Black Holes at the Centers of Nearby Dwarf Galaxies: The X-ray Perspective

by

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Chapter 1

Background

Despite masses that can exceed $10^9 M_\odot$, supermassive black holes (SMBHs) do not have the gravitational power to affect their surroundings more than a short distance away. A SMBH’s sphere of influence, or region in which its gravitational potential overwhelms that of the galaxy, is generally orders of magnitude smaller than the galactic radius. For this reason, astronomers were perplexed to discover correlations between SMBH masses and large-scale galactic properties that could not logically have been affected by the black holes.

Observations of a number of extremely luminous, distant galaxies have established the presence of quasars powered by black holes of up to $10^9 M_\odot$ at $z > 6$, or about 1 Gyr after the Big Bang. There is compelling evidence that the SMBHs detected today in nearby galaxies are the quiescent remnants of these energetic objects, and that they once began as collapsing stars, just like stellar-mass black holes in the present-day universe. However, the existence of these objects in the early Universe presents an obstacle: there isn’t enough time between the epoch of galaxy formation and $z \approx 6$ to grow a stellar-mass black hole to $10^9 M_\odot$, even if it were accreting constantly at the Eddington rate, i.e., the accretion rate at which the generated luminosity halts the accretion flow (Volonteri 2010). This discrepancy implies that SMBHs formed in the very early universe, when galaxies were still in their infancy, and through processes that created much larger black
hole “seeds” than the stellar-mass black holes formed in the universe today.

Numerous studies have demonstrated a strong relationship between the mass of a galaxy’s central black hole ($M_{BH}$) and the velocity dispersion of the stars ($\sigma_*$) in the galactic bulge (Ferrarese & Merritt 2000; Gebhardt et al. 2000) (see Fig. 1.2). Even before this $M_{BH}$-$\sigma_*$ relationship was established, Kormendy & Richstone (1995) found that black hole masses are correlated with the luminosity and mass of the galactic bulge, in one of the early studies that established the existence of SMBHs at the centers of galactic nuclei. Successive observations have refined and provided further evidence for the correlations between $M_{BH}$ and bulge luminosity and $M_{BH}$ and bulge mass (see Figures 1.1 and 1.2) (Kormendy & Richstone 1995; Magorrian et al. 1998; Marconi & Hunt 2003).

These correlations between $M_{BH}$ and various galactic properties, which could not possibly be directly influenced by the black holes, suggest SMBHs and their host galaxies have evolved together via a single, common process. The most likely
Figure 1.2: $M_{BH}$ vs. $\sigma_c$, the central velocity dispersion of the bulge or host elliptical galaxy (filled circles). Open circles indicate the rms velocity measured at 1/4 the effective radius, with lower limits given by crosses. The best linear fits for $\sigma_c$ and $v_{rms}$ are denoted by the solid and dashed lines, respectively (Ferrarese & Merritt 2000).
mechanism for this coevolution is that of mergers between galaxies, a theory based on the hierarchical model of galaxy evolution, which suggests that mergers of smaller bodies play a pivotal role in galactic formation and evolution \cite{Volonteri2010}. Such interactions would allow for concurrent SMBH and stellar growth through regulation of the amount of gas available in the central regions of the galaxy. However, the details of such a process are far from certain, and a number of troubling issues remain unresolved. The initial formation mechanisms for galaxies and “seed” black holes has a critical effect on the evolutionary process, but is still an open question—sufficient observational evidence is not yet available to distinguish between the different possible scenarios. Further, because the mechanisms behind the observed scaling relations are still not well understood, it is unclear how consistent these relations are across drastically different galaxies, and how they might depend on factors such as mass, luminosity, or morphology. Although it is still difficult to form a complete picture of galactic and SMBH evolution through galaxy mergers alone, it functions as a basic paradigm in our attempt to understand how SMBHs evolved to their current massive state and to characterize their structures today \cite{GreeneHo2004}.

1.1 Intermediate-Mass Black Holes

One effective way to gain a better understanding of the coevolution of galaxies and SMBHs is to search for the least massive nuclear black holes. Typically, black holes are found in one of two mass ranges: stellar-mass BHs (on the order of tens of $M_\odot$), and the supermassive black holes that have been found to lurk in the centers of most (if not all) galaxies with bulges ($10^6$–$10^9 M_\odot$) \cite{GreeneHo2004}. In recent years this gap has been filled by a third class: intermediate-mass black
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Intermediate-mass black holes (IMBHs), which have masses ranging from $10^3$ to $10^6\ M_\odot$ and are presumably located in the least-luminous and least-massive galaxies (based on the scaling relations described above). Generally found in early-type, relatively isolated galaxies that seem to have very little history of merger activity, these objects essentially allow us to look back in time to a previous stage in the evolutionary process (Greene & Ho 2007b).

