keV}}/F_{[\text{OIII}],\text{obs}}$</td>
<td>0.236</td>
<td>0.099</td>
</tr>
<tr>
<td>$F_{2-10 \text{keV}}/F_{[\text{OIV}]}$</td>
<td>0.001</td>
<td>0.993</td>
</tr>
<tr>
<td>$F_{2-10 \text{keV}}/F_{\text{MIR}}$</td>
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<td>0.946</td>
</tr>
<tr>
<td>Fe K$\alpha$ EW</td>
<td>-0.228</td>
<td>0.140</td>
</tr>
</tbody>
</table>

$^1$Probability that the null hypothesis, that the two quantities are uncorrelated, is correct. Quantities are statistically significantly correlated if $P<0.05$. 

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Figure 4.1 Histograms showing the distribution of obscuration diagnostic ratios ($F_{2-10\text{keV}}/F_{\text{isotropic}}$). Dark blue histogram represents the non-variable 12µm sources, cyan reflects the X-ray variable 12µm sources (X-ray fluxes are averaged for each source), red denotes the [OIII]-sample and the gray shaded region illustrates the average value for Sy1s from a) Heckman et al. (2005), log ($<F_{2-10\text{keV}}/F_{\text{[OIII]}\text{,obs}}>$) = 1.59 ± 0.49 dex, b) Diamond-Stanic et al. (2009), log ($<F_{2-10\text{keV}}/F_{\text{[OIV]}>$) = 1.92 ± 0.60 dex and c) Gandhi et al. (2009), log ($<F_{2-10\text{keV}}/F_{\text{MIR}>}$) = -0.34 ± 0.30 dex. The left facing arrows represent X-ray upper limits in a), b) and c) and right facing arrows illustrate the [OIV] upper limits in b); these values are not included in the histogram.
Figure 4.2 X-ray luminosity versus proxies of intrinsic AGN luminosity. Blue diamonds represent the non-variable 12µm sources, cyan diamonds illustrate the variable 12µm sources, with the observed flux values from Table 3.8 for each source connected by a straight line, and red triangles denote the [OIII]-sources. Error bars for the variable sources represent the upper error on the maximum X-ray flux and lower error on the minimum X-ray flux. Variable sources NGC 5506 and NGC 7172 do not have error bars plotted as they are smaller than the symbol size. The dashed line represents the relationship for Sy1s from a) Heckman et al. (2005), slope = 1.4 dex with intercept -0.15 dex, b) Diamond-Stanic et al. (2009), slope = 0.86 dex with intercept = 7.53 dex and c) Gandhi et al. (2009), slope = 0.85 dex with intercept 6.27 dex. In all cases, the majority of the Sy2s are below this relationship, illustrating that Sy2s have weaker X-ray emission than their Sy1 counterparts.
Figure 4.3 Fe Kα EW as a function of flux obscuration diagnostic ratios. Color coding is similar to 4.2, though a dashed line is used for variable source NGC 7582 to avoid confusion with other variable sources having similar values. The statistically significant anti-correlations among all three relationships (Spearman’s ρ= -0.647, -0.650, -0.653, respectively, calculated from survival analysis) indicate obscuration is primarily responsible for X-ray attenuation. In b), the two sources with lower limits on $F_{2-10keV}/F_{[OIV]}$ are plotted for illustrative purposes and were not included in the survival analysis calculations. The fitted relationships are a) slope = -0.36 ± 0.07 dex with $σ=0.37$ dex and intercept of -0.05 dex, b) slope = -0.47 ± 0.07 dex with $σ=0.34$ dex and intercept of -0.008 dex and c) slope = -0.40 ± 0.06 dex with $σ=0.33$ dex and intercept of -0.96 dex.
Figure 4.4 Fitted $N_H$ as a function of obscuration diagnostics. The sources without error bars either had the best-fit absorption equal to the Galactic value, and therefore frozen at this value during fitting, or had $N_H$ error bars smaller than the symbol size. The dashed lines indicate the boundary for a Compton-thick column density ($N_H \geq 1.5 \times 10^{24} \text{ cm}^{-2}$) and the dashed-dotted line indicates nominal Compton-thick boundaries based on obscuration diagnostics ($\log (F_{2-10\text{keV}}/F_{[OIV]}) \leq 0.9 \text{ dex}$, an order of magnitude less than the average value for Sy1s, and Fe Kα $\text{EW} \geq 1 \text{ keV}$). Sources that are likely heavily obscured according to the obscuration diagnostics, yet have low fitted column densities, are labeled. Color coding same as Figure 4.3.
Figure 4.5 Obscuration diagnostics vs. intrinsic AGN luminosity, parametrized by $L_{[OIV]}$. The lower limits on $F_{2-10\text{keV}}/F_{[OIV]}$ are displayed for illustrative purposes and not included in the survival analysis calculation. Survival analysis indicates a marginal statistically significant correlation among $F_{2-10\text{keV}}/F_{\text{MIR}}$ ($\rho=0.218, 0.116, 0.364$ and $-0.256$, respectively), however a wide scatter is evident. Color coding same as Figure 4.2.
Figure 4.6 Obscuration diagnostics vs. Eddington ratio. The lower limits on $F_{2-10keV}/F_{[OIV]}$ are displayed for illustrative purposes and not included in the survival analysis. With the exception of $F_{2-10keV}/F_{MIR}$, which survival analysis suggests is marginally significantly correlated with Eddington parameter, no trends are present: $ho=0.081, 0.033, 0.327$ and $-0.168$, respectively. Color coding same as Figure 4.2.
Figure 4.7 Obscuration diagnostics vs. $M_{BH}$. The lower limits on $F_{2-10keV}/F_{[OIV]}$ are displayed for illustrative purposes and not included in the survival analysis. No statistically significant trends are present: $\rho=0.148, 0.092, -0.036$ and $-0.234$, respectively. Color coding same as Figure 4.2.
Figure 4.8 Obscuration diagnostics vs. $F_{\text{OIV}}/F_{\text{NeII}}$, a proxy for the relative strength of the ionizing continuum from the AGN versus starburst activity. The lower limits on $F_{\text{OIV}}/F_{\text{NeII}}$ and $F_{2-10\text{keV}}/F_{\text{OIV}}$ are displayed for illustrative purposes and not included in the survival analysis. With the exception of $F_{2-10\text{keV}}/F_{\text{MIR}}$, which survival analysis suggests is marginally significantly correlated with $F_{\text{OIV}}/F_{\text{NeII}}$, no statistically significant trends are apparent: $\rho = 0.037, 0.012, 0.316$ and -0.111, respectively. Color coding same as Figure 4.2.
Figure 4.9 Obscuration diagnostics vs. the EW of the PAH 17 µm feature, which parametrizes star formation rate. The lower limits on $F_{2-10keV}/F_{[OIV]}$ are displayed for illustrative purposes and not included in the survival analysis. No statistically significant trends are apparent: $\rho=0.135$, $0.071$, $-0.0535$ and $-0.192$, respectively. Color coding same as Figure 4.2.
Figure 4.10 Obscuration diagnostics vs. alpha$_{20-30\mu m}$, which parametrizes star formation rate. The lower limits on $F_{2-10keV}/F_{[OIV]}$ are displayed for illustrative purposes and not included in the survival analysis. No statistically significant trends are apparent: $\rho=0.236, 0.001, -0.010$ and $-0.228$. Color coding same as Figure 4.2.
Chapter 5

Connection between AGN Activity and Host Galaxy Star Formation

Observations from the past decade have revealed that central supermassive black holes are well correlated with the velocity of their parent galactic bulges, an effect known as the M-σ relation (Ferrarese & Merritt (2000), Gebhardt et al. (2000), Tremaine et al. (2002)). This relationship demonstrates that supermassive black holes are linked with their host galaxies through co-evolution. Many theoretical models have been explored to describe this link including mergers of galaxies turning on both starburst activity and accretion (e.g. Hopkins et al. (2008)) and “secular” evolution where galactic sized bars or spiral arms drive gas to the galactic center, feeding the black hole and potentially triggering star formation (e.g. Kormendy & Kennicutt (2004), Cisternas et al. (2011), Schawinski et al. (2011)). Studying the link between star formation and AGN activity can provide clues as to the nature of the interplay between these two processes. Here we explore this relationship by examining the multi-wavelength properties of quiescent galaxies and active systems.

In addition to the two Sy2 samples discussed in the previous chapters, we add two samples of predominantly star-forming galaxies to this analysis: the Spitzer SDSS GALEX Spectroscopic Survey (SSGSS, O’Dowd et al. (2009)) and the Spitzer SDSS Statistical Spectroscopic Survey (S5, PI: Schiminovich). Both samples have SDSS spectra and Spitzer data in the long-low, short-low and short-high modules. Such
an expanded data set gives us the opportunity to explore the connections between quiescent and active galaxies over a range of multi-wavelength parameter space. We categorized the galaxies based on their location in the BPT diagram. For this analysis, there are 264 star-forming galaxies, 51 composites, and 73 Sy2s\(^1\).

5.1 From Star-forming Galaxies to AGN

We investigate the optical and infrared properties that characterize AGN and star formation activity along the sequence of star-forming galaxies to composites to AGN. We investigate the effects of AGN activity on parameters used to describe host galaxy star formation. Which SFR proxies agree the best among star-forming galaxies, composites and AGN and are thus most reliable to apply to systems across the spectrum of nuclear activity? For diagnostics that trace the intrinsic AGN flux, we examine the relationships among \(L_{[OIII]}\) (both observed and reddening corrected), \(L_{MIR}\) and \(L_{[NeV]}\) across the galaxy sub-samples. We further probe the connections between those diagnostics that most accurately trace star formation processes and AGN flux. Finally, we compare diagnostics that parametrize the relative importance of star formation to AGN activity.

Our analysis is two-fold. We present scatter plots of the various proxies plotted against each other to test their agreement and to look for any systematic offset in galaxy sub-type. Alongside each scatter plot, we show histograms of the ratios of these parameters. We report the average values of these ratios as well as the results of two-sample tests among the sub-groups to test for differences due to nuclear activity. We utilized the Kolmogorov-Smirnov (K-S) test when all data points were detected but used survival analysis (ASURV) to account for upper limits. In the following plots, the symbol denotes sample and the color represents galaxy type: crosses are the S5 sample, circles stand for the SSGSS, squares indicate the \([OIII]\) sample and diamonds mark the 12\(\mu\)m sample. Arrows represent 5\(\sigma\) upper or lower limits, which were calculated following the procedure in 2.3. Star-forming galaxies are colored in

\(^1\)We note however that only about 1/3 of the SSGSS sources, a sub-sample consisting of the brightest galaxies, have high resolution spectra.
blue, composites are green and AGN are red.

5.1.1 Parametrizing Star Formation Rates: Effects of AGN Activity

5.1.1.1 SDSS SFRs and Neon Emission Lines

Optical and IR fluxes have been utilized to calibrate SFRs in quiescent galaxies. The SDSS SFR$_{fiber}$ is calculated from the H$\alpha$ luminosity, corrected for dust extinction, through the 3” SDSS fiber for star-forming galaxies. Using the relationship between the Dn(4000) break, a break in the optical spectrum at 4000Å which indicates the age of the host galaxy stellar population, and SDSS SFR$_{fiber}$ for star-forming galaxies, Brinchmann et al. (2004) calibrated a SFR for Sy2s based on Dn(4000). SDSS SFR$_{total}$ is an estimate of the galaxy-wide star formation rate based on an aperture correction to SDSS SFR$_{fiber}$ using host galaxy colors from photometry (Brinchmann et al., 2004).

In the infrared, [NeII] at 12.81µm has an ionization potential of 21.56 eV and is therefore excited by star formation activity. [NeIII] at 15.56µm has a higher ionization potential than [NeII] (41 eV), but it becomes more dominant in lower-metallicity and lower-luminosity systems (e.g. Wu et al. (2006)). Ho & Keto (2007) have demonstrated that the sum of [NeII] and [NeIII] correlates better with total infrared luminosity (a reliable proxy of SFR) than just [NeII] as this sum better accommodates the low metallicity systems. They subsequently calibrated a SFR based on [NeII] + [NeIII].

In Figures 5.1, we plot the relationship between SDSS SFR$_{total}$ and SFR$_{fiber}$. The AGN and composites are not systematically offset with respect to the best-fit trend from the star-forming galaxies (blue dashed line), though there is a large dispersion. The K-S test confirms that the galaxy sub-groups do not differ significantly (Table 5.2), indicating that the aperture correction used to derive a galaxy-wide SFR is not biased by AGN activity.

[NeII] luminosity is not biased by AGN activity (Figure 5.2 and Table 5.2) though the sum of [NeII] and [NeIII] is: Figure 5.3 demonstrates that the AGN are system-
atically offset to higher [NeII] + [NeIII] values with respect to star-forming galaxies.\(^2\) Indeed, the distribution of [NeII] + [NeIII] normalized by SDSS SFR\(_{\text{total}}\) and SFR\(_{\text{fiber}}\) is statistically different between star-forming galaxies and AGN (Table 5.2). The harder ionization field from the AGN is boosting [NeIII] to higher values, biasing the sum as a SF indicator in active systems. This result is consistent with previous works (e.g. Deo et al. (2007), Tommasin et al. (2008), Meléndez et al. (2008) and Pereira-Santaella et al. (2010)) that demonstrated that [NeIII]/[NeII] is correlated with AGN activity. Interestingly, the composite galaxies are not affected: their [NeII] + [NeIII] sum differs significantly from AGN, but not from star-forming galaxies. Hence, the SFR calibrated on [NeII] + [NeIII] is reliable for star-forming and composite galaxies, but not AGN.

Due to the agreement in [NeII] luminosity between star-forming galaxies and AGN, we modified the Ho & Keto (2007) relation to calibrate a SFR based solely on [NeII] luminosity. To account for the starburst contribution to the [NeIII] line, the [NeII] emission should be scaled by an appropriate factor. For non low-metallicity (log([NII]/H\(_\alpha\)) > -0.6 dex) star-forming galaxies, the median ([NeII] + [NeIII])/[NeII] ratio is 1.22. If we use the fiducial values of \(f_+ = 0.75\) and \(f_{+2} = 0.25\) from Ho & Keto (2007), the sum of the [NeII] and [NeIII] luminosities would be normalized by a factor of 1.17 (see their Eq. 13), which compensates for boosting the [NeII] emission to account for the starburst contribution to [NeIII]. We therefore modify their calibration by setting \(L_{[\text{NeIII}]} = 0\), \(f_+ = 1\) and \(f_{+2} = 0\). For consistency with the SDSS derived SFRs, and to use the most up-to-date calibrations based on more recent observations, we divided their normalization by 1.44 to convert from a Salpeter initial mass function (IMF) Salpeter (1955) to a Kroupa IMF Kroupa & Weidner (2003) (e.g. Kennicutt et al. (2009)) and obtain SFR\(_{[\text{NeII}]}\). We show SFR\(_{[\text{NeII}]}\) vs. SFR\(_{\text{total}}\) in Figure 5.4, which illustrates that AGN and composites agree with the star-forming galaxies. From survival analysis on the full sample, we find a best fit slope of 0.96±0.04, with intercept 0.09±0.02 and \(\sigma = 0.27\), which is consistent with the two quantities being equal.

\(^2\)In these plots and subsequent plots of IR emission line and PAH fluxes, the error bars are smaller than or on the order of the symbol size and therefore not plotted. These relatively small errors are due to the stringent 5\(\sigma\) threshold we required for detection.
5.1.1.2 PAH Luminosities

The luminosities of polycyclic aromatic hydrocarbons are thought to trace host galaxy star formation: they are very prominent in the spectra of star forming galaxies (Smith et al., 2007b) and are ionized by single ultraviolet or even optical photons (Li & Draine, 2002). However, studies have indicated that PAH strength is anti-correlated with AGN activity, possibly due to the destruction of dust grains by the hard ionization field from the central engine (Voit, 1992), with smaller molecules perhaps being preferentially destroyed (O’Dowd et al., 2009; Treyer et al., 2010). We investigate the effects of increasing ionization field hardness on PAH luminosities at 7.7$\mu$m, 11.3 $\mu$m and 17 $\mu$m by comparing these features with SFR proxies that are unbiased by AGN activity (SDSS SFRs and [NeII] luminosity).

To minimize biases introduced by aperture effects, we perform this analysis on a subset of our sources. The Spitzer Short-High module, through which [NeII] was measured, has an aperture size of 4.7” x 11.3” whereas the Spitzer Long-Low module has an aperture size of 10.5” x 168.” For sources at low redshift, these aperture sizes sample different regions of the galaxy. As our comparison star forming samples (SSGSS and S5) are at systematically higher redshifts than the Sy2 samples, we impose a redshift cut based on the minimum redshift of these samples, $z \approx 0.03$. This cut eliminates most of the 12$\mu$m sources and almost half of the [OIII] sample. However we can be more confident that any differences between quiescent and active galaxies represent true differences rather than biases introduced by sampling different flux levels due to aperture size. Also, for consistency with the SSGSS and S5 samples, we ran PAHFIT using mixed, rather than screen (see Chapter 2), extinction.

Both [NeII] and PAH luminosities are upper limits for at least a handful of sources. Since ASURV is unable to accommodate doubly censored data points, we calculated the ratio means and performed two-sample tests using upper limits on [NeII] and PAH luminosities separately. We report the results of both analyses in Tables 5.1 and 5.2, including the number of sources for each calculation.

As Figures 5.5 - 5.7 demonstrate, many AGN are consistent with the star-forming galaxy values, but a handful are far displaced from this relation. We obtain mixed
results as to whether AGN are associated with weaker PAH emission: when the PAH 7.7 and 11.3 μm features are normalized by the SDSS SFRs and [NeII] luminosity, the AGN have systematically lower PAH values than the star-forming galaxies (see Table 5.1). Conversely, the PAH 17 μm feature seems to be boosted in AGN as compared to quiescent systems. However, these differences, suppressed PAH 7.7 and 11.3 μm emission and enhanced PAH 17 μm emission in AGN relative to star-forming galaxies, are marginal. In some cases, two sample tests indicate the \( L_{PAH}/SFR \) populations do differ at a significant level (e.g. \( L_{PAH11.3\mu m}/L_{[NeII]} \)), but in other instances, they are not significantly disparate (e.g. \( L_{PAH17\mu m}/SFR_{fiber} \)). However, each PAH feature, when normalized by at least one SFR proxy, does show a significant difference between AGN and star-forming galaxies, which suggests that PAHs are biased estimators of starburst activity in AGN. Conversely, composite systems do not exhibit any significant differences from star-forming galaxies in their \( L_{PAH}/L_{SFR} \) ratios.

### 5.1.2 AGN Flux Proxies

As discussed in Chapter 2, \( L_{[OIII]} \) and \( L_{MIR} \) are diagnostics of the inherent AGN power. Since the SSGSS and S5 samples only have SH and not LH spectra, we are unable to use \( L_{[OIV]} \) in this analysis. We therefore explore [NeV] at 14.32 μm as an intrinsic AGN flux proxy. Similar to [OIV] and [OIII], it forms in the narrow line region. Due to its high ionization potential (97.1 eV), [NeV] has been claimed to be an unambiguous signature of AGN activity (Goulding et al., 2010). However, in a majority of cases, this feature was not significant above the noise, so we plot the detections only. Figure 5.8 illustrates that the [NeV] flux is well-correlated with \( L_{[OIII]_{obs}} \), \( L_{[OIII]_{corr}} \) and \( L_{MIR} \) at a significant level (\( \rho=0.77 \), \( P_{uncorr}=5.4\times10^{-8} \); \( \rho=0.55 \), \( P_{uncorr}=6.1\times10^{-4} \); \( \rho=0.84 \), \( P_{uncorr}=9.2\times10^{-10} \), respectively), reaffirming that it is a reliable diagnostic of intrinsic AGN flux. We note that one star-forming galaxy and two composite systems have [NeV] detections, which may suggest that these sources are harboring “hidden” AGN, i.e. AGN embedded in very dusty host galaxies that are attenuating the optical signatures used to identify AGN.
In §5.1.4, we utilize the upper limits on [NeV] from stacked spectra to investigate the agreement among diagnostics of the ionization field hardness.

Figure 5.9 demonstrates that AGN and composites have systematically higher $L_{[O\text{III}],\text{corr}}$ luminosities than star-forming galaxies (also see Tables 5.3 and 5.4). However, the MIR flux, when normalized by $L_{[O\text{III}]}$, is significantly higher in star-forming galaxies and composites than AGN. This enhancement of relative MIR flux results from two effects: boosted [OIII] flux in active systems and a greater relative amount of star-formation activity in quiescent galaxies. These results still apply when we remove the [OIII] sample from the calculations (see last column of Table 5.3), which suggests that this trend represents a real difference between AGN and star-forming galaxies rather than the inclusion of [OIII]-bright sources biasing the results.

### 5.1.2.1 Decomposing MIR Flux

MIR flux in active galaxies has contributions from host galaxy star formation and emission from the toroidal obscuring medium. To quantify the relative importance of these two effects, we solve:

$$L_{\text{MIR}} = \alpha L_{\text{SFR}} + \beta L_{\text{AGN}}$$

We set $L_{\text{SFR}} = L_{[Ne\text{II}]}$ and $L_{\text{AGN}} = L_{[O\text{III}],\text{AGN}}$. To calculate $L_{[O\text{III}],\text{AGN}}$, we use Equation 3 in Wild et al. (2010), which scales the observed [OIII] flux based on the source’s position in the BPT diagram. For the Sy2s where this correction failed (i.e. $L_{[O\text{III}],\text{AGN}} > L_{[O\text{III}],\text{obs}}$), we set $L_{[O\text{III}],\text{AGN}} = L_{[O\text{III}],\text{obs}}$. For the composite and star-forming galaxies where this correction failed (i.e. $L_{[O\text{III}],\text{AGN}} < 0$), we set $L_{[O\text{III}],\text{AGN}} = 0$.

Using the sources that had [NeII] detections, we calculated $\alpha$ and $\beta$ by using a least squares trimmed regression, a robust regression technique that removes outliers, of the above equation and obtain $\alpha=89$ and $\beta=130$. In Figure 5.12, we plot $L_{\text{MIR}}$ vs. $\alpha L_{\text{SFR}} + \beta L_{\text{AGN}}$ (i.e. $89 \times L_{[Ne\text{II}]} + 130 \times L_{[O\text{III}],\text{AGN}}$), with the overplotted line indicating where the two quantities are equal. No systematic offsets among galaxy sub-type are present. This relationship can therefore be valuable for estimating the MIR flux due to star-formation (or conversely from the torus) in active galaxies.
5.1.3 Connection between AGN and SFR

It is widely recognized that galaxies and their supermassive black holes are linked through co-evolution. Here we empirically investigate the relationship between AGN activity and host galaxy star formation in active systems. To undertake this comparison, the diagnostics used for intrinsic AGN flux should ideally be unaffected by starburst activity. We therefore use the [NeV] flux, which due to its high ionization potential, should be negligibly impacted by star formation. We also correct the [OIII] and MIR luminosities for starburst contamination, obtaining $L_{\text{[OIII],AGN}}$ (using Eq. 3 from Wild et al. (2010) as discussed above) and $L_{\text{MIR,AGN}}$, where $L_{\text{MIR,AGN}} = (L_{\text{MIR}} - \alpha L_{\text{SFR}})$, with $L_{\text{SFR}} = L_{\text{[NeII]}}$ and $\alpha$ found from § 5.1.2.1. We note, however, that in several cases the starburst contamination removal to $L_{\text{MIR}}$ failed (i.e. $L_{\text{MIR,AGN}} < 0$); these sources were excluded from the analysis. We compare these AGN flux proxies with the SDSS SFRs and in the case of $L_{\text{[NeV]}}$ and $L_{\text{[OIII],AGN}}$, with [NeII] luminosity; since $L_{\text{MIR,AGN}}$ was calculated using $L_{\text{[NeII]}}$, we do not compare these parameters to avoid possible degeneracies. As the [NeII] flux and SFR$_{fiber}$ are measured through relatively small apertures that only encompass the center of the galaxy (11.3" and 3" respectively), they most accurately trace circumnuclear starburst activity.

We present the relationships between $L_{\text{AGN}}$ and SFR in Figures 5.13 - 5.15. Statistically significant trends are found in almost all cases (see Table 5.5), though with wide scatter. As we have attempted to minimize the starburst contamination to $L_{\text{AGN}}$, the significant correlations demonstrate a real link between AGN activity and circumnuclear star formation, as parametrized by the $L_{\text{[NeII]}}$ flux and SFR$_{fiber}$. The correlation between $L_{\text{AGN}}$ and SFR$_{total}$ suggests that AGN activity and galaxy-wide star formation are also related. These results provide additional evidence of the co-evolution implied by the M-σ relation: accretion feeding the black hole is correlated with star formation that builds up the galactic bulge. This trend is consistent with previous studies that have found in tandem growth of supermassive black holes and bulges in the local universe (e.g. Heckman et al. (2004)).
5.1.4 Relative Importance of AGN to Star Formation Activity

As discussed in §2.4.4, [OIV]/[NeII] is a reliable tracer of the incident radiation field hardness. However, we do not have LH coverage for the SSGSS and S5 samples. We therefore use [NeV]14.32 µm/[NeII] in lieu of [OIV]/[NeII]: figure 5.16 illustrates the significant agreement between these two ratios ($\rho = 0.757$, giving a probability that the parameters are not correlated of $3.2 \times 10^{-6}$). Similar to [OIV], [NeV] has a much higher ionization potential than [NeII], so the ratio of the two parametrizes the amount of radiation due to AGN versus star-formation. However, as mentioned in §5.1.2, a vast majority of sources do not have [NeV] detections. Rather than employing individual upper limits, we consider these non-detections in aggregate, stacking the spectra among sub-groups of galaxy type. We compare this ratio with other diagnostics we introduced in §2.4.4 that indicate the relative contributions of AGN activity to starburst processes on the radiation field: the optical D parameter, which is the distance a source lies on the BPT diagram from the locus of star-forming galaxies; $\alpha_{2-30\mu m}$ which steepens in the presence of cold dust associated with star formation activity; and the PAH EWs which are expected to decrease as AGN activity becomes more dominant. We also compare these proxies amongst each other to expand the parameter space we explored in Chapter 2. For the PAH EWs, we only include the sources where the feature was detected at a significant level.

5.1.4.1 [NeV] Stacked Spectra

To stack the short-high spectra, we separated star-forming galaxies, composites and AGN into two groups each, based on their location in the BPT diagram, in order of increasing nuclear activity. Figure 5.17 illustrates the method we used. The left hand plot is a BPT diagram for our full sample, with the unbroken black lines showing the Kewley et al. (2001) (upper) and Kauffmann et al. (2003) (lower) demarcations between star-forming galaxies, composites and AGN. The dashed lines illustrate the additional empirical separations we used, approximately tracing the halfway point.
within each region. These lines correspond, in order of lowest to highest, to the following equations:

\[
\log\left(\frac{[OIII]/H\beta}{[NII]/H\alpha}\right) = 0.61 \left(\log\left(\frac{[NII]/H\alpha}{0.1}\right) + 1.3\right)
\]

\[
\log\left(\frac{[OIII]/H\beta}{[NII]/H\alpha}\right) = 0.61 \left(\log\left(\frac{[NII]/H\alpha}{-0.2}\right) + 1.3\right)
\]

\[
\log\left(\frac{[OIII]/H\beta}{[NII]/H\alpha}\right) = 0.61 \left(\log\left(\frac{[NII]/H\alpha}{-1}\right) + 1.19\right)
\]

We also employed a cut on \([NII]/H\alpha\) to exclude low metallicity systems: Log \([NII]/H\alpha\) > -0.6 dex for star-forming galaxies and Log \([NII]/H\alpha\) > -0.2 dex for AGN. The right-hand panel of Figure 5.17 shows our resulting sub-groups depicted in different colors with the Kewley et al. (2001) (upper) and Kauffmann et al. (2003) (lower) demarcations overplotted: star-forming group 1 - dark blue, star-forming group 2 - light blue, composite group 1 - dark green, composite group 2 - light green, AGN group 1 - gold, AGN group 2 - red.

We stacked together the IRS SH spectra for the sources in each color bin from Figure 5.17 b) not detected in \([NeV]\). Each spectrum was shifted to the rest-frame, rebinned to a common wavelength grid of equal pixel spacing and normalized by the the average MIR flux between 13.25μm and 13.75μm; this window was chosen since it is free of strong emission features. Figure 5.18 shows the stacked SH spectra for each galaxy bin. We used 3σ clipping on the average flux in each pixel to reject outliers that would have otherwise introduced erroneous features into our stacked spectra due to noise. \([NeV]\) was detected above the 5σ level in just one of these bins, AGN group 2. For the other bins, we obtained \([NeV]\) upper limits using the procedure outlined in §2.3.1. \([NeV]/[NeII]\) was calculated by normalizing the \([NeV]\) upper limit/detection by the stacked \([NeII]\) emission feature in each group, which was detected at high significance in all cases. In the following analysis, we plot the \([NeV]/[NeII]\) detections and stacked \([NeV]/[NeII]\) upper limits against the average optical D value, PAH EW and \(\alpha_{20-30\mu m}\) for its corresponding galaxy bin. The \([NeV]\) stacked detection is illustrated by the triangle in the subsequent figures.

Figures 5.19 - 5.20 illustrate the trends between \([NeV]/[NeII]\) and the other diagnostics of radiation field hardness. As expected, \([NeV]/[NeII]\) is significantly cor-
related with D and significantly anti-correlated with $\alpha_{20-30\mu m}$ and PAH EWs (Table 5.6). The stacked [NeV] detection appears on the higher range of [NeV]/[NeII] values in relation to PAH EWs. Interestingly, the star-forming galaxy and two composite systems with [NeV] detections have other IR parameters more consistent with star-forming galaxies and composites respectively, rather than AGN. This association would argue against the interpretation that they are harboring strong “hidden” AGN, which may call into question using solely [NeV] as an unambiguous signature of AGN activity.

5.1.5 $\alpha_{20-30\mu m}$

We plot $\alpha_{20-30\mu m}$ as a function of the optical D parameter in Figure 5.21. A wide range of $\alpha_{20-30\mu m}$ values are present for the star-forming galaxies. Consequently, there is no significant anti-correlation present in the full sample ($\rho=-0.195$). However, if we consider just the AGN, a significant trend is apparent: $\rho=-0.474$. This correspondence likely drives the significant anti-correlation found for [NeV]/[NeII] vs $\alpha_{20-30\mu m}$. The IR spectral index is thus useful in parametrizing the relative contribution of star formation in active galaxies but this appears to break down in the quiescent galaxy regime. Consequently, we only utilize D to explore the connections between PAH EW strength and ionization field hardness.

5.1.6 PAH EWs and Flux Ratios

Previous works have suggested that shorter-wavelength PAHs are preferentially destroyed as the radiation field hardens due to AGN activity (e.g. O’Dowd et al. (2009), Treyer et al. (2010), Diamond-Stanic & Rieke (2010)). However, these studies have been limited to samples of predominantly star-forming galaxies and weaker AGN (O’Dowd et al. (2009), Treyer et al. (2010)) or of active galaxies only (Diamond-Stanic & Rieke, 2010). This expanded data set that spans the range from quiescent systems to strong AGN provides the opportunity to test this scenario over a full range of incident radiation field strength. For this analysis, we use the full sample rather than
employing the redshift cut used in §5.1.1.2 so that we include a substantial fraction of AGN dominated sources. For the parameters we are analyzing, biases introduced by sampling different flux levels due to different aperture sizes are less of a concern: the continuum flux is divided out in the EWs and PAH fluxes are measured through the same aperture, making their ratios unaffected by aperture bias.

Figure 5.22 plots the PAH EW at 7.7 µm, 11.3 µm and 17 µm as a function of the optical D parameter. Significant anti-correlations are present (Table 5.7). If the increase in the incident radiation field preferentially affects the smaller dust grains, the anti-correlation between PAH EW and D should decrease and the best-fit slope between the two quantities should flatten with increasing wavelength. However, such trends are not found. The best-fit slope among the EWs are consistent, as well as their correlation coefficients. Similar to the findings of O’Dowd et al. (2009) and Treyer et al. (2010), there is not a significant anti-correlation between EW and strength of the ionization field for star-forming galaxies and composites: ρ = -0.227, -0.125 and -0.230 for the 7.7 µm, 11.3 µm and 17 µm features, respectively. Hence, the harder radiation field associated with AGN seem to be necessary to noticeably affect PAH emission.

Though the D parameter and PAH EWs should not be affected by the different flux levels captured by various aperture sizes, aperture bias may still play a role in these results. For systems at lower redshifts, the AGN dominates the emission whereas the aperture more fairly samples the host galaxy for more distant sources. Could these significant anti-correlations between PAH EWs and the optical D parameter be driven by low redshift systems where the AGN dilutes the PAH features? To test this, we undertake the same analysis as above using sources at a redshift of z ≥ 0.03.

As noted in §5.1.1.2, this eliminates the majority of our Sy2 samples, yet we retain a handful of [OIII] sources and are thus able to test the relationship between PAH EWs and ionization field hardness over a wide range of nuclear galactic activity. Figure 5.23 illustrates that the trends found for the full sample still hold for this pared down sample: AGN at higher D values are associated with suppressed PAH features at a statistically significant level even when the host galaxy is more fully sampled (see Table 5.7).

Similar to the work of O’Dowd et al. (2009) and Diamond-Stanic & Rieke (2010),
we investigate the relationship between radiation field hardness and the ratios of the PAH fluxes in Figures 5.24 and 5.25. Using \([\text{NeV}]/[\text{NeII}]\) as a probe of the ionization field, a significant anti-correlation exists with \(L_{\text{PAH}11.3\mu m}/L_{\text{PAH}17\mu m}\) \((\rho=-0.564)\), but a significant correlation is present with \(L_{\text{PAH}7.7\mu m}/L_{\text{PAH}11.3\mu m}\) \((\rho=0.611)\). Such a correlation contradicts the results of O’Dowd et al. (2009) and Diamond-Stanic & Rieke (2010) who find that \(L_{\text{PAH}7.7\mu m}/L_{\text{PAH}11.3\mu m}\) is suppressed in active nuclei. However, when using the optical D parameter as a diagnostic of the ionization field hardness, which has the advantage of considering individual source detections rather than aggregate upper limits in \([\text{NeV}]\), only \(L_{\text{PAH}11.3\mu m}/L_{\text{PAH}17\mu m}\) remains significant, albeit with wide scatter \((\rho=-0.193, -0.364 \text{ and } 0.179 \text{ for } L_{\text{PAH}7.7\mu m}/L_{\text{PAH}17\mu m}, L_{\text{PAH}11.3\mu m}/L_{\text{PAH}17\mu m} \text{ and } L_{\text{PAH}7.7\mu m}/L_{\text{PAH}11.3\mu m}, \text{ respectively})\). A handful of AGN at high D \((\geq 1.4)\) are displaced to systematically higher \(L_{\text{PAH}7.7\mu m}/L_{\text{PAH}11.3\mu m}\) values, yet the majority of these AGN are consistent with the ratios of star-forming galaxies.

### 5.2 Soft X-ray Perspective on Disentangling AGN Activity from Host Galaxy Star Formation

X-ray emission has been used as a star formation rate indicator in quiescent galaxies (e.g. Ranalli et al. (2003), Persic & Rephaeli (2007), and Lehmer et al. (2008)). However, disentangling the AGN contribution to the 2-10 keV emission from star formation processes, i.e. that due to X-ray binaries, supernova remnants and shocks, is prohibitively difficult when the nucleus is not resolved since the AGN dominates at these energies. The soft X-ray emission \((0.5 - 2 \text{ keV})\) in active galaxies could have comparable contributions from thermal gas associated with host galaxy star formation and scattered/reflected AGN emission. For our two Sy2 samples, we investigate disentangling these two processes in the soft X-ray band. As noted in Chapter 3, we included an APEC component, which describes emission from a collisionally ionized plasma, to accommodate the possibility of starburst activity. Indeed, several 12\(\mu m\)
sources required this model component to properly fit the spectrum below 2 keV.