The search for increasingly lower-mass IMBHs makes it possible to investigate whether the scaling relationships ($M_{BH}$-$\sigma_*$ and $M_{BH}$-luminosity) still hold true at low masses and luminosities. Indeed, models constructed by Volonteri & Natarajan (2009) imply that the $M_{BH}$-$\sigma_*$ relation can be explained as “purely a reflection of the merging hierarchy of massive dark matter haloes,” and that lower-mass galaxies will initially lie below the relation, migrating onto it as they undergo merger events. Because surveys seeking galaxies with IMBHs could reveal deviations from the $M_{BH}$-$\sigma_*$ relation, they offer the possibility of identifying whether that migration happens earlier or later in the evolutionary process. Further, the process by which this migration occurs depends critically upon the formation mechanism for massive black hole seeds in the early universe. Measuring a current-day mass distribution and occupation fraction (i.e., the fraction of galaxies at a given $\sigma_*$ that contain a SMBH) for IMBHs would allow us to distinguish between the different models for seeding the universe. Ultimately, these objects

\footnote{Intermediate-mass black holes are also commonly discussed in the context of binary systems and high-density stellar environments. These studies are also interested in the mass gap between stellar-mass and supermassive black holes and the evolutionary processes involved in accreting mass. The IMBHs they describe, though, are less massive ($10^2$–$10^4\ M_\odot$), can be detected by different techniques due to the gravitational effects of binaries, need not be located at the galactic nucleus, and are generally treated as a different field of inquiry (Miller 2002; Liu & Bregman 2001).}

\footnote{For example, the collapse of Population III stars, formed from zero-metallicity gas, would result in significantly smaller, more numerous black holes; whereas the “heavy” seeds created through direct collapse of primordial gas would yield a full range of masses, peaking at the higher-mass end (Volonteri 2010).}
1. Background

offer a new opportunity to probe the evolution of canonical structures, allowing us to set new, tighter constraints on formation mechanisms \cite{Volonteri2010}.

Unfortunately, their very nature makes IMBHs difficult to find because detection of black holes depends on observing their effects on their environments. Dynamical detections of stellar velocity dispersions can only be made for very nearby galaxies whose nuclei can be resolved—we don’t have the capacity to resolve gravitational spheres of influence for BHs as small as $\sim 10^5 \, M_\odot$ beyond the Local Group of galaxies. For IMBHs, which are most likely to be found in dwarf galaxies, this kind of detection becomes even less viable. Instead, we must search indirectly for evidence of a black hole based on radiative signatures of AGN activity. The best way to survey IMBHs, then, is to look for AGN in dwarf galaxies \cite{Greene2004}.

1.2 The Nature of Active Galactic Nuclei

The term active galactic nucleus, or AGN, generally refers to a compact source of non-stellar emission at the center of a galaxy. This emission is generally accepted as arising from an accretion disc surrounding a black hole. Although several subclasses of AGN exist, the two most common types are quasars and Seyfert galaxies. These are distinguished somewhat arbitrarily based on their luminosities; the total energy emitted by the nucleus of a typical Seyfert galaxies is about equal to that emitted by all the stars in the galaxy, while quasars’ nuclear sources are generally a hundred times or more brighter than their stars.\footnote{The distinction between quasars and Seyferts is largely historical; quasars’ extreme luminosities make them quite rare, and, accordingly, they tend to be found only at very large distances. This combination of distance and luminosity made it very difficult to detect the host galaxy in ground-based images. It was not until some years after the first observations of these objects that they were recognized to be galaxies—hence the misnomer, “quasi-stellar” \cite{Peterson1997}.}
Seyfert galaxies are characterized by unusually broad emission lines in their spectra, which show evidence of being ionized by a very high-energy source. They are commonly divided into two subclasses based on the presence or absence of certain emission lines. Type 1 Seyfert galaxies have two sets of superimposed emission lines. The first set consists of permitted and forbidden lines (characteristic of low-density ionized gas) with linewidths slightly broader than those in normal (non-AGN) galaxies. These are known as narrow lines. The second set consists of even broader permitted lines (resulting from high-density gas); these are referred to as broad lines. Type 2 Seyfert galaxies differ from type 1s in that their spectra have only narrow lines (Osterbrock 1991; Peterson 1997).

A common method for distinguishing the emission from Seyfert galaxies from the emission associated with photoionization by hot stars in H II regions (in normal galaxies) is to examine the ratios of several emission lines. One way to identify a galaxy as a Seyfert is to check that the flux ratio $[\text{OIII}]\lambda 5007/\text{H}\beta > 3$. However, this criterion is not definitive, as low-metallicity H II regions can also achieve this ratio. These objects can, however, be well-segregated based on the ratios of two different pairs of lines (Baldwin, Phillips, & Terlevich 1981). BPT diagrams (named for Baldwin, Phillips, and Terlovich) are effective because line strengths depend on the shape of the ionizing continuum, so different relative line strengths can be used to distinguish between different kinds of ionizing spectra.