Since we are investigating host galaxy star formation, we utilized a larger Chandra extraction region than reported in Chapter 3. For the sources in the 12μm sample that had both Chandra and XMM-Newton data, we extracted the Chandra spectrum from an aperture that matched the XMM-Newton region size (NGC 424, NGC 1386, F05189-2524, NGC 3982, NGC 4388, NGC 4501, Mrk 463 and NGC 7582). We increased the extraction region for the 12μm sources that had only Chandra data to encompass all visible extended emission. NGC 1068 has been omitted from this analysis since it has been established that the soft emission is due to photoionization from the central AGN and not host galaxy star formation.

The soft X-ray fit for nine 12μm Sy2s were significantly improved by adding a second APEC component to the model (NGC 424, NGC 1320, NGC 1386, NGC 4388, M-3-34-64, NGC 5194, Mrk 463, XMM-Newton observation of NGC 7582 and NGC 7674). This second thermal component indicates the presence of multiple temperature plasma, associated with multiple episodes of star formation. However, none of the [OIII]-selected Sy2s were better accommodated by the addition of a second APEC component. In Tables 5.8 and 5.9, we report the parameters for the APEC and power law fits for the [OIII] sample and 12μm sample, respectively. In the cases of a double power law fit, $\Gamma_1 = \Gamma_2 = \Gamma$. The sources without a listed $N_{H,2}$ were best fit by a single power law. Three Sy2s from the [OIII] sample had an unconstrained APEC fit and are omitted from Table 5.8 and the subsequent analysis: CGCG 064-017, CGCG 218-007 and 2MASX J13463217+6423247. NGC 4388 and NGC 7582 are listed separately for the Chandra and XMM-Newton observations in Table 5.9, since as noted in Chapter 3, inconsistencies in parameters from the matched aperture extractions indicate source variability.

The fluxes from these fits are listed in Tables 5.10 and 5.11, where the first column lists the total 0.5 - 2 keV flux and the second column lists the flux from the APEC component only. The APEC fluxes for NGC 0291 and 2MASX J11110693+0228477 were poorly constrained (error bars over an order of magnitude larger than the value) and are consequently omitted from the following analysis. The fluxes for NGC 4388 and NGC 7582 were consistent between the Chandra and XMM-Newton observations.
and were therefore averaged.

Though we utilize broad-band (0.5 - 8 keV) power law fitting to account for the AGN contribution in the soft band, removing this component when examining the APEC flux, unresolved emission from AGN photoionization can still potentially contaminate the soft emission. How well then does this APEC flux truly trace thermal emission from host galaxy star formation?

### 5.2.1 Relationship Between APEC Flux and Multi-wavelength Star Formation Rate Indicators

In Section 5.1, we demonstrated that the [NeII] flux and SDSS star formation rates are relatively unaffected by AGN activity. In Figure 5.26, we show the relation between the APEC flux and [NeII] flux, which according to survival analysis, is statistically significant ($\rho=0.652$, $P_{uncorr}=1\times10^{-4}$).

(Ranalli et al., 2003) have demonstrated that the soft X-ray emission in star-forming galaxies correlates with the far infrared and radio luminosities (at 1.4 GHz), parameters which are used to calibrate star formation rates. They thus obtain a soft X-ray SFR: $\text{SFR} = 2.2\times10^{-40}L_{0.5-2\text{keV}} \text{ M}_\odot/\text{yr}$. Using the APEC fluxes listed in Tables 5.10 and 5.11, we calculate $\text{SFR}_{\text{APEC}}$ and compare with total SDSS SFR (Figure 5.27, with a line to indicate where the values are equal). A relatively good agreement between the two SFRs is evident, albeit with large error bars. If unresolved AGN luminosity was contributing to the APEC flux, $\text{SFR}_{\text{APEC}}$ would be boosted and systematically higher than $\text{SFR}_{\text{total}}$. This effect is not present, suggesting moderate success in removing the AGN contribution in soft X-rays using the APEC model.

Though the correlations between the APEC flux and SFR proxies suggest moderate success in disentangling star formation activity from AGN processes in soft X-rays, a degeneracy may still exist: these trends could be partially driven by the link between AGN activity and host galaxy star formation (see §5.1.3). Other checks are therefore necessary to determine the effectiveness in separating these two effects.
5.2.2 Grating Spectroscopy

The X-ray analysis thus far has focused on low-resolution CCD spectra. In order to resolve narrow emission lines, high resolution grating spectroscopy is necessary. Emission lines between 0.5 and 2 keV provide a wealth of information that can be used to disentangle AGN emission due to photoionization from star formation resulting from collisional ionization. These diagnostics include the width of the radiative recombination continua (RRC), which result from electron recombination to the ground state of H- and He-like ions (C, N and O are the relevant ions in this energy range), and ratios of the forbidden (f), intercombination (i) and resonance (r) lines in the OVII triplet. In collisionally ionized plasmas, the RRC is broad, on the order of the initial electron energy, whereas this feature is narrow, on the order several eV, in cooler photoionized plasma Liedahl & Paerels (1996). For the OVII triplet, the ratio $G = (f + i)/r$ indicates the dominant ionization mechanism since photoionization produces a weak resonance line while collisional ionization creates a stronger resonance line: $G > 4$ in photoionized plasma but is $\sim 1$ in plasmas collisionally ionized Porquet & Dubau (2000). Guainazzi et al. (2009) presented a diagnostic diagram to empirically separate starburst emission from AGN, using the ratio the OVIII Ly$\alpha$ line to the forbidden transition of OVII against the integrated luminosity of the oxygen lines. Starburst galaxies lie in a region of lower $L_O$ luminosity ($< 2 \times 10^{41}$) and higher ratios ($>0.4$, see their Fig. 9).

For the handful of 12$\mu$m sources that have published high resolution spectral data (from the reflection grating spectrometer, RGS, on XMM-Newton), we compare these diagnostics with our “thermal” ($F_{APEC}$) and “AGN” ($F_{0.5-2keV} - F_{APEC}$) decomposition listed in Table 5.11.

5.2.2.1 NGC 424

About 1/3 of the soft X-ray flux in NGC 424 can be attributable to thermal emission. This is somewhat consistent with the findings of Marinucci et al. (2011) who find that photoionization dominates the emission: $G \geq 4.3$ and narrow RRC features are detected in OVIII, OVII and CVI. Our lower resolution decomposition
somewhat overpredicts the importance of collisional ionization, however there are wide error bars on this “thermal” flux.

5.2.2.2 NGC 5506

Guainazzi & Bianchi (2007) report upper limits on the OVII and CV RRC of 5.6 eV and 1.1 eV, which is suggestive of a photoionization origin. This is consistent with our decomposition which suggests that 0-~ 2% of the soft flux could be attributable to star formation. However, this source also lies in the starburst region of OVIII Lyα/OVII(f) vs. $L_O$, which would indicate a substantial contribution from collisional ionization (Guainazzi et al., 2005).

5.2.2.3 NGC 7582

According to our measured “thermal” and “AGN” fluxes, starburst activity contributes almost 40% of the 0.5 - 2 keV emission. The OVII RRC is measured to have an upper limit of 6.3 eV which indicates the dominance of photoionization (Guainazzi & Bianchi, 2007). However, according to the diagnostic diagram of OVIII Lyα/OVII(f) vs. $L_O$ in Guainazzi et al. (2009), NGC 7582 is one of the Sy2 outliers that live in the starburst galaxy parameter space, suggesting an appreciable contribution from collisional ionization. These findings are consistent with our decomposition which indicates that photoionization is dominant while starburst activity plays a non-negligible role.

5.3 Summary

We have explored the multi-wavelength parameter space where star-forming galaxies, composites and AGN live. We have investigated which diagnostics are least biased in describing star formation in galaxies over a range of nuclear activity level. Using decomposition of AGN flux proxies to disentangle star-formation from pure AGN activity, we have examined the relationship between these two processes. We have
also explored the diagnostics that probe the relative amount of AGN activity to star-formation activity to test their agreement from quiescent galaxies to active systems and to test the effects of an increasing radiation field hardness on PAH survival. Finally, we attempt to separate out the effects of scattered/reflected AGN flux from thermal emission due to starburst activity in the 0.5 - 2 keV range. Our results are summarized as follows:

SFR diagnostics SDSS derived SFRs and the [NeII] 12.81\(\mu\)m luminosity are the most reliable SF proxies to use for star-forming galaxies, composites and AGN. The sum of [NeII] and [NeIII] 15.56\(\mu\)m is systematically offset to higher values for AGN due to the active nucleus boosting the [NeIII] flux.

SFR diagnostics: PAHs We have tested whether the PAH luminosities at 7.7, 11.3 and 17 \(\mu\)m could be used as reliable tracers of star formation in active systems. We find that \(L_{PAH}/L_{SFR}\) is significantly different between star-forming galaxies and AGN for at least one SFR proxy, though not all. This result suggests that the PAHs represent a biased view of star formation in AGN and may therefore not be a useful diagnostic to cleanly trace starburst activity in these systems.

SFR diagnostics: Composite Systems Though we have found evidence that AGN emission affects the utility of [NeII] and PAH luminosity as reliable SFR tracers, the weaker nuclear activity in composites does not seem to affect these features. Composites are more similar to star-forming galaxies and are significantly different from AGN in terms of [NeIII] emission and they exhibit no significant difference in \(L_{PAH}/L_{SFR}\) from star-forming galaxies.

Disentangling MIR Emission We have fit the equation \(L_{MIR} = \alpha L_{SFR} + \beta L_{AGN}\) to determine \(\alpha\) and \(\beta\). We set \(L_{SFR} = L_{[NeII]}\) and \(L_{AGN} = L_{[OIII],AGN}\) where in \(L_{[OIII],AGN}\), we have subtracted out the estimated starburst contribution to the [OIII] flux using Eq. 3 in Wild et al. (2010). We find \(\alpha = 89\) and \(\beta = 130\).

[NeV] Due to the high ionization potential of [NeV] (97.1 eV), it is potentially an unequivocal signature of AGN activity. However, this feature is not detected.
in a vast majority of sources. We then considered [NeV] in aggregate, stacking spectra for non-detections in bins of increasing ionization field hardness to test the correlation between [NeV]/[NeII] with other diagnostics of the relative contributions of AGN activity to star formation. We demonstrate that significant trends do exist. However, one star-forming galaxy and two composites have [NeV] detections, yet other IR parameters (i.e. EW values) more consistent with their optical designations rather than AGN, which could argue against these sources being considered strong “hidden” AGN.

**AGN Activity and Star Formation** Using proxies uncontaminated by starburst activity ($L_{[NeV]}$, $L_{[OIII]}$, $L_{MIR,AGN}$, estimated using the above equation), we have demonstrated a significant correlation between AGN emission and star formation. This result suggests that the growth of supermassive black holes through accretion and the galactic bulge via star formation are co-temporal and likely linked. This trend is consistent with the finding of previous studies of type 2 AGN in the local universe (Heckman et al., 2004).

**Ionization Field Hardness** The spectral slope between 20-30 $\mu$m ($\alpha_{20-30\mu m}$) exhibits a wide range of values for star-forming galaxies, though it is significantly anti-correlated with other proxies of ionization field hardness for AGN ($L_{[NeV]}/L_{[NeII]}$, the optical D parameter). PAH EWs also show a significant anti-correlation with increasing radiation field, but this is driven by AGN activity: when considering just the star-forming galaxies, no trend exists between incident radiation and the strength of the resulting PAH feature, which agrees with the findings of O’Dowd et al. (2009) and Treyer et al. (2010). This result is consistent with the hypothesis that AGN activity is responsible for PAH destruction. Unlike previous studies (O’Dowd et al. (2009), Treyer et al. (2010)) we find at best tenuous evidence to support selective destruction of shorter wavelength PAHs. $L_{PAH11.3\mu m}/L_{PAH17\mu m}$ is anti-correlated with radiation field hardness, though $L_{PAH7.7\mu m}/L_{PAH17\mu m}$ and $L_{PAH7.7\mu m}/L_{PAH11.3\mu m}$ show no significant trends with the incident ionization field. The best-fit slope between PAH EW and the optical D parameter is also consistent between the PAH fea-
tures we have considered, which argues against selective destruction of smaller PAH grains. This inconsistency with previous results is likely due to the inclusion of more AGN dominated sources in our sample.

**Soft X-rays** We have fit the broad-band X-ray continuum (0.5 - 8 keV) of the Sy2s with power law models to constrain the AGN emission. In soft X-ray (0.5 - 2 keV), we have added a thermal component (APEC) to account for possible starburst activity. We find a significant correlation between this APEC flux and [NeII] emission. Using the SFR calibration from Ranalli et al. (2003) and $F_{APEC}$, we illustrated that this is well correlated with SDSS SFR$_{fiber}$, and not systematically offset to higher values which would be expected if unresolved AGN emission was contributing significantly to the “thermal” flux. For the handful of sources with high resolution grating spectroscopy, this AGN/thermal decomposition is mostly consistent with the measured RRCs, $G$ ratio and/or OVIII Ly$_{\alpha}$/OVI(f) vs. L$_{CO}$ diagnostic plot (Marinucci et al. (2011), Guainazzi & Bianchi (2007), Guainazzi et al. (2009)).
Figure 5.1 Left: SDSS SFR$_{total}$ vs SFR$_{fiber}$. The symbol coding is as follows: S5 - crosses, SSGSS - circles, [OIII] sample - squares, 12µm sample - diamonds. Blue data points represent star-forming galaxies, green indicates composites and red denotes AGN. The blue dashed line delineates the best-fit trend to the star forming galaxies. Right: Distribution of log(SDSS SFR$_{total}$/SDSS SFR$_{fiber}$). No significant offsets among sub-groups are apparent.
Figure 5.2 Left: $L_{[NeII]}$ vs. SDSS SFR$_{total}$. Right: Distribution of $\log(L_{[NeII]}/$SDSS SFR$_{total}$). For these and subsequent plots with IR emission line and PAH fluxes, error bars are smaller or on the order of the symbol size and therefore not plotted. No significant offsets among sub-groups are apparent. Color, symbol and line coding same as Figure 5.1.

Figure 5.3 Left: $L_{[NeII]} + L_{[NeIII]}$ vs. SDSS SFR$_{total}$. Right: Distribution of $\log((L_{[NeII]} + L_{[NeIII]})/$SDSS SFR$_{total}$). The AGN are systematically offset to higher values of $L_{[NeII]} + L_{[NeIII]}$ due to the harder ionization field from the central engine.
Figure 5.4 Left: SFR$_{[NeII]}$ vs. SDSS SFR$_{total}$. The two quantities are consistent with each other over a range of galactic nuclear activity. The overplotted line depicts where the two quantities are equal. Color and symbol coding same as Figure 5.1.
Figure 5.5 PAH 7.7\(\mu\)m feature vs. other indicators of star formation activity for sources at \(z \geq 0.03\). Color, symbol and line coding same as Figure 5.1.
Figure 5.6 PAH 11.3µm feature vs. other indicators of star formation activity for sources at \( z \geq 0.03 \). Color, symbol and line coding same as Figure 5.1.
Figure 5.7 PAH 17\(\mu\)m feature vs. other indicators of star formation activity for sources at \(z \geq 0.03\). Color, symbol and line coding same as Figure 5.1.
Figure 5.8 $L_{\text{[NeV]}}$ vs. AGN flux proxies we presented in Chapter 2. [NeV] is significantly correlated with these luminosities: a) $L_{\text{[NeV]}}$ vs. $L_{\text{[OIII],obs}}$: $\rho=0.77$, $P_{\text{uncorr}}=5.4 \times 10^{-8}$; b) $L_{\text{[NeV]}}$ vs $L_{\text{[OIII],corr}}$: $\rho=0.55$, $P_{\text{uncorr}}=6.1 \times 10^{-4}$; c) $L_{\text{[NeV]}}$ vs $L_{\text{MIR}}$: $\rho=0.84$, $P_{\text{uncorr}}=9.2 \times 10^{-10}$. Color and symbol coding same as Figure 5.1.
Figure 5.9 Left: $L_{\text{[OIII],corr}}$ vs. $L_{\text{[OIII],obs}}$. Right: Distribution of $\log(L_{\text{[OIII],corr}}/L_{\text{[OIII],obs}})$. Color, symbol and line coding same as Figure 5.1. The AGN are systematically offset to higher $L_{\text{[OIII],corr}}$ values.

Figure 5.10 Left: $L_{\text{MIR}}$ vs. $L_{\text{[OIII],obs}}$. Right: Distribution of $\log(L_{\text{MIR}}/L_{\text{[OIII],obs}})$. Color, symbol and line coding same as Figure 5.1. Star-forming galaxies have a relatively greater amount of MIR flux than AGN.
Star-forming galaxies have a relatively greater amount of MIR flux than AGN.

Figure 5.11 Left: $L_{MIR}$ vs. $L_{[OIII]_{corr}}$. Right: Distribution of $\log(L_{MIR}/L_{[OIII]_{corr}})$. Color, symbol and line coding same as Figure 5.1.

Figure 5.12 $L_{MIR}$ vs. $\alpha L_{SFR} + \beta L_{AGN}$, where $L_{SFR} = L_{[NeII]}$ and $L_{AGN} = L_{[OIII]_{AGN}}$. $\alpha$ and $\beta$ were found by using a least trimmed squares regression: $\alpha=89$, $\beta=130$. The dashed line indicates where the two quantities are equal. Color coding same as Figure 5.1.
Figure 5.13 $L_{[NeV]}$ vs. SFR proxies. In 2 out of 3 cases, a significant correlation is found. a) $L_{[NeV]}$ vs SFR$_{fiber}$: $\rho=0.275$, $P_{uncorr}=0.090$; b) $L_{[NeV]}$ vs. SFR$_{total}$: $\rho=0.377$, $P_{uncorr}=0.024$; c) $L_{[NeV]}$ vs. $L_{[NeII]}$: $\rho=0.470$, $P_{uncorr}=6\times10^{-4}$. Color and symbol coding same as Figure 5.1.
Figure 5.14 “AGN-only” component of $L_{\text{[OIII]}}$ vs. SFR proxies. A significant correlation is present. a) $L_{\text{[OIII]}}$,AGN vs. SFR$_{\text{fiber}}$: $\rho=0.533$, $P_{\text{uncorr}}=6.9\times10^{-5}$; b) $L_{\text{[OIII]}}$,AGN vs. SFR$_{\text{total}}$: $\rho=0.367$, $P_{\text{uncorr}}=0.009$; c) $L_{\text{[NeII]}}$ vs $L_{\text{[OIII]}}$,AGN: $\rho=0.343$, $P_{\text{uncorr}}=0.006$. Color and symbol coding same as Figure 5.1.
Figure 5.15 “AGN-only” component of $L_{MIR}$ vs SDSS SFRs. A significant correlation exists. a) $L_{MIR,AGN}$ vs. SFR$_{fiber}$: $\rho=0.583$, $P_{uncorr}=0.001$; b) $L_{MIR,AGN}$ vs. SFR$_{total}$: $\rho=0.554$, $P_{uncorr}=0.003$. Color and symbol coding same as Figure 5.1.
Figure 5.16 $L_{\text{[NeV]}}/L_{\text{[NeII]}}$ vs. $L_{\text{[OIV]}}/L_{\text{[NeII]}}$ for $12\mu m$ and [OIII]-selected sources with [NeV], [OIV] and [NeII] detections. The significant correlation ($\rho=0.757$, $P_{\text{uncorr}}=3.2\times10^{-6}$) illustrates that $L_{\text{[NeV]}}/L_{\text{[NeII]}}$ is a robust trace of the ionization field hardness. Color and symbol coding same as Figure 5.1.
Figure 5.17 Left: BPT diagram for all sources in our sample. The unbroken black lines indicate the Kewley et al. (2001) (upper) and Kauffmann et al. (2003) (lower) demarcations between star-forming galaxies, composites and AGN. The dashed black lines illustrate the dividing lines we used to separate the sample to stack the short-high IRS spectra. Color and symbol coding same as Figure 5.1. Right: After removing the low-metallicity systems and using the demarcations shown in the left-hand plot, the groups into which our sample were separated our indicated by the colors in this plot: star-forming group 1 - dark blue, star-forming group 2 - light blue, composite group 1 - dark green, composite group 2 - light green, AGN group 1 - gold, AGN group 2 - red.
Figure 5.18 Stacked SH spectra around the [NeV] emission line at 14.32 µm for each group of galaxies illustrated in Figure 5.17 b). The dashed line indicates the nominal [NeV] wavelength. [NeV] was detected above the 5σ level in AGN group 2 only.
Figure 5.19 Left: \( L_{[NeV]} / L_{[NeII]} \) vs. the optical D parameter. Right: \( L_{[NeV]} / L_{[NeII]} \) vs. \( \alpha_{20-30\mu m} \). These quantities are statistically correlated and anti-correlated: \( \rho = 0.562 \) and \( \rho = -0.568 \), respectively. The red triangle indicates the [NeV] detection for the stacked spectra in AGN group 2. Color and symbol coding same as Figure 5.1.
Figure 5.20 a) $L_{[NeV]}/L_{[NeII]}$ vs. PAH EW at 7.7 μm. b) $L_{[NeV]}/L_{[NeII]}$ vs. PAH EW at 11.3 μm. c) $L_{[NeV]}/L_{[NeII]}$ vs. PAH EW at 17 μm. These quantities are statistically anti-correlated: $\rho=-0.702$, $\rho=-0.779$ and $\rho=-0.628$, respectively. The red triangle indicates the [NeV] detection for the stacked spectra in AGN group 2. Color and symbol coding same as Figure 5.1.
Figure 5.21 $\alpha_{20-30\mu m}$ vs. the optical D parameter. These parameters are correlated for AGN, $\rho=-0.474$, but not for the full sample, $\rho=-0.195$. Color and symbol coding same as Figure 5.1.
Figure 5.22 The optical D parameter vs a) PAH EW at 7.7 µm, b) PAH EW at 11.3 µm and c) PAH EW at 17 µm. These quantities are statistically anti-correlated: $\rho=-0.679$, $\rho=-0.747$ and $\rho=-0.658$, respectively. Color and symbol coding same as Figure 5.1.
Figure 5.23 The optical D parameter vs a) PAH EW at 7.7 μm, b) PAH EW at 11.3 μm and c) PAH EW at 17 μm for sources with \( z \geq 0.03 \). These quantities are statistically anti-correlated: \( \rho = -0.566 \), \( \rho = -0.653 \) and \( \rho = -0.549 \), respectively. Color and symbol coding same as Figure 5.1.
Figure 5.24 $L_{[NeV]}/L_{[NeII]}$ vs. a) $L_{PAH7.7\mu m}/L_{PAH17\mu m}$ (no significant trend, $\rho=-0.241$), b) $L_{PAH11.3\mu m}/L_{PAH17\mu m}$ (significant anti-correlation, $\rho=-0.564$) and c) $L_{PAH7.7\mu m}/L_{PAH11.3\mu m}$ (significant correlation, $\rho=0.611$). The red triangle indicates the $[NeV]$ detection for the stacked spectra in AGN group 2. Color and symbol coding same as Figure 5.1.
Figure 5.25 Optical D parameter vs. a) $L_{PAH 7.7 \mu m}/L_{PAH 17 \mu m}$ (no significant trend, $\rho=-0.193$), b) $L_{PAH 11.3 \mu m}/L_{PAH 17 \mu m}$ (significant anti-correlation, $\rho=-0.364$) and c) $L_{PAH 7.7 \mu m}/L_{PAH 11.3 \mu m}$ (no significant trend $\rho=0.179$). Color and symbol coding same as Figure 5.1.
Table 5.1. Ratios of SFR proxies

<table>
<thead>
<tr>
<th>Ratio</th>
<th>Star-forming Galaxies</th>
<th>N²</th>
<th>Composites</th>
<th>N</th>
<th>AGN</th>
<th>N</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>SFR\textsubscript{total}/SFR\textsubscript{fiber}</td>
<td>0.42±0.26</td>
<td>264</td>
<td>0.47±0.37</td>
<td>50</td>
<td>0.53±0.48</td>
<td>48</td>
<td></td>
</tr>
<tr>
<td>L[NeII]/SFR\textsubscript{fiber}</td>
<td>40.97±0.26</td>
<td>223</td>
<td>40.91±0.26</td>
<td>32</td>
<td>40.92±0.26</td>
<td>39³</td>
<td></td>
</tr>
<tr>
<td>L[NeII]/SFR\textsubscript{total}</td>
<td>40.55±0.10</td>
<td>223</td>
<td>40.56±0.26</td>
<td>32</td>
<td>40.49±0.32</td>
<td>39³</td>
<td></td>
</tr>
<tr>
<td>(L[NeII]+L[NeIII])/SFR\textsubscript{fiber}</td>
<td>40.84±0.17</td>
<td>223</td>
<td>40.74±0.05</td>
<td>32</td>
<td>41.11±0.21</td>
<td>39</td>
<td></td>
</tr>
<tr>
<td>(L[NeII]+L[NeIII])/SFR\textsubscript{total}</td>
<td>40.45±0.19</td>
<td>223</td>
<td>40.45±0.17</td>
<td>32³</td>
<td>40.66±0.27</td>
<td>39</td>
<td></td>
</tr>
</tbody>
</table>

PAH Luminosities

<table>
<thead>
<tr>
<th>L\textsubscript{PAH7.7μm}/SFR\textsubscript{fiber}</th>
<th>42.44±0.16</th>
<th>260</th>
<th>42.45±0.08</th>
<th>46</th>
<th>42.48±0.35</th>
<th>40</th>
</tr>
</thead>
<tbody>
<tr>
<td>L\textsubscript{PAH7.7μm}/SFR\textsubscript{total}</td>
<td>42.02±0.11</td>
<td>260</td>
<td>42.00±0.11</td>
<td>46</td>
<td>41.88±0.14</td>
<td>43</td>
</tr>
<tr>
<td>L\textsubscript{PAH7.7μm}/L[NeII]</td>
<td>1.43±0.04</td>
<td>206</td>
<td>1.49⁴</td>
<td>30</td>
<td>1.30±0.06</td>
<td>21</td>
</tr>
<tr>
<td>L[NeII]/L\textsubscript{PAH7.7μm}</td>
<td>-1.45±0.03</td>
<td>208³</td>
<td>-1.51±0.11</td>
<td>30</td>
<td>-1.46±0.17</td>
<td>22</td>
</tr>
<tr>
<td>L\textsubscript{PAH11.3μm}/SFR\textsubscript{fiber}</td>
<td>41.92±0.15</td>
<td>261</td>
<td>41.94±0.14</td>
<td>46</td>
<td>41.84±0.37</td>
<td>35</td>
</tr>
<tr>
<td>L\textsubscript{PAH11.3μm}/SFR\textsubscript{total}</td>
<td>41.50±0.09</td>
<td>261³</td>
<td>41.46±0.13</td>
<td>46</td>
<td>41.34±0.34</td>
<td>35³</td>
</tr>
<tr>
<td>L\textsubscript{PAH11.3μm}/L[NeII]</td>
<td>0.90±0.04</td>
<td>207</td>
<td>0.92±0.04</td>
<td>30</td>
<td>0.77±0.07</td>
<td>23</td>
</tr>
<tr>
<td>L[NeII]/L\textsubscript{PAH11.3μm}</td>
<td>-0.92±0.03</td>
<td>218³</td>
<td>-0.94±0.08</td>
<td>31</td>
<td>-0.84⁴</td>
<td>27</td>
</tr>
<tr>
<td>L\textsubscript{PAH17μm}/SFR\textsubscript{fiber}</td>
<td>41.61±0.22</td>
<td>261</td>
<td>41.74±0.12</td>
<td>46</td>
<td>41.81±0.18</td>
<td>35³</td>
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</table>

²
³
Table 5.1 (cont’d)

<table>
<thead>
<tr>
<th>Ratio</th>
<th>Star-forming Galaxies</th>
<th>N&lt;sup&gt;2&lt;/sup&gt;</th>
<th>Composites</th>
<th>N</th>
<th>AGN</th>
<th>N</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>( L_{PAH17\mu m}/SFR_{total} )</td>
<td>41.19±0.23</td>
<td>261&lt;sup&gt;3&lt;/sup&gt;</td>
<td>41.30±0.08</td>
<td>46</td>
<td>41.27±0.31</td>
<td>35&lt;sup&gt;3&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td>( L_{PAH17\mu m}/L_{[NeII]} )</td>
<td>0.62±0.13</td>
<td>207</td>
<td>0.76±0.11</td>
<td>30</td>
<td>0.73±0.18</td>
<td>23</td>
<td>PAH UL</td>
</tr>
<tr>
<td>( L_{[NeII]}/L_{PAH17\mu m} )</td>
<td>-0.73±0.06</td>
<td>142&lt;sup&gt;3&lt;/sup&gt;</td>
<td>-0.81±0.14</td>
<td>26</td>
<td>-0.88±0.16</td>
<td>23</td>
<td>[NeII] UL</td>
</tr>
</tbody>
</table>

<sup>1</sup>Ratios in log space. All ratios, except for \( SFR_{total}/SFR_{fiber} \) were calculated using survival analysis. Error bars on \( SFR_{total}/SFR_{fiber} \) are the standard deviation about the mean. Error bars for other ratios represent the values at the 75th and 25th percentiles.

<sup>2</sup>Number of sources in each galaxy sub-group used in calculation of mean values.

<sup>3</sup>Upper limit data point changed to a detection for Kaplan-Meier computation, which biases the mean estimate.

<sup>4</sup>Error in percentile calculation, so error bars are not reported.
Table 5.2. Two-Sample Tests on SFR Proxies between Galaxy Sub-Samples

<table>
<thead>
<tr>
<th>Ratio</th>
<th>SF vs. Composites</th>
<th>Composites vs. AGN</th>
<th>SF vs. AGN</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>$SFR_{\text{total}}/SFR_{\text{fiber}}$</td>
<td>0.627</td>
<td>0.697</td>
<td>0.393</td>
<td>312</td>
</tr>
<tr>
<td>$L_{[NeII]}/SFR_{\text{fiber}}$</td>
<td>0.127</td>
<td>0.598</td>
<td>0.624</td>
<td>223</td>
</tr>
<tr>
<td>$L_{[NeII]}/SFR_{\text{total}}$</td>
<td>0.882</td>
<td>0.709</td>
<td>0.599</td>
<td>262</td>
</tr>
<tr>
<td>$(L_{[NeII]}+L_{[NeIII]})/SFR_{\text{fiber}}$</td>
<td>0.175</td>
<td>0.0005</td>
<td>0.599</td>
<td>262</td>
</tr>
<tr>
<td>$(L_{[NeII]}+L_{[NeIII]})/SFR_{\text{total}}$</td>
<td>0.651</td>
<td>0.0021</td>
<td>0.599</td>
<td>262</td>
</tr>
</tbody>
</table>

PAH Luminosities

| $L_{\text{PAH7.7\mu m}}/SFR_{\text{fiber}}$ | 0.759             | 0.850              | 0.693      | 300      | ASURV    |
| $L_{\text{PAH7.7\mu m}}/SFR_{\text{total}}$ | 0.285             | 0.460              | 0.693      | 300      | ASURV    |
| $L_{\text{PAH7.7\mu m}}/L_{[NeII]}$        | 0.928             | 0.009              | 0.002      | 227      | PAH UL   |
| $L_{[NeII]}/L_{\text{PAH7.7\mu m}}$        | 0.939             | 0.139              | 0.079      | 230      | [NeII] UL|
| $L_{\text{PAH11.3\mu m}}/SFR_{\text{fiber}}$ | 0.861             | 0.327              | 0.292      | 296      | ASURV    |
| $L_{\text{PAH11.3\mu m}}/SFR_{\text{total}}$ | 0.354             | 0.615              | 0.273      | 296      | ASURV    |
| $L_{\text{PAH11.3\mu m}}/L_{[NeII]}$       | 0.878             | 0.022              | 0.002      | 230      | PAH UL   |
| $L_{[NeII]}/L_{\text{PAH11.3\mu m}}$       | 0.986             | 0.078              | 0.024      | 245      | [NeII] UL|
Table 5.2 (cont’d)

<table>
<thead>
<tr>
<th>Ratio</th>
<th>SF vs. Composites</th>
<th>Composites vs. AGN</th>
<th>SF vs. AGN</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_{PAH17\mu m}/SFR_{fiber}$</td>
<td>0.107</td>
<td>0.529</td>
<td>0.020</td>
</tr>
<tr>
<td>$L_{PAH17\mu m}/SFR_{total}$</td>
<td>0.644</td>
<td>0.614</td>
<td>0.161</td>
</tr>
<tr>
<td>$L_{PAH17\mu m}/L_{[NeII]}$</td>
<td>0.085</td>
<td>0.836</td>
<td>0.077</td>
</tr>
<tr>
<td>$L_{[NeII]}/L_{PAH17\mu m}$</td>
<td>0.501</td>
<td>0.209</td>
<td>0.023</td>
</tr>
</tbody>
</table>

SF refers to star-forming galaxies.

Number of sources in two-sample tests.

K-S test used for detected data points. ASURV was used to account for upper limits. For the PAH and [NeII] ratios, survival analysis was performed twice: once to account for [NeII] upper limits and once to accommodate the PAH luminosity upper limits. Here, we report the survival analysis probability from Gehan’s Generalized Wilcoxon Test, permutation variance. A $P$ value $\leq 0.05$ indicates that the two sub-populations differ at a statistically significant level.
Table 5.3. Ratios\(^1\) of AGN proxies

<table>
<thead>
<tr>
<th>Ratio</th>
<th>Star-forming Galaxies</th>
<th>Composites</th>
<th>AGN</th>
<th>AGN sub-sample(^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(L_{[OIII],corr}/L_{[OIII],obs})</td>
<td>0.46±0.23</td>
<td>0.59±0.29</td>
<td>0.64±0.49</td>
<td>0.75±0.52</td>
</tr>
<tr>
<td>(L_{MIR}/L_{[OIII],obs})</td>
<td>3.37±0.55</td>
<td>3.35±0.48</td>
<td>2.51±0.52</td>
<td>2.62±0.53</td>
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<tr>
<td>(L_{MIR}/L_{[OIII],corr})</td>
<td>2.91±0.41</td>
<td>2.77±0.40</td>
<td>1.86±0.50</td>
<td>1.85±0.57</td>
</tr>
</tbody>
</table>

\(^1\)Ratios in log space. Errors represent standard deviation about the mean.

\(^2\)[OIII] sample removed from analysis.

Table 5.4. Two-Sample Tests on AGN Proxies between Galaxy Sub-Samples\(^1\)

<table>
<thead>
<tr>
<th>Ratio</th>
<th>SF vs. Composites</th>
<th>Composites vs. AGN</th>
<th>SF vs. AGN</th>
</tr>
</thead>
<tbody>
<tr>
<td>(L_{[OIII],corr}/L_{[OIII],obs})</td>
<td>0.0028</td>
<td>0.349</td>
<td>0.0002</td>
</tr>
<tr>
<td>(L_{MIR}/L_{[OIII],obs})</td>
<td>0.0652</td>
<td>6.1×10(^{-13})</td>
<td>1.85×10(^{-21})</td>
</tr>
<tr>
<td>(L_{MIR}/L_{[OIII],corr})</td>
<td>0.0016</td>
<td>7.2×10(^{-16})</td>
<td>2.66×10(^{-31})</td>
</tr>
</tbody>
</table>

\(^1\)SF refers to star-forming galaxies. K-S test used. A \(P\) value ≤0.05 indicates that the two sub-populations differ at a statistically significant level.
Table 5.5. Correlation between AGN Activity and SFR

<table>
<thead>
<tr>
<th>Diagnostic</th>
<th>$\rho$</th>
<th>$P_{uncorr}^1$</th>
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</thead>
<tbody>
<tr>
<td>$L_{[NeV]}$ vs. SFR$_{fiber}^2$</td>
<td>0.275</td>
<td>0.090</td>
</tr>
<tr>
<td>$L_{[NeV]}$ vs. SFR$_{total}^2$</td>
<td>0.366</td>
<td>0.024</td>
</tr>
<tr>
<td>$L_{[NeV]}$ vs. $L_{[NeII]}^2$</td>
<td>0.470</td>
<td>$6 \times 10^{-4}$</td>
</tr>
<tr>
<td>$L_{[OIII],AGN}$ vs. SFR$_{fiber}$</td>
<td>0.533</td>
<td>$6.9 \times 10^{-5}$</td>
</tr>
<tr>
<td>$L_{[OIII],AGN}$ vs. SFR$_{total}$</td>
<td>0.367</td>
<td>0.009</td>
</tr>
<tr>
<td>$L_{[NeII]}$ vs. $L_{[OIII],AGN}^3$</td>
<td>0.343</td>
<td>0.006</td>
</tr>
<tr>
<td>$L_{MIR,AGN}$ vs. SFR$_{fiber}$</td>
<td>0.630</td>
<td>$5.7 \times 10^{-4}$</td>
</tr>
<tr>
<td>$L_{MIR,AGN}$ vs. SFR$_{total}$</td>
<td>0.584</td>
<td>0.002</td>
</tr>
</tbody>
</table>

$^1$Probability the two quantities are not correlated. A $P_{uncorr}$ value $\leq 0.05$ indicates a significant correlation.

$^2$Used ASURV to account for upper limits in $L_{[NeV]}$.

$^3$Used ASURV to account for upper limits in $L_{[NeII]}$. 
Table 5.6. Correlation between Diagnostics of Relative Importance of AGN Activity to Star formation

<table>
<thead>
<tr>
<th>Diagnostic</th>
<th>$\rho$</th>
<th>$P_{uncorr}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_{[NeV]}/L_{[NeII]}$ vs. $D^2$</td>
<td>0.562</td>
<td>$4 \times 10^{-4}$</td>
</tr>
<tr>
<td>$L_{[NeV]}/L_{[NeII]}$ vs. $\alpha_{20-30\mu m}^2$</td>
<td>-0.568</td>
<td>$6 \times 10^{-4}$</td>
</tr>
<tr>
<td>$L_{[NeV]}/L_{[NeII]}$ vs. PAH EW 7.7 $\mu m^2$</td>
<td>-0.702</td>
<td>$1 \times 10^{-4}$</td>
</tr>
<tr>
<td>$L_{[NeV]}/L_{[NeII]}$ vs. PAH EW 11.3 $\mu m^2$</td>
<td>-0.779</td>
<td>$&lt; 1 \times 10^{-4}$</td>
</tr>
<tr>
<td>$L_{[NeV]}/L_{[NeII]}$ vs. PAH EW 17 $\mu m^2$</td>
<td>-0.628</td>
<td>$2 \times 10^{-4}$</td>
</tr>
</tbody>
</table>

$^1$Probability the two quantities are not correlated. A $P_{uncorr}$ value $\leq0.05$ indicates a significant correlation.

$^2$Used ASURV to account for upper limits in $L_{[NeV]}$. 
Table 5.7. Relationship between PAH EWs and Ionization Field Hardness

<table>
<thead>
<tr>
<th>Diagnostic</th>
<th>$\rho$</th>
<th>$m^1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>D vs. PAH EW 7.7 $\mu$m</td>
<td>-0.679</td>
<td>-0.90</td>
</tr>
<tr>
<td>D vs. PAH EW 11.3 $\mu$m</td>
<td>-0.747</td>
<td>-0.90</td>
</tr>
<tr>
<td>D vs. PAH EW 17 $\mu$m</td>
<td>-0.658</td>
<td>-0.84</td>
</tr>
</tbody>
</table>

Star-forming Galaxies and Composites Sub-sample

<table>
<thead>
<tr>
<th>Diagnostic</th>
<th>$\rho$</th>
<th>$m^1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>D vs. PAH EW 7.7 $\mu$m</td>
<td>-0.227</td>
<td>-0.19</td>
</tr>
<tr>
<td>D vs. PAH EW 11.3 $\mu$m</td>
<td>-0.125</td>
<td>-0.17</td>
</tr>
<tr>
<td>D vs. PAH EW 17 $\mu$m</td>
<td>-0.230</td>
<td>-0.16</td>
</tr>
</tbody>
</table>

Sources with $z \geq 0.03$

<table>
<thead>
<tr>
<th>Diagnostic</th>
<th>$\rho$</th>
<th>$m^1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>D vs. PAH EW 7.7 $\mu$m</td>
<td>-0.566</td>
<td>-0.72</td>
</tr>
<tr>
<td>D vs. PAH EW 11.3 $\mu$m</td>
<td>-0.653</td>
<td>-0.78</td>
</tr>
<tr>
<td>D vs. PAH EW 17 $\mu$m</td>
<td>-0.549</td>
<td>-0.63</td>
</tr>
</tbody>
</table>

$^1$Slope from linear regression.
Table 5.8.  [OIII] Sample: APEC model parameters (solar abundance)

<table>
<thead>
<tr>
<th>Target</th>
<th>$N_{H,1}$</th>
<th>$kT_1$</th>
<th>$\Gamma$</th>
<th>$N_{H,2}$</th>
<th>$\chi^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$10^{22}$ cm$^{-2}$</td>
<td>keV</td>
<td></td>
<td>$10^{22}$ cm$^{-2}$</td>
<td>DOF</td>
</tr>
<tr>
<td>NGC 0291$^2$</td>
<td>$&lt;0.40$</td>
<td>$0.20^{+0.18}_{-0.10}$</td>
<td>$2.65^{+1.43}_{-1.35}$</td>
<td>$72^{+284}_{-48}$</td>
<td>40.3 (39)</td>
</tr>
<tr>
<td>Mrk 0609$^1$</td>
<td>0.04</td>
<td>$0.27^{+0.05}_{-0.04}$</td>
<td>$1.77^{+0.05}_{-0.04}$</td>
<td>...</td>
<td>160 (203)</td>
</tr>
<tr>
<td>IC 0486</td>
<td>$&lt;0.06$</td>
<td>$&lt;0.16$</td>
<td>$1.23^{+0.08}_{-0.07}$</td>
<td>$1.00^{+0.10}_{-0.09}$</td>
<td>636 (629)</td>
</tr>
<tr>
<td>2MASX J08035923+2345201$^2$</td>
<td>$0.55^{+0.21}_{-0.41}$</td>
<td>$&lt;0.21$</td>
<td>$4.88^{+1.81}_{-3.46}$</td>
<td>$70.3^{+92.7}_{-43.9}$</td>
<td>24.1 (40)</td>
</tr>
<tr>
<td>2MASX J08244333+2959238$^1$</td>
<td>0.03</td>
<td>$0.18^{+0.04}_{-0.06}$</td>
<td>$2.49^{+0.18}_{-0.19}$</td>
<td>$22.1^{+2.3}_{-1.9}$</td>
<td>215 (163)</td>
</tr>
<tr>
<td>2MASX J10181928+3722419$^1$</td>
<td>0.01</td>
<td>$0.18^{+0.04}_{-0.05}$</td>
<td>$2.63^{+0.64}_{-0.69}$</td>
<td>...</td>
<td>52.1 (61)</td>
</tr>
<tr>
<td>2MASX J11110693+0228477$^3$</td>
<td>$&lt;0.62$</td>
<td>$0.23^{+0.05}_{-0.09}$</td>
<td>$2.04^{+1.88}_{-0.88}$</td>
<td>...</td>
<td>37.5 (36)</td>
</tr>
<tr>
<td>CGCG 242-028$^2$</td>
<td>$0.69^{+0.17}_{-0.23}$</td>
<td>$&lt;0.15$</td>
<td>$0.31^{+0.46}_{-0.49}$</td>
<td>...</td>
<td>87.0 (90)</td>
</tr>
<tr>
<td>SBS 1133+572</td>
<td>$&lt;0.10$</td>
<td>$0.824^{+0.23}_{-0.21}$</td>
<td>$3.08^{+0.61}_{-0.38}$</td>
<td>$57.6^{+45.4}_{-30.2}$</td>
<td>38.1 (48)</td>
</tr>
<tr>
<td>Mrk 1457</td>
<td>$0.66^{+0.12}_{-0.12}$</td>
<td>$0.14^{+0.03}_{-0.03}$</td>
<td>$1.29^{+1.37}_{-1.14}$</td>
<td>$27.5^{+15.8}_{-9.3}$</td>
<td>35.2 (35)</td>
</tr>
<tr>
<td>2MASX J11570483+5249036</td>
<td>$&lt;0.11$</td>
<td>$0.20^{+0.05}_{-0.03}$</td>
<td>$2.71^{+0.41}_{-0.38}$</td>
<td>$117^{+62}_{-39}$</td>
<td>79.6 (55)</td>
</tr>
<tr>
<td>2MASX J12183945+4706275$^1$</td>
<td>0.02</td>
<td>$&lt;0.24$</td>
<td>$1.95^{+0.70}_{-0.86}$</td>
<td>$87.2^{+66.8}_{-34.1}$</td>
<td>15 (19)</td>
</tr>
<tr>
<td>2MASX J12384342+0927362</td>
<td>$&lt;0.09$</td>
<td>$&lt;0.22$</td>
<td>$2.37^{+0.45}_{-0.28}$</td>
<td>$32.6^{+4.4}_{-3.1}$</td>
<td>168 (123)</td>
</tr>
<tr>
<td>Target</td>
<td>$N_{H,1}$</td>
<td>kT$_1$</td>
<td>$\Gamma$</td>
<td>$N_{H,2}$</td>
<td>$\chi^2$</td>
</tr>
<tr>
<td>-----------</td>
<td>-----------</td>
<td>---------</td>
<td>----------</td>
<td>-----------</td>
<td>----------</td>
</tr>
<tr>
<td>NGC 5695</td>
<td>$&lt;0.59$</td>
<td>0.24$^{+0.73}_{-0.12}$</td>
<td>2.55$^{+0.68}_{-0.52}$</td>
<td>...</td>
<td>75.7 (62)</td>
</tr>
</tbody>
</table>

1. Best fit absorption same as Galactic absorption. This parameter was then frozen to the Galactic value.
2. Used c-stat.
3. PN only, MOS1 and MOS2 had low signal-to-noise spectra.
Table 5.9. APEC model parameters (solar abundance)

<table>
<thead>
<tr>
<th>Target</th>
<th>$N_{H,1}$</th>
<th>kT$_1$</th>
<th>kT$_2$</th>
<th>$\Gamma$</th>
<th>$N_{H,2}$</th>
<th>$\chi^2$ 2 APECs</th>
<th>DOF</th>
<th>$\chi^2$ 1 APEC</th>
<th>DOF</th>
</tr>
</thead>
<tbody>
<tr>
<td>NGC 0424</td>
<td>0.07$^{+0.03}_{-0.03}$</td>
<td>0.69$^{+0.10}_{-0.05}$</td>
<td>&lt;0.12</td>
<td>2.54$^{+0.30}_{-0.38}$</td>
<td>18.2$^{+23.8}_{-3.0}$</td>
<td>242 (178)</td>
<td>259 (180)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NGC 1144$^1$</td>
<td>0.06</td>
<td>0.37$^{+0.29}_{-0.06}$</td>
<td>...</td>
<td>1.91$^{+0.37}_{-0.24}$</td>
<td>47.0$^{+3.5}_{-3.2}$</td>
<td>...</td>
<td>175 (149)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NGC 1320$^1$</td>
<td>0.04</td>
<td>0.37$^{+0.03}_{0.02}$</td>
<td>0.75$^{+0.05}_{0.06}$</td>
<td>3.03$^{+0.03}_{0.14}$</td>
<td>51.8$^{107}_{-18.2}$</td>
<td>221 (169)</td>
<td>269 (182)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NGC 1386</td>
<td>0.03$^{+0.01}_{-0.01}$</td>
<td>0.66$^{+0.03}_{0.03}$</td>
<td>0.13$^{+0.02}_{0.002}$</td>
<td>2.62$^{+0.29}_{0.11}$</td>
<td>37.9$^{+37.0}_{-15.4}$</td>
<td>360 (306)</td>
<td>398 (308)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NGC 1667$^2$</td>
<td>0.05</td>
<td>0.33$^{+0.07}_{-0.04}$</td>
<td>...</td>
<td>2.18$^{+0.34}_{-0.37}$</td>
<td>...</td>
<td>...</td>
<td>49.8 (38)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>F05189-252$^2$</td>
<td>0.02</td>
<td>0.1</td>
<td>...</td>
<td>2.05$^{+0.14}_{-0.14}$</td>
<td>6.77$^{+0.44}_{-0.42}$</td>
<td>...</td>
<td>501 (374)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NGC 3982$^2$</td>
<td>0.01</td>
<td>0.29$^{+0.03}_{-0.03}$</td>
<td>...</td>
<td>2.39$^{+0.18}_{-0.15}$</td>
<td>40.3$^{+25.5}_{-16.3}$</td>
<td>...</td>
<td>174 (160)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NGC 4388 (XMM)$^2$</td>
<td>0.03</td>
<td>0.60$^{+0.04}_{-0.03}$</td>
<td>0.15$^{+0.02}_{-0.03}$</td>
<td>1.25$^{+0.12}_{-0.12}$</td>
<td>24.3$^{+1.1}_{-1.0}$</td>
<td>510 (495)</td>
<td>580 (498)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NGC 4388 (Chandra)$^2$</td>
<td>0.03</td>
<td>0.60$^{+0.04}_{-0.04}$</td>
<td>0.15$^{+0.04}_{-0.03}$</td>
<td>0.38$^{+0.29}_{-0.30}$</td>
<td>25.6$^{+3.1}_{-2.9}$</td>
<td>210 (166)</td>
<td>269 (168)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NGC 4501$^2$</td>
<td>0.03</td>
<td>0.36$^{+0.05}_{-0.05}$</td>
<td>...</td>
<td>1.52$^{+0.30}_{-0.29}$</td>
<td>...</td>
<td>...</td>
<td>94.2 (102)</td>
<td></td>
<td></td>
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<tr>
<td>TOLOLO 1238-36$^2,3$</td>
<td>0.06</td>
<td>0.71$^{+0.12}_{-0.13}$</td>
<td>...</td>
<td>2.40$^{+0.28}_{-0.27}$</td>
<td>...</td>
<td>...</td>
<td>47.6 (82)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NGC 4968$^2,3$</td>
<td>0.08</td>
<td>0.68$^{+0.12}_{-0.12}$</td>
<td>...</td>
<td>1.72$^{+0.21}_{-0.21}$</td>
<td>...</td>
<td>...</td>
<td>325 (268)</td>
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<td></td>
</tr>
<tr>
<td>M-3-34-64$^2$</td>
<td>0.05</td>
<td>2.85$^{+0.34}_{-0.38}$</td>
<td>0.77$^{+0.02}_{-0.02}$</td>
<td>3.24$^{+0.19}_{-0.23}$</td>
<td>53.6$^{+2.9}_{-3.6}$</td>
<td>780 (492)</td>
<td>848 (493)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NGC 5135$^2$</td>
<td>0.05</td>
<td>0.73$^{+0.03}_{-0.03}$</td>
<td>...</td>
<td>2.34$^{+0.07}_{-0.08}$</td>
<td>...</td>
<td>...</td>
<td>166 (114)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NGC 5194</td>
<td>0.04$^{+0.01}_{-0.01}$</td>
<td>0.18$^{+0.01}_{-0.01}$</td>
<td>0.62$^{+0.01}_{-0.01}$</td>
<td>3.18$^{+0.14}_{-0.14}$</td>
<td>10.2$^{+0.80}_{-0.75}$</td>
<td>1560 (1291)</td>
<td>2021 (1293)</td>
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<td></td>
</tr>
<tr>
<td>Target</td>
<td>$N_{H,1}$</td>
<td>kT$_1$</td>
<td>kT$_2$</td>
<td>$\Gamma$</td>
<td>$N_{H,2}$</td>
<td>$\chi^2$ 2 APECs</td>
<td>$\chi^2$ 1 APEC</td>
<td>DOF</td>
<td>DOF</td>
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<td>------------------</td>
<td>-----</td>
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</tr>
<tr>
<td>NGC 5347$^{2,3}$</td>
<td>0.02</td>
<td>&lt;0.21</td>
<td>...</td>
<td>1.53$^{+0.30}_{-0.29}$</td>
<td>32.6$^{+24.1}_{-19.6}$</td>
<td>...</td>
<td>69.9 (82)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mrk 463$^2$</td>
<td>0.02</td>
<td>0.20$^{+0.06}_{-0.04}$</td>
<td>0.74$^{+0.04}_{-0.03}$</td>
<td>1.68$^{+0.14}_{-0.16}$</td>
<td>36.2$^{+4.2}_{-3.7}$</td>
<td>388 (291)</td>
<td>424 (293)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NGC 5506</td>
<td>0.11$^{+0.01}_{-0.01}$</td>
<td>0.74$^{+0.05}_{-0.05}$</td>
<td>...</td>
<td>1.71$^{+0.02}_{-0.01}$</td>
<td>2.69$^{+0.02}_{-0.03}$</td>
<td>...</td>
<td>2646 (2380)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NGC 5506</td>
<td>&quot;</td>
<td>0.94$^{+0.39}_{-0.24}$</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NGC 5506</td>
<td>0.17$^{+0.01}_{-0.01}$</td>
<td>...</td>
<td>...</td>
<td>1.83$^{+0.02}_{-0.02}$</td>
<td>2.80$^{+0.01}_{-0.02}$</td>
<td>...</td>
<td>3982 (3137)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NGC 5506</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>1.76$^{+0.01}_{-0.00}$</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NGC 5506</td>
<td>0.12$^{+0.01}_{-0.00}$</td>
<td>0.83$^{+0.03}_{-0.03}$</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NGC 5506</td>
<td>&quot;</td>
<td>0.96$^{+0.05}_{-0.05}$</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Arp 220$^{1,2}$</td>
<td>0.04</td>
<td>0.79$^{+0.04}_{-0.04}$</td>
<td>...</td>
<td>0.96$^{+0.25}_{-0.24}$</td>
<td>...</td>
<td>...</td>
<td>356 (354)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NGC 6890$^3$</td>
<td>&lt;0.22</td>
<td>0.78$^{+0.24}_{-0.19}$</td>
<td>...</td>
<td>3.28$^{+0.88}_{-0.74}$</td>
<td>27.4$^{+18.4}_{-11.3}$</td>
<td>...</td>
<td>164 (148)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>IC 5063$^{2,4}$</td>
<td>0.06</td>
<td>0.60$^{+0.10}_{-0.11}$</td>
<td>...</td>
<td>1.85$^{+0.16}_{-0.21}$</td>
<td>21.0$^{+1.1}_{-1.2}$</td>
<td>...</td>
<td>198 (141)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NGC 7130$^3$</td>
<td>0.06$^{+0.03}_{-0.02}$</td>
<td>0.63$^{+0.03}_{-0.03}$</td>
<td>...</td>
<td>2.43$^{+0.25}_{-0.18}$</td>
<td>75.4$^{+55.6}_{-38.1}$</td>
<td>...</td>
<td>334 (240)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NGC 7172$^2$</td>
<td>0.02</td>
<td>0.28$^{+0.05}_{-0.04}$</td>
<td>...</td>
<td>1.56$^{+0.02}_{-0.03}$</td>
<td>7.36$^{+0.10}_{-0.10}$</td>
<td>...</td>
<td>2074 (1746)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NGC 7172$^2$</td>
<td>&quot;</td>
<td>0.26$^{+0.02}_{-0.02}$</td>
<td>...</td>
<td>1.54$^{+0.02}_{-0.03}$</td>
<td>8.13$^{+0.11}_{-0.11}$</td>
<td>&quot;</td>
<td>&quot;</td>
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<td></td>
</tr>
<tr>
<td>NGC 7582 (Chandra)$^2$</td>
<td>0.01</td>
<td>0.72$^{+0.05}_{-0.05}$</td>
<td>...</td>
<td>1.94$^{+0.11}_{-0.10}$</td>
<td>24.6$^{+1.8}_{-1.6}$</td>
<td>...</td>
<td>355 (301)</td>
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Table 5.9 (cont’d)

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<th>Target</th>
<th>$N_{H,1}$</th>
<th>$kT_1$</th>
<th>$kT_2$</th>
<th>$\Gamma$</th>
<th>$N_{H,2}$</th>
<th>$\chi^2$ 2 APECs</th>
<th>$\chi^2$ 1 APEC</th>
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<tr>
<td>NGC 7582 (XMM)$^2$</td>
<td>0.01</td>
<td>0.18$^{+0.02}_{-0.04}$</td>
<td>0.72$^{+0.01}_{-0.01}$</td>
<td>1.75$^{+0.05}_{-0.03}$</td>
<td>27.0$^{+1.5}_{1.5}$</td>
<td>1438 (886)</td>
<td>1586 (888)</td>
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<td>NGC 7674$^{2,3}$</td>
<td>0.04</td>
<td>&lt;0.11</td>
<td>0.67$^{+0.07}_{-0.05}$</td>
<td>0.62$^{+0.47}_{-0.43}$</td>
<td>89.0$^{+69.0}_{-40.2}$</td>
<td>66.6 (70)</td>
<td>113 (72)</td>
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$^1$All abundances frozen to solar except for Arp 220 which has an abundance of $0.17^{+0.11}_{-0.05}$.

$^2$Best fit absorption same as Galactic absorption. This parameter was then frozen to the Galactic value.

$^3$Used c-stat.

$^4$Used pile-up model.
<table>
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<th>Galaxy</th>
<th>Flux$_{0.5\text{-}2\text{keV}}$</th>
<th>Flux$_{\text{APEC}}$</th>
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<tr>
<td>NGC 0291</td>
<td>2.83$^{+28.6}_{-1.40}$</td>
<td>0.84$^{+28.5}_{-0.76}$</td>
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<tr>
<td>Mrk 0609</td>
<td>79.1$^{+3.62}_{-3.62}$</td>
<td>4.82$^{+2.14}_{-2.15}$</td>
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<td>IC 0486</td>
<td>35.0$^{+17.6}_{-8.84}$</td>
<td>0.45$^{+1.12}_{-0.39}$</td>
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<td>2MASX J08035923+2345201</td>
<td>1.12$^{+3.66}_{-0.71}$</td>
<td>0.60$^{+3.65}_{-0.58}$</td>
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<td>2MASX J08244333+2959238</td>
<td>4.43$^{+0.81}_{-0.49}$</td>
<td>0.74$^{+0.73}_{-0.33}$</td>
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<td>2MASX J10181928+3722419</td>
<td>2.27$^{+0.92}_{-0.62}$</td>
<td>1.04$^{+0.80}_{-0.43}$</td>
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<td>2MASX J11110693+0228477</td>
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<td>0.42$^{+4.19}_{-0.36}$</td>
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<tr>
<td>CGCG 242-028</td>
<td>1.17$^{+2.52}_{-0.75}$</td>
<td>0.80$^{+2.50}_{-0.73}$</td>
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<tr>
<td>SBS 1133+572</td>
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<td>0.52$^{+0.36}_{-0.35}$</td>
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<tr>
<td>Mrk 1457</td>
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<td>2.36$^{+10.3}_{-1.79}$</td>
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<tr>
<td>2MASX J11570483+5249036</td>
<td>3.45$^{+1.23}_{-0.75}$</td>
<td>0.94$^{+1.02}_{-0.47}$</td>
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<td>2MASX J12183945+4706275</td>
<td>1.54$^{+2.15}_{-0.54}$</td>
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<td>2MASX J12384342+0927362</td>
<td>4.42$^{+4.24}_{-0.64}$</td>
<td>0.62$^{+4.09}_{-0.29}$</td>
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<td>NGC 5695</td>
<td>2.57$^{+5.37}_{-0.90}$</td>
<td>0.64$^{+4.31}_{-0.56}$</td>
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</table>
Table 5.11. 12 μm Sample: Soft X-ray Flux $10^{-14}$ erg s$^{-1}$ cm$^{-2}$

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<tr>
<th>Galaxy</th>
<th>Flux$_{0.5-2keV}$</th>
<th>Flux$_{APEC}$</th>
<th>Notes</th>
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<td>NGC 0424</td>
<td>$30.3^{+8.8}_{-8.3}$</td>
<td>$8.90^{+7.95}_{-7.35}$</td>
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<tr>
<td>NGC 1144</td>
<td>$8.39^{+1.25}_{-1.61}$</td>
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<td>NGC 1320</td>
<td>$24.5^{+8.0}_{-5.3}$</td>
<td>$9.42^{+7.86}_{-5.08}$</td>
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<tr>
<td>NGC 1368</td>
<td>$22.9^{+18.5}_{-4.3}$</td>
<td>$10.8^{+17.4}_{-4.2}$</td>
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<tr>
<td>NGC 1667</td>
<td>$7.31^{+1.45}_{-1.52}$</td>
<td>$3.22^{+1.03}_{-1.10}$</td>
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<td>F05189-2524</td>
<td>$12.1^{+2.0}_{-1.0}$</td>
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<td>NGC 3982</td>
<td>$9.14^{+0.90}_{-0.96}$</td>
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<td>NGC 4388</td>
<td>$28.5^{+16.0}_{-7.0}$</td>
<td>$17.8^{+15.8}_{-6.6}$</td>
<td>Chandra &amp; XMM-Newton observations averaged</td>
</tr>
<tr>
<td>NGC 4501</td>
<td>$7.24^{+1.57}_{-1.30}$</td>
<td>$3.83^{+1.06}_{-0.95}$</td>
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<tr>
<td>TOLOLO 1238-364</td>
<td>$9.49^{+1.72}_{-1.59}$</td>
<td>$3.92^{+1.21}_{-1.14}$</td>
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<td>NGC 4968</td>
<td>$5.85^{+1.14}_{-1.05}$</td>
<td>$1.27^{+0.67}_{-0.60}$</td>
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<td>M-3-34-64</td>
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<td>NGC 5135</td>
<td>$34.5^{+1.7}_{-1.7}$</td>
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<tr>
<td>NGC 5194</td>
<td>$69.6^{+6.8}_{-6.1}$</td>
<td>$52.7^{+6.7}_{-6.0}$</td>
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<td>$2.94^{+0.87}_{-0.46}$</td>
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<td>$6.80^{+2.04}_{-2.12}$</td>
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<tr>
<td>NGC 5506</td>
<td>$308^{+56}_{-53}$</td>
<td>$6.08^{+4.48}_{-4.56}$</td>
<td>2001, July 2004 observations</td>
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<tr>
<td>Galaxy</td>
<td>Flux$_{0.5-2\text{keV}}$</td>
<td>Flux$_{\text{APEC}}$</td>
<td>Notes</td>
</tr>
<tr>
<td>-----------</td>
<td>--------------------------</td>
<td>----------------------</td>
<td>--------------------------------------------</td>
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<tr>
<td>Arp 220</td>
<td>4.93$^{+1.22}_{-1.29}$</td>
<td>3.08$^{+1.00}_{-1.18}$</td>
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<td>2.62$^{+1.64}_{-1.40}$</td>
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<td>IC 5063</td>
<td>22.9$^{+3.1}_{-3.2}$</td>
<td>4.57$^{+1.58}_{-1.58}$</td>
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<td>NGC 7130</td>
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<td>12.1$^{+6.0}_{-5.1}$</td>
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<tr>
<td>NGC 7172</td>
<td>20.3$^{+2.3}_{-2.5}$</td>
<td>2.05$^{+0.50}_{-0.51}$</td>
<td>2007 observation</td>
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<td></td>
<td>11.8$^{+0.8}_{-0.7}$</td>
<td>2.06$^{+0.27}_{-0.28}$</td>
<td>2002 and 2004 observations</td>
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<tr>
<td>NGC 7582</td>
<td>40.3$^{+3.2}_{-3.7}$</td>
<td>15.2$^{+2.5}_{-3.1}$</td>
<td>Chandra &amp; XMM-Newton observations averaged</td>
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<tr>
<td>NGC 7674</td>
<td>17.5$^{+2.9}_{-5.0}$</td>
<td>13.6$^{+2.2}_{-4.7}$</td>
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Figure 5.26 Log (F$_{[NeII]}$) vs. F$_{APEC}$. The best-fit relation from survival analysis is overplotted: slope = 0.67±0.13 dex, with $\sigma$=0.44 dex and an intercept at -4.2 dex. The relationship is significant (Spearman’s $\rho$=0.65, giving $P_{uncorr}$=1×10$^{-4}$, which suggests that the APEC flux may be adequately describing thermal emission from host galaxy star formation. The red triangles (blue diamonds) represent the [OIII] (12$\mu$m sample). The cyan diamonds, connected with a straight line, reflect the data for NGC 5506, where the APEC flux varied between multiple observations.
Figure 5.27 Log (SFR$_{APEC}$) vs. log (SDSS SFR$_{total}$). SFR$_{APEC}$ calculated using the Ranalli et al. (2003) relation between total L$_{0.5-2keV}$ and SFR. The dotted line indicates where the two quantities are equal.
Chapter 6

Concluding Remarks

6.1 Our Story So Far

In this work, we have explored which diagnostics most accurately describe the intrinsic AGN power and may thus provide the most robust AGN selection criteria. Of the AGN flux proxies we have considered, the [OIII], [OIV] and MIR fluxes provide the most fair sampling of the Type 1 and Type 2 local AGN populations. Radio and hard X-ray (E > 10 keV) fluxes fair more poorly. Our results indicate that contrary to previous claims, hard X-ray selection, at least at the relatively modest flux levels probed by current surveys, is somewhat biased against the heavily obscured AGN population.

Using 2-10 keV X-ray analysis, we have investigated the distributions of toroidal obscuration responsible for X-ray attenuation. For such analysis, we have relied on parameters least affected by the choice of spectral models used to fit the data, diagnostics that describe physical observables rather than derived quantities that are intended to explain these physical observables, such as fitted column densities (N_H). Indeed, we have shown that when using simple spectral models, such derived quantities sometimes do a poor job of parametrizing the column densities implied by our more model-independent diagnostics. The obscuration diagnostics we have used are the observed X-ray flux normalized by intrinsic AGN flux, as this ratio will be much lower in sources where the X-ray emission is attenuated due to high column
densities, and the EW of the Fe Kα line, which reaches values of several hundred eV to over 1 keV in Compton-thick sources. We have demonstrated that a majority of sources exhibit signatures of heavy and potentially Compton-thick obscuration. In order to confirm if these sources are indeed Compton-thick, observations above 10 keV are necessary. We predict that a majority of these Compton-thick candidates could be detected by NuSTAR, which will lead to better constraints on the fitted column densities of the obscuring medium.

Expanding our dataset to include ∼250 star-forming galaxies, ∼50 composites and an additional ∼20 Sy2s, we have explored the optical and IR parameter space in which these sources live. We have found that composite systems often behave more like star-forming galaxies, in terms of diagnostics that trace starburst activity, rather than AGN. We have calibrated a relation which decomposes the MIR flux into a starburst and AGN component. We have demonstrated moderate success in disentangling these two processes in the soft X-ray band (0.5 - 2 keV). Using star formation rates unaffected by AGN activity (SDSS derived star-formation rates and [NeII] flux) and AGN flux proxies negligibly impacted by star formation ([NeV] flux and the AGN only component of the [OIII] flux), we have demonstrated a strong correlation between host galaxy star formation and AGN power. Consistent with previous results, this link demonstrates that in the local universe, SMBH and galaxy bulge growth are contemporaneous.

6.2 Looking Ahead to the Future

Current and future surveys provide complementary methods in identifying and characterizing obscured AGN. In the near future, catalog matching between Wide-Field Infrared Survey Explorer (WISE) and SDSS can help elucidate the limitations and biases between IR and optical AGN selection. What percentage of IR-selected AGN live in the star-forming locus of the optical BPT diagram? How many optically selected AGN are missed by IR color selection, either identified as star-forming galaxies in the IR or missed entirely? If no IR counterparts of the optically identified
type 2 AGN exist (i.e. no IR signatures of an obscuring medium as found in Hao et al. (2011) and Ho (2008)), what limitations would this place on the unified model?

Upcoming deeper hard X-ray (E > 10 keV) missions, such as NuStar, will unveil the more heavily obscured AGN population. Current hard X-ray surveys, such as the Swift-BAT, are limited to a shallow depth. Probing to deeper flux levels will allow for the detection of many type 2 AGN currently missed, including the majority of the Compton-thick candidates we identified in the [OIII] and 12\(\mu\)m samples. The complex geometry of these systems can then be more accurately modeled. A more reliable estimate of the local Compton-thick fraction can then be derived and the X-ray background can be more reliably modeled. The energy released by accretion onto SMBHS over cosmic time can then be better understood.

Future X-ray missions, like Astro-H, will provide improved sensitivity for high resolution observations to resolve the RRC and He-like triplets. With a larger number of sources with well resolved soft X-ray emission lines, another dimension of the relative importance of AGN to starburst activity will be added to the wealth of existing multi-wavelength diagnostics. This multi-wavelength view mitigates biases in any individual energy range, providing a more complete picture of the interplay between AGN and star formation processes and whether one process is more dominant in a particular wave band. Such observations provide crucial constraints on theoretical modeling which seeks to describe the physical mechanisms responsible for the link between SMBH and galaxy co-evolution.
Appendix A

Aperture Bias

As the optical data for the 12 µm sample were culled from the literature, we examined the data to see if an aperture bias was evident. The aperture sizes used for the optical data ($\theta_{OIII}$) ranged from 3 to 14" for the 12 µm sources and was 3" for all the SDSS Sy2s. For several of our sources, we found the size of the NLR ($\theta_{NLR}$) from Schmitt et al (2003a) and estimated the NLR for the remainder using $\log R_{maj} = (0.31 \pm 0.04) \times \log L[OIII] - 10.08 \pm 1.80$ (Schmitt et al 2003b). As shown in Figure A.1 (same color coding as Figure 1 in the main text), the aperture was large enough to encompass the full NLR for all sources. Hence, we are not “missing” any of the NLR optical flux.

But are we observing too much [OIII] flux, perhaps from starburst contamination in the host galaxy which would affect [OIII] emission more than [OIV]? If this is the case, we would expect the $F_{[OIV]} / F_{[OIII],obs}$ ratio to decrease as the projected size of the aperture increases and the “PAH-strong” sources to lie at systematically higher aperture sizes. However, neither of these trends are apparent (Figure A.2), reaffirming the results in the main text where we find no evidence for starburst bias on [OIII] emission. We also note that the opposite effect is also absent, namely increase of $F_{[OIV]} / F_{[OIII],obs}$ with aperture size. This indicates that though the [OIV] flux is collected from the Long-High module which has a larger aperture than the [OIII] data, the [OIV] flux is not produced in regions outside of the NLR. Hence the dispersion present in the flux ratios is not due to sampling the galaxies at different
Figure A.1 Ratio of the NLR size to the optical aperture size used for the [OIII] flux and Hα and Hβ values. In all cases, the optical aperture encompasses the full NLR scales between the separate IR and optical observations.
Figure A.2 Left: Log (F_{OIV}/F_{OIII,obs}) vs log (θ_{OIII}). Right: Log (F_{OIV}/F_{OIII,obs}) vs log (θ_{NLR}/θ_{OIII}). The lack of significant trends suggest that the [OIV] flux originates in the NLR, consistent with the [OIII] flux, and that star formation processes in the host galaxy are not enhancing [OIII] emission.
Appendix B

Starburst Contribution to the MIR

As discussed in the main text, in many cases the Spitzer IRS data show evidence for the presence of both an AGN and active star formation. This implies that the MIR continuum will include emission from warm dust heated by both the AGN and massive stars. Since we are interested in using the MIR luminosity as an indicator of the intrinsic luminosity of the AGN, we would need a way to subtract off the contribution from the dust heated by stars.

We attempted to make this correction by using a simple dilution model based on the EW of the PAH features bracketing the continuum around 15.5µm (the PAH EW complexes at 11.3µm and 17µm, c.f. Genzel et al. 1998, Wu et al. 2009). This approach assumes that for starbursts there is a simple linear relationship between the PAH luminosity and that of the MIR continuum, and that the only effect of the AGN is to produce an additional source of MIR continuum emission, while not affecting the PAH luminosity.

As we have shown, the PAH EWs are indeed correlated with other indicators of star formation activity. We therefore compared the average PAH EWs for starburst galaxies ($<EW_{11.3\mu m,SB}>$=2.87 and $<EW_{17\mu m,SB}>$=1.74, O’Dowd et al. 2009; Treyer private communication) to the measured EWs for our Sy2s and used this to derive the fraction of the MIR emission that is attributed to the AGN heating of the
Figure B.1 Left: Distribution of $F_{\text{MIR,AGN}}/F_{\text{[OIV]}}$, where $F_{\text{MIR,AGN}}$ subtractions out the starburst contribution using the simple dilution model in the text. Right: Log ($F_{\text{MIR,AGN}}$) vs log ($F_{\text{[OIV]}}$). Compared with the raw MIR flux, this corrected flux leads to a poorer agreement with the [OIV] flux and seems to over-subtract the AGN contribution to the MIR flux for the “PAH-strong” sources.

torus (i.e. $f_{\text{AGN}} = 1 - EW_{\text{Sy2}}/ < EW_{\text{SB}}>$). In most cases, this correction was negligible. However, in the composite (strong PAH) AGN, this procedure seemed to subtract too much MIR flux, leading to poorer agreement with the other proxies and strong systematic trends with AGN luminosity (e.g. Figure B.1 as compared with Figure 2.3).

Such results indicate that accurately isolating the amount of MIR flux due to the AGN in strongly composite systems requires more detailed modeling that takes account of the possible influence of the AGN on the PAHs themselves. In the tight linear correlation we see between the uncorrected MIR and [OIV] luminosities (Figure 2.3) there is no evidence that the strong-PAH sources have systematically higher MIR luminosities. Taken at face value this would imply that in these sources the starburst does not dominate the MIR continuum. This would in turn imply that the EW of these long-wavelength PAHs with respect to the pure starburst MIR continuum is unusually high. This can not be understood as resulting from the destruction of PAHs by the AGN (e.g. Treyer et al. 2010), as the effect is in the opposite direction.
Appendix C

X-ray Analysis Notes on $12\mu$m Sources

NGC 424 - The default Chandra aperture extraction spectrum and XMM-Newton spectra were consistent and fit simultaneously using a double absorbed power law with a Gaussian component to accommodate the Fe Kα emission; including a thermal component did not statistically significantly improve the fit. We note that fitting the 3 - 8 keV continuum with a power law plus a Gaussian led to a tighter constraint on the Fe Kα emission and a more realistic EW value. Matt et al. (2003) analyzed the Chandra and XMM-Newton spectra independently using a slightly more complicated model, including Gaussian components at 0.55 and 0.90 keV to account for emission features, possibly from the OVIII recombination line and the OVIII recombination continuum or Ne IX recombination line, respectively. They also added a component for cold reflection, the PEXRAV model in XSpec. However, their 2-10 keV flux ($16 \times 10^{-13}$ erg s$^{-1}$ cm$^{-2}$) and Fe Kα EW values ($\sim 0.88$ keV) are consistent with the values we obtained ($11.5^{+6.4}_{-3.7} \times 10^{-13}$ erg s$^{-1}$ cm$^{-2}$ and $1.33^{+0.36}_{-0.39}$ keV, respectively) using a simpler model.

NGC 1068 - The PN and MOS1 XMM-Newton spectra for both observations showed evidence of pileup according to epatplot and were therefore not included in the spectral fit; archival Chandra data also exists for NGC 1068, but was not used in
this study due to the effects of pileup. Also, as several strong emission features were present below 1 keV (which are not important for the purposes of this study), we fitted the spectrum from 1 keV to 8 keV. The MOS2 spectra were best fit by an absorbed double power law with a thermal model and Gaussian components at 2.0 keV, 2.43 keV, 6.4 keV (neutral Fe Kα), 6.66 keV (likely ionized Fe Kα) and 6.95 keV. The neutral Fe Kα line was detected at a statistically significant level. Pounds & Vaughan fitted the 3.5 - 15 keV XMM-Newton spectra with two continuum components, a cold reflection model (PEXRAV) and a series of Gaussian emission features from 6 - 8 keV (where nine of these features were detected at a significant level). Based on this fit, they find a 3-15 keV flux of $63 \times 10^{-13}$ erg s$^{-1}$ cm$^{-2}$, which is consistent with our 2 - 10 keV flux of $54.2_{-32.0}^{+110} \times 10^{-13}$ erg s$^{-1}$ cm$^{-2}$, and a neutral Fe Kα EW of 0.60±0.10 keV, which agrees with our neutral Fe Kα EW value (0.60±0.05 keV). However, as noted in the main text, Matt et al. (2004) obtained an EW value of 1.2 keV, using a PEXRAV model, power law and a series of Gaussians for emission line features.

**NGC 1144** - The XMM-Newton spectra were best fit by a double absorbed power law with a thermal component and a Gaussian component for the Fe Kα emission. When fitting the 3 - 8 keV continuum to obtain a local fit for the Fe Kα component, a double power law was needed to accommodate the spectrum shape; the power law indices of the two components were tied together with the normalizations and an absorption component attenuating the second power law allowed to vary. Winter et al. (2008) fit NGC 1144 with the partial covering model in XSpec (which is akin to a double absorbed power law model with the photon indices tied together, which we have done) and a blackbody component for the soft emission. They derived comparable 2 - 10 keV flux ($30 \times 10^{-13}$ erg s$^{-1}$ cm$^{-2}$) and Fe Kα EW (0.22 keV) values as us ($33.4_{-12.9}^{+36.6} \times 10^{-13}$ erg s$^{-1}$ cm$^{-2}$ and $0.25_{-0.06}^{+0.06}$ keV, respectively).

**NGC 1320** - The XMM-Newton spectrum was best fit by an absorbed double power law component with a thermal component and a Gaussian component to accommodate the Fe Kα emission. Greenhill et al. (2008) used a cold reflection model (PEXRAV) as well as two thermal components (using MEKAL whereas we used
APEC) for the soft emission; a Gaussian had also been included to model the Fe Kα emission. We derive consistent Fe Kα EWs (3.02$_{-0.50}^{+0.46}$ keV vs. 2.20$_{-0.43}^{+0.44}$ keV), yet their 2 - 10 keV flux is over an order of magnitude higher than ours (3.84$_{-1.39}^{+2.83}$ × 10$^{-13}$ erg s$^{-1}$ cm$^{-2}$ vs. $\sim$43×10$^{-13}$ erg s$^{-1}$ cm$^{-2}$).

**NGC 1386** - As noted in the main text, the spectral parameters between the XMM-Newton and Chandra observations were consistent, except for a lower multiplicative factor for the Chandra observation, indicating extended emission contaminated the XMM-Newton observation. Though the Chandra data were grouped by a minimum of 5 counts per bin, the XMM-Newton spectra were grouped by a minimum of 15 counts, so we used $\chi^2$ statistics in this analysis. To derive the 2 - 10 keV flux, we fitted spectra from both observatories simultaneously to better constrain the Chandra spectrum, using a double absorbed power law with a thermal component and a Gaussian feature at 6.4 keV to accommodate the Fe Kα emission, yet we report the Chandra flux only. We fit the Chandra spectrum independently, both globally and locally, to derive the Fe Kα parameters, binning the data by a minimum of three counts and using C-stat. Levenson et al. (2006) fit the Chandra 4 - 8 keV nuclear spectrum with a reflection model (PEXRAV) and a Gaussian component at the Fe Kα energy. We obtain consistent 2 - 10 keV flux values (1.55$_{-0.33}^{+0.74}$ × 10$^{-13}$ erg s$^{-1}$ cm$^{-2}$ vs. 2.1±0.1 × 10$^{-13}$ erg s$^{-1}$ cm$^{-2}$) and Fe Kα EWs (2.30$_{-0.78}^{+1.00}$ vs. 2.3±1.5 keV).

**NGC 1667** - The XMM-Newton spectra were best fit with a single absorbed power law plus a thermal component. To constrain the Fe Kα EW in the local continuum fit (i.e. 3 - 8 keV), the spectra were binned by a minimum of 2 counts versus the 15 counts used for the global fit; C-stat was utilized in this local fit. Bianchi et al. (2005) fit the spectra with a reflection model (PEXRAV) with a soft excess, including a line at $\sim$0.9 keV. Our Fe Kα EWs are consistent (0.86$_{-0.50}^{+0.66}$ vs. $<$0.60 keV), however our 2 - 10 keV flux values disagree by about a factor of two (0.43$_{-0.11}^{+0.15}$ × 10$^{-13}$ erg cm$^{-2}$ s$^{-1}$ vs 10$^{-13}$ erg cm$^{-2}$ s$^{-1}$).

**F05189-2524** - Since the spectral parameters were consistent between the XMM-
**Newton** and **Chandra** observations, other than a lower constant multiplicative factor for the **Chandra** spectra, we fit these spectra simultaneously to constrain the 2 - 10 keV flux. However, we only report the flux from the **Chandra** observation as we have demonstrated that extended emission contaminates the **XMM-Newton** field of view. The spectra were best fit by a double absorbed power law plus a thermal component, though the temperature was not constrained. The **Chandra** spectra were fit independently to model the Fe Kα emission. Though this feature was not detected, we derived an upper limit on the EW of 0.17 keV, consistent with the results of Ptak et al. (2003) who fit the 2002 **Chandra** observation with a single power law plus thermal component (MEKAL). We also obtain similar 2 - 10 keV fluxes \((23.5^{+5.5}_{-4.9} \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1})\) vs. \(37\times10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1}\).

**NGC 3982** - As noted in the main text, the parameters, flux and Fe Kα EW values listed are from the model fits to **Chandra** spectrum only as extended emission is present in the **XMM-Newton** field of view. The spectrum was best-fit by an absorbed power law model with a thermal component, using the C-statistic on data grouped by 3 counts. We used ZGAUSS to test for the presence of an Fe Kα line, but the EW was unconstrained in both the global and local fit, where in the latter, it was necessary to group by 1 count per bin to fit the continuum. Guainazzi et al. (2005) fit the **Chandra** spectrum in a similar fashion (single absorbed power law with a thermal component) and obtained an upper limit on the 2 - 10 keV X-ray flux of \(0.5\times10^{-13} \text{ erg s}^{-1} \text{ cm}^{-2}\), which is consistent with our value of \(0.56^{+1.15}_{-0.35} \text{ erg s}^{-1} \text{ cm}^{-2}\). They also report a 1σ detection on the Fe Kα EW of \(8\pm5 \text{ keV}\), which may indicate this parameter is unconstrained.

**NGC 4388** - This source varied between the **XMM-Newton** observations from July to December 2002, increasing in flux and decreasing in Fe Kα EW. Both observations were best fit by a double absorbed power law (allowing the normalization of the second power law component to vary between the two observations), a thermal component (necessary to fit the soft emission), and a Gaussian component to accommodate the Fe Kα line. The spectral shape of the local continuum (3 - 8 keV, to constrain the
Fe Kα EW) for the December observation and Chandra observation required a base model of a double power law with an absorption component attenuating the second power law; a single power law base model was sufficient to fit the local continuum for the July observation. Beckmann et al. (2004) fit the XMM-Newton spectra with a single absorbed power law and a Raymond-Smith thermal plasma model; they also detect Fe Kα and a possible Fe Kβ line at $\sim 6.89$ keV. Our derived Fe Kα EWs are consistent ($0.62^{+0.10}_{-0.10}$ keV vs. 0.57 keV and $0.18^{+0.03}_{-0.02}$ keV vs. 0.22 keV for the July and December observations, respectively); they do not report a 2 - 10 keV flux or luminosity. The Chandra flux for NGC 4388, from the June 2001 observation, is consistent with the XMM-Newton July 2002 flux, though the Fe Kα EW increased, which could be due to the presence of extended emission the XMM-Newton field of view. Iwasawa et al. (2003) found the nucleus from the Chandra observation to be moderately affected by pileup, but we did not see evidence of this when we applied the jdpileup model to the spectrum in Sherpa. We obtain consistent Fe Kα EW values as Iwasawa et al. (0.29$^{+0.11}_{-0.10}$ vs. 0.44±0.09 keV), though a somewhat higher 2 - 10 keV flux ($74.6^{+88.5}_{-38.5} \times 10^{-13}$ erg s$^{-1}$ cm$^{-2}$) than their reported 2 - 7 keV flux ($27 \times 10^{-13}$ erg s$^{-1}$ cm$^{-2}$), though these values are likely consistent given the error bars on their flux and the more limited energy range over which they integrated.

**NGC 4501** - We report the parameters from the Chandra spectral fit as the XMM-Newton observation is contaminated by extended emission. The spectrum was best fit by an absorbed power law with a thermal component and we utilized the C-statistic as the data were grouped by 3 counts per bin. Brightman & Nandra (2008) also find the XMM-Newton field of view to be contaminated by extended emission. They fit the Chandra spectrum with a reflection component, ontop of an absorbed thermal power law model. Similar to our work, they do not detect the Fe Kα emission line in the global spectral fit.

**TOLOLO 1238-364** - The Chandra spectrum was best fit by an absorbed power law with a thermal component and a Gaussian to accommodate the Fe Kα emission. The data were binned by a minimum of 2 counts and we therefore employed
the C-statistic. Ghosh et al. (2007) fit this spectrum with an absorbed power law plus thermal bremsstrahlung model after binning by a minimum of 20 counts which washes out the Fe Kα feature. They detected the line at low signal to noise after re-binning by constant width, but obtain an unconstrained EW whereas we detected this feature.

**NGC 4968** - The two *XMM-Newton* observations for this source were best fit by an absorbed single power law model with a Gaussian component at the Fe Kα energy, using the C-statistic on data binned by 2 - 3 counts; we saw no evidence for variability between the two observations. Bianchi et al. (2005) fitted these spectra were fit independently with a reflection model (PEXRAV) with fixed photon index (Γ = 1.7), a power law component for the soft excess and gaussian for the Fe Kα line. We obtained consistent 2 - 10 keV flux \(2.08^{+0.26}_{-0.26} \times 10^{-13}\) erg cm\(^{-2}\) s\(^{-1}\) vs. \(2.7\pm0.08, 2.3\pm0.08 \times 10^{-13}\) erg cm\(^{-2}\) s\(^{-1}\)\) and Fe Kα EW values \(3.06^{+0.99}_{-0.78}\) keV vs. \(1.9\pm0.9, 3.2\pm1.1\) keV) using the simpler power law model.

**M-3-34-64** - The *XMM-Newton* spectra were fit by a double absorbed powerlaw with a thermal component and a Gaussian at the Fe Kα line energy. Miniutti et al. (2007) fit this source with a reflection model, with the soft emission accommodated by a power law model with two thermal components and a photoionized gas model and Gaussian components at 6.4 and 6.8 keV. Our observed 2 - 10 keV flux values approximately agree \(32.5^{+3.1}_{-3.1} \times 10^{-13}\) erg s\(^{-1}\) cm\(^{-2}\) vs. \(21\pm2 \times 10^{-13}\) erg s\(^{-1}\) cm\(^{-2}\), as well as our Fe Kα EWs derived from the global fits \(0.17^{+0.04}_{-0.03}\) keV vs. \(0.11\pm0.02\) keV), though our local continuum fit results in a higher EW \(0.31^{+0.05}_{-0.04}\) keV).

**NGC 5135** - *Chandra* observations of NGC 5135 reveal two X-ray point sources near the nucleus of the galaxy. The northern source was identified by Levenson et al. (2004) as the active nucleus, so we restrict our analysis to this source, using an extraction region of 1.2.” They find the AGN spectrum to be best fit by a model consisting of two thermal components, a Gaussian component at \(~2\) keV and at the Fe Kα energy, and an absorbed power law. We grouped the data by a minimum of
3 counts per bin, employed the C-statistic and find that a double absorbed power law with a Gaussian component to accommodate the Fe Kα emission reasonably fits the spectrum. Despite the different models used between Levenson et al. (2004) and us, we obtain consistent 2 - 10 keV fluxes ($2.31_{-1.68}^{+0.98} \times 10^{-13}$ erg cm$^{-2}$ s$^{-1}$ vs. $2.10_{-0.68}^{+0.19} \times 10^{-13}$ erg cm$^{-2}$ s$^{-1}$) and Fe Kα EWs ($2.44_{-0.82}^{+0.94}$ keV vs. $2.4_{-0.5}^{+1.8}$ keV).

**NGC 5194** - The nuclear region of NGC 5194 contains several X-ray emitting features: the AGN and diffuse emission to the North and South (see Terashima et al. 2001). *Chandra* is necessary to isolate the Seyfert nucleus and we therefore present the results of the *Chandra* analysis only, and do not include the archival data from *XMM-Newton*. Similar to Terashima et al. (2001), we extracted a source region centered on the optical center of the galaxy with a 1.5” radius from the *Chandra* data. The data were binned by a minimum of 3 counts and we utilized the C-statistic. The spectra were best fit by a double absorbed power law with a thermal component and a Gaussian component to accommodate the Fe Kα emission. Terashima et al. fit the 2001 observation with an absorbed power law model and a reflection model, both of which yield consistent fluxes ($\sim 1.2 \times 10^{-13}$ erg s$^{-1}$ cm$^{-2}$) and high EW values ($3.5_{-1.6}^{+2.7}$ keV and $4.8_{-2.5}^{+4.3}$ keV, respectively) which agree with the values we obtain ($1.04_{-0.73}^{+2.28} \times 10^{-13}$ erg s$^{-1}$ cm$^{-2}$ and $4.64_{-1.47}^{+1.42}$ keV).

**NGC 5347** - The *Chandra* spectrum is best fit by a double absorbed power law. To fit the local continuum to test for the presence of the Fe Kα line, we rebinned the spectrum by a minimum of 3 counts, utilized the C-statistic and detected the line at the 3σ level. Levenson et al. (2006) applied a reflection model (PEXRAV) to the higher energy range of the spectrum (4 - 8 keV) and fit the lower energy portion with power laws, a thermal component and line emission. Our 2 - 10 keV flux and Fe Kα EW values agree, $2.58_{-1.341}^{+1.20} \times 10^{-13}$ erg s$^{-1}$ cm$^{-2}$ vs. $2.2 \pm 0.4 \times 10^{-13}$ erg s$^{-1}$ cm$^{-2}$ and $1.35_{-0.44}^{+0.53}$ keV vs. $1.3 \pm 0.5$ keV, respectively.

**Mrk 463** - Extended emission was evident in the *XMM-Newton* field of view as indicated by the lower observed flux from the *Chandra* spectrum. Indeed, the *XMM-Newton*...
Newton is likely contaminated by the double nucleus (see Bianchi et al. 2008), which the Chandra observation is able to resolve. However, other than the constant multiplicative factor, the spectral parameters were consistent among the Chandra and three XMM-Newton spectra. The observations were consequently fit simultaneously to better constrain the Chandra parameters, though only the flux for the Chandra spectrum (for the Eastern source) is reported. To test for the presence of the Fe Kα line, the Chandra spectrum was rebinned by a minimum of 3 counts and the C-statistic was employed in the local (3 - 8 keV) fit; the line was detected at greater than the 99% confidence level according to our simulations. Bianchi et al. (2008) also employed a double absorbed power law model to fit the spectrum and we obtain consistent 2 - 10 keV flux values and Fe Kα EWs, $2.95^{+1.84}_{-0.82} \times 10^{-13}$ erg s$^{-1}$ cm$^{-2}$ vs. $4.1^{+1.8}_{-1.5} \times 10^{-13}$ erg s$^{-1}$ cm$^{-2}$ and $0.20^{+0.16}_{-0.13}$ keV vs. $0.21^{+0.15}_{-0.12}$ keV, respectively.

NGC 5506 - The XMM-Newton MOS1 spectra showed evidence of mild pile-up above 6 keV according to the SAS tool epatplot for all eight observations and were therefore not fit. For four of these (the 2001, 2002, 2008 and 2009 observations), the MOS2 spectra was also slightly piled and we excluded them from fitting. Archival Chandra data for this source does exist, but were not included in this study because they were severely affected by pile-up. We find the spectra to be best fit by a double absorbed power law with a thermal component and several Gaussian components to fit Fe K emission, at energies $\sim 6.4$ keV (neutral Fe Kα), $\sim 6.7$ keV and $\sim 6.95$-7.0 keV; however we note that for the local continuum fits, sometimes only two components were needed. The source varies by a factor of $\sim 1.5$ in flux on the time scale of approximately several months, though the Fe Kα EW remains relatively constant. For the purposes of our analysis, we use the average flux and Fe Kα EW among the 2001 and July 2004 observations ($<\text{EW}> = 0.14^{+0.05}_{-0.06}$ keV) and among the 2002, August 2004, 2008 and 2009 observations ($<\text{EW}> = 0.13^{+0.05}_{-0.04}$ keV; i.e. Figures 4.3 - 4.10). Guainazzi et al. (2010) studied the Fe Kα emission of these observations in depth, using a suite of physically motivated models (i.e. a combination of relativistically/non-relativistically broadened Fe Kα emission with relativistic/non-relativistic Compton reflection); the Fe Kα EWs are consistent among these various
fits. We derive EW values that agree with Guainazzi et al. (2010) using simpler modeling of the local (4 - 8 keV) spectrum with a power law model and Gaussian components.

**Arp 220** - The *XMM-Newton* and *Chandra* spectra were best fit by a single absorbed power law model with a thermal component; only the absorption varied between the *XMM-Newton* and *Chandra* observations, though this had a negligible impact on the observed flux. We discarded the *XMM-Newton* spectra from 2005 from our fitting due to low signal-to-noise, though we note the best-fit parameters were consistent with the other *XMM-Newton* spectra. To test for the presence of Fe Kα emission in the nuclear region, we utilized the *Chandra* data only and rebinned by a minimum of 3 counts, employing the C-statistic, but the line was not detected. We note, however, that an emission line for ionized Fe Kα at E = 6.51 keV was detected, consistent with Iwasawa et al. (2005). The *Chandra* data were first analyzed by Clements et al. (2002) who report a double nucleus and a halo of extended emission. We obtain consistent fluxes between their 3’ extraction area (which encompasses the double nuclei) and our 4.5’ extraction region: 1.07±0.18 × 10^{-13} erg s^{-1} cm^{-2} vs 1.0 × 10^{-13} erg s^{-1} cm^{-2}

**NGC 6890** - The *XMM-Newton* spectra were grouped by a minimum of 3 counts per bin and were fit with the C-statistic. The data were best fit by a double absorbed power law model and the Fe Kα line was marginally detected at the ~93% confidence level. Shu et al. (2008) fit this source with a single power law and did not detect the Fe Kα line, though this likely due to their choice of binning the data by a minimum of 20 counts which would eradicate the weak Fe Kα feature. We obtain consistent 2 - 10 keV flux values given the error range on our derived flux: 1.20^{+4.01}_{-0.88} × 10^{-13} erg s^{-1} cm^{-2} vs. 0.69 × 10^{-13} erg s^{-1} cm^{-2}.

**IC 5063** - The *Chandra* spectrum was moderately affected by pileup, ~14% according to the jdpileup model in *Sherpa*. We therefore included a pileup model in the XSpec spectral fits, allowing only the grade migration parameter (α) to be free,
and obtained an $\alpha$ value of 0.37; excluded the pileup component when calculating the observed 2 - 10 keV flux. The jdpileup model indicated no pileup in the local 4 - 8 keV spectral fit, so it was modeled without a pileup component in XSpec. The broadband spectrum was best fit by a double absorbed power law and our simulations indicate that the Fe K$\alpha$ emission feature is significant at greater than the 2.5$\sigma$ level. This Chandra spectrum has not been previously analyzed.

**NGC 7130** - The Chandra spectrum of NGC 7130 was best fit by a double absorbed power law with a thermal component for the soft emission and a Gaussian feature at the Fe K$\alpha$ energy; we used the C-statistic with the data binned by 2 counts. This source was studied in detail by Levenson et al. (2005) where they fit the AGN spectrum with a double absorbed power law with a gaussian component as well as two thermal components. Though they added an extra thermal component, our derived 2 - 10 keV flux and Fe K$\alpha$ EW values are consistent ($2.07^{+2.09}_{-1.04} \times 10^{-13}$ erg cm$^{-2}$ s$^{-1}$ vs. $1.6^{+0.3}_{-0.4} \times 10^{-13}$ erg cm$^{-2}$ s$^{-1}$ and $0.82^{+0.48}_{-0.33}$ keV vs $1.8^{+0.7}_{-0.8}$, respectively).

**NGC 7172** - The XMM-Newton observations were best fit by a double absorbed power law with a thermal component and Gaussian feature at the Fe K$\alpha$ energy. The normalization of the second power law was consistent between the the 2002 and 2004 observations, yet had to be fit independently for the 2007 observation. We only fit the PN and MOS2 spectra for the 2007 observation as the MOS1 spectrum showed evidence for milder pileup at higher energies from the task epatplot. Our results indicate that the source increased by about a factor of 2 in flux between 2004 and 2007. The Fe K$\alpha$ emission features were fit independently among the three observations, though we use the average Fe K$\alpha$ EW for the 2002 and 2004 observations in the plots ($<\text{EW}> = 0.16^{+0.06}_{-0.04}$ keV; i.e. Figures 4.3 - 4.10) as the 2 - 10 keV flux values are consistent between the two observations and the EW values are not widely discrepant in both the local and global fits, indicating that the variations in the independent Gaussian fits are likely not significant. Noguchi et al. (2009) fit the 2007 observation with a double absorbed power law, thermal component (using MEKAL whereas we used APEC) and two Gaussian components, one at the Fe K$\alpha$ energy and the other
at 1.7 keV; we obtain consistent 2 - 10 keV fluxes \((517^{+43}_{-40} \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1})\) vs. \(423 \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1}\) and Fe Kα EWs \((0.10^{+0.02}_{-0.01} \text{ keV})\) vs. \(0.07 \pm 0.01 \text{ keV}\). Shu et al. fit the spectra from the 2002 \textit{XMM-Newton} observation by a double absorbed power law with a Gaussian component at the Fe Kα energy, similar to our analysis, though they do not include a thermal component. Our 2 - 10 keV flux values are consistent \((234^{+19}_{-18} \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1})\) vs. \(220 \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1}\), but our Fe Kα EWs are not \((0.14^{+0.03}_{-0.03} \text{ keV})\) from the global continuum fit vs. \(0.04 \pm 0.03 \text{ keV}\). This discrepancy could be due to constraints placed on their modeling of the Fe Kα line: they froze the energy at 6.4 keV, whereas we allowed this parameter to be free and it is not clear whether they placed a similar constraint on \(\sigma\). Regardless of this discrepancy, both EW values are consistent with a Compton-thin source. Analysis of the EPIC data for the 2004 observation has not been previously published, making our analysis the first for this dataset.

\textit{NGC 7582} - This source varied between the 2000 \textit{Chandra} observations and later \textit{XMM-Newton} observations, as well as between the 2001 and 2005 \textit{XMM-Newton} observations; the \textit{Chandra} and \textit{XMM-Newton} observations were fit independently. The \textit{Chandra} spectra were moderately affected by pileup (\(~30 - 49\%\) according to the jdpileup model in Sherpa) and were therefore fit with a pileup model component in XSpec, with only \(\alpha\), the grade migration parameter, allowed to vary; the pileup component was discarded before calculating the flux and the Fe Kα EW. The broad-band \textit{Chandra} spectra were best fit by a double absorbed power law whereas the \textit{XMM-Newton} spectra required a thermal component and Gaussian components at the Fe Kα energy and at ionized Fe Kα energies (\(~6.72 \text{ keV}\) for the 2005 observation and \(~6.97 \text{ keV}\) for the 2001 observation)\(^1\), \(~1.84 \text{ keV}\) and \(~2.47 \text{ keV}\). The neutral Fe Kα feature was detected at a statistically significant level for all observations according to our simulations. NGC 7582 dimmed between the \textit{Chandra} observation and each subsequent \textit{XMM-Newton} observation and the Fe Kα EW increased. This decrease

\(^1\)However, in the local (3 - 8 keV) fits, this higher energy Gaussian is more consistent with Fe Kβ emission, with a best-fit centroid energy of 7.08 keV for the 2001 observation, and shifts to a best-fit centroid energy of 6.91 keV for the 2005 observation.
in flux with increase in Fe Kα EW could reflect a variation in the obscuring medium, where the obscuration enhanced over time. Indeed, such an interpretation is favored by Piconcelli et al. (2007), who postulate the existence of multiple absorption components in this system: a higher column-density absorber (possibly mildly Compton-thick) attributed to the putative torus and a lower-column density absorber acting as a screen to both the reflected and transmitted radiation. Though Piconcelli et al. (2007) fit the XMM-Newton observations with a more complex model (PEXRAV) we obtain consistent fluxes (21.1$^{+1.7}_{-1.8}$ × 10$^{-13}$ erg s$^{-1}$ cm$^{-2}$ vs. 23.5×10$^{-13}$ erg s$^{-1}$ cm$^{-2}$ for the 2005 observation and 38.6$^{+3.0}_{-3.1}$ × 10$^{-13}$ erg s$^{-1}$ cm$^{-2}$ vs. 40.2×10$^{-13}$ erg s$^{-1}$ cm$^{-2}$ for the 2001 observation), though lower Fe Kα EW values (2005: 0.58$^{+0.04}_{-0.04}$ keV vs. 0.77$^{+0.05}_{-0.04}$ keV; 2001: 0.31$^{+0.05}_{-0.05}$ keV vs 0.62$^{+0.07}_{-0.08}$). Dong et al. (2004) fit the Chandra spectra independently with a double absorbed power law, yet obtain an observed flux about half of ours (164$^{+263}_{-87}$ × 10$^{-13}$ erg s$^{-1}$ cm$^{-2}$ vs. ∼75 ×10$^{-13}$ erg s$^{-1}$ cm$^{-2}$), though this discrepancy could result from us modeling pileup whereas they did not; we obtain consistent Fe Kα EW values (0.15$^{+0.07}_{-0.07}$ keV vs. an averaged ∼0.19 keV).

NGC 7674 - The global XMM-Newton spectra were best fit with a double absorbed power law. To fit the local continuum between 3 - 8 keV, the data were binned to a minimum of 3 counts and the C-statistic was utilized; the Fe Kα feature was detected a statistically significant level. Analysis of the broad-band XMM-Newton spectra for this source has not been previously published.
Appendix D

Simulated NuSTAR Detections: 10-40 keV

Using ARF, RMF and background files provided by the NuSTAR team, which include separate ARF and background files for a 45” and 101” point spread function (useful for weak and strong sources, respectively) we generated a simulated NuSTAR spectrum in the 10-40 keV energy range as described in the main text. If the net count rate was $> 10^{-2}$ s$^{-1}$, we utilized the simulated spectrum corresponding to the larger PSF, otherwise we used the spectrum generated with the smaller PSF. In Tables D.1 and D.2, we list the simulated source count rate and corresponding exposure time for the target to be detected at greater than the $5\sigma$ level above the background, which was either $\sim 8 \times 10^{-4}$ s$^{-1}$ or $\sim 4 \times 10^{-3}$ s$^{-1}$, depending on the PSF. For the sources where this derived exposure time is under 5 ks, we instead list the exposure time necessary for at least 100 counts to be detected; if this exposure time is also under 5 ks, we adopt a minimum exposure time of 5 ks. For the three 2-10 keV non-detections from the 12µm sample, we list the exposure times using a spectrum simulated from the PLCABs model in XSpec, with $N_H = 10^{24}$ cm$^{-2}$, the number of scatterings set to 5, $\Gamma=1.8$ and the normalization adjusted such that the 2-10 keV flux equals the $3\sigma$ upper limit. Again, we note that such a flux estimate is quite optimistic and the corresponding derived exposure times necessary for detection should be considered lower limits and are listed as such in Table D.2.
Table D.1. [OIII] Sample: NuSTAR Simulation Summary

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$^1$Exposure time needed for source to be detected above the background at greater than the $5\sigma$ level.

$^2$Exposure time listed is for a detection of 100 counts as a $5\sigma$ detection above the background is $<5$ ks.

$^3$Minimum exposure time of 5.0 ks is adopted as the exposure times for both a $5\sigma$ detection above the background and for a detection of at least 100 counts are $<5$ ks.
Table D.2. 12µm Sample: NuSTAR Simulation Summary

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<td>9.00×10^{-4}</td>
<td>53</td>
</tr>
<tr>
<td>IC 5063³</td>
<td>6.22×10^{-1}</td>
<td>5.0</td>
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<tr>
<td>NGC 7130</td>
<td>3.14×10^{-3}</td>
<td>10</td>
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<tr>
<td>NGC 7172³</td>
<td>7.67×10^{-1}</td>
<td>5.0</td>
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<tr>
<td>NGC 7582³</td>
<td>4.68×10^{-2}</td>
<td>5.0</td>
</tr>
<tr>
<td>NGC 7590³</td>
<td>3.52×10^{-2}</td>
<td>&gt;5.0</td>
</tr>
<tr>
<td>NGC 7674²</td>
<td>6.17×10^{-3}</td>
<td>16</td>
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</table>
Table D.2  (cont’d)

<table>
<thead>
<tr>
<th>Galaxy</th>
<th>Simulated Source Count Rate</th>
<th>Exposure Time$^1$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>counts/sec</td>
<td>ks</td>
</tr>
</tbody>
</table>

$^1$Exposure time needed for source to be detected above the background at greater than the $5\sigma$ level.

$^2$Exposure time listed is for a detection of 100 counts as a $5\sigma$ detection above the background is $<5$ ks.

$^3$Minimum exposure time of 5.0 ks is adopted as the exposure times for both a $5\sigma$ detection above the background and for a detection of at least 100 counts are $<5$ ks.
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Vita

Stephanie LaMassa, born April 2, 1981, grew up in Mt. Vernon, NY, a non-sleepy suburb of New York City. She attended Cardinal Spellman High School in the Bronx from 1995 to 1999. She graduated with a Regents diploma, ranked number one in her graduating class and in keeping with her passion for science, earned the English award.

Steph then trekked North to begin her undergraduate studies at Boston University, majoring in astronomy and physics. She became actively involved in research her sophomore year, ultimately studying solar wind phenomena which became the central topic of her senior thesis under Profs. Nancy Crooker and Harlan Spence. In 2003, Steph graduated *magna cum laude*, with distinction, with a BA in astronomy and physics and was awarded The Center for Space Physics Award for Excellence in Space Physics.

The summer of 2003, Steph started a position at the Harvard-Smithsonian Center for Astrophysics in Cambridge, MA as a mission planner for the *Chandra* X-ray Observatory. While at the CfA, she pursued research opportunities within the High
Energy Astrophysics division, working on X-ray analysis of quasars with Dr. Aneta Siemiginowska and the Vela pulsar wind nebula with Dr. Pat Slane. After seven formative years in the greater Boston area, Steph bid a fond farewell to Massachusetts in 2006 to embark on her graduate student career.

Traveling back down the East Coast, Steph began graduate school at The Johns Hopkins University in Baltimore, MD in the fall of 2006. She was a teaching assistant her first year and was awarded the Rowland Prize for Innovation and Excellence in Teaching. She worked that summer with Prof. Bill Blair on producing an atlas of FUSE sight line data to stars in the Magellanic Clouds and studying the distribution of warm hot gas in the Large Magellanic Cloud. Steph began work with Prof. Tim Heckman and Dr. Andy Ptak in the spring of 2008 on X-ray analysis of obscured AGN, which became the start of her dissertation work. From 2008 to 2011, she has researched the efficacy of different proxies of intrinsic AGN luminosity, the distribution of absorption in obscured AGN and the connection between AGN and host galaxy star formation.

Steph continues her East Coast tour with a post-doctoral position with Prof. Meg Urry at Yale University in New Haven, CT, studying the co-evolution of supermassive black holes and their host galaxies.