BPT diagrams also allow us to separate Seyfert galaxies from LINERS (low ionization nuclear emission-line region galaxies). First identified by Heckman (1980), these objects constitute the most common and least energetic known active galaxies. They resemble Seyfert 2s spectroscopically, but are distinguished by strong forbidden line transitions from low ionization states (e.g. $[\text{OI}]\lambda 6300$ and $[\text{NII}]\lambda\lambda 6548,6583$) relative to higher-ionization lines, and have lower $[\text{OIII}]/\text{H}\beta$. 
flux ratios than Seyferts. Classically, the total energy in LINER spectral lines is significantly lower than in Seyfert galaxies, often by as much as a factor of 100. However, as discussed above, a single ratio of two line intensities, such as $[\text{O III}]/H\beta$, cannot be used to unambiguously distinguish between Seyferts, LINERS, and other kinds of emission-line regions. Commonly-compared line-ratios include $[\text{O III}]/H\beta$, $[\text{N II}]/H\alpha$, $[\text{S II}]/H\alpha$, and $[\text{O I}]/H\alpha$ (see Fig. 1.3).

![Figure 1.3: BPT diagrams for J1009+2656, one of the objects for which we have Chandra observations. J1009+2656 is indicated by a blue dot. The lower objects to the right of the red line are LINERS and the higher are Seyferts; star-forming galaxies reside to the lower left of the curve (Moran et al. 2013).](image)

Evidence that broad emission lines do indeed arise from photoionization by radiation from the central source has been found by looking for variability. The fluxes of these broad lines have been shown to fluctuate significantly in response to variations in the continuum radiation, a correlation that also indicates that the region from which the broad lines arise is located close to the center. Models indicate that this broad line region (BLR) contains dense photoionized clouds, while the narrow line region (NLR) is less dense and located at a greater distance from the galactic center, sometimes extending tens to hundreds of parsecs—enough
to be resolved for nearby galaxies. Yet although these morphologies seem to be clearly delineated by the emission line profiles, attempts to model the inner structures of Seyfert 1 and 2s have historically been uncertain. At least as early as 1978, attempts were made to develop a unified model, based on obscuration of the central regions and the effects of orientation, that could describe all the different kinds of Seyferts (Peterson 1997). Today, the unification model is largely accepted, if with some reservations (Antonucci & Miller 1985, 1993).

According to this model, the differences between types 1 and 2 arise from the presence of a parsec-scale obscuring torus surrounding the continuum source and BLR. Although emission from the NLR can be seen directly from all angles, the plane of the opaque, dusty torus blocks the BLR from certain viewing angles. Type 2 Seyferts, then, would be viewed close to edge-on while an observer seeing the galaxy along the axis of the torus would see the NLR, the BLR, and the source and identify it as a type 1. Therefore, a type 2 AGN should have the same properties as a type 1 if the effects of this obscuration could be removed (Osterbrock 1991; Peterson 1997). Fig. 1.4 shows a diagram of a unified model for AGN.

Some studies, however, have offered observational evidence that while most narrow-line (type 2) AGN do indeed have hidden broad-line regions and are therefore intrinsically broad-line (type 1) AGN, the unification model does not hold true for all type 2 AGN. Laor (2003) suggests that “true” type 2 AGN do, in fact, exist below a certain luminosity limit. He argues that the line width of the BLR seems to increase as luminosity decreases for a given black hole mass. Observing that there seems to be a physical upper limit to the width of the broad emission lines (possibly due to a maximum velocity dispersion at which the BLR “clouds” can survive), Laor concludes that if this cutoff is true, then the BLR will cease to exist
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Jet Obscuring Torus

Figure 1.4: Geometric model for an AGN (not to scale). (C.M Urry & P. Padovani)
below a certain luminosity. At the same time, the rest of the AGN might retain its “normal” structure, resulting in an AGN with only a narrow line-emitting region (NLR). On the other hand, Chakravorty et al. (2012) suggest that below a certain radius for the BLR the broad emission lines are inefficiently produced. For lower-mass black holes, then, the broad line region may simply be undetectable. Both scenarios, though, lead to a higher expected fraction of type 2 AGN in lower-mass galaxies.

1.3 AGN in Low-Mass Galaxies

Before IMBHs were commonly observed, the question of whether or not AGN structure remained the same below a certain luminosity could not be answered observationally. Therefore, the discovery of the first dwarf galaxy to contain an intermediate-mass black hole opened a whole new area of inquiry about the nature of AGN. We are particularly interested in the way in which AGN structure changes at low luminosity. The use of X-ray spectroscopy offers the possibility of revealing whether or not absorption is actually occurring; in type 2 IMBH systems such observations can serve as a test of AGN structure. Detecting the presence of absorption would allow us to refine our understanding of the current unification model for AGN at lower masses. If no evidence for absorption is found, it is likely that we have a direct view of the innermost regions around the BH, possibly allowing us to estimate the black hole’s mass—a measurement that is extremely difficult if not impossible to make for obscured AGN.

We have conducted a search for IMBH candidates in nearby low-mass galaxies. This search, designed to detect both type 1 and type 2 galaxies, has yielded a sample of 28 objects with similar expected black hole masses. Interestingly,
almost all of the AGN in our sample are type 2—only two are type 1. This is unusual considering that surveys of luminous Seyfert galaxies have shown a ratio of Seyfert 2s to 1s of least 2:1, and possibly as high as 4:1 \cite{Osterbrock & Shaw 1988, Maiolino & Rieke 1995}. From the start, this discrepancy strongly suggests that the low-luminosity dwarf galaxies in our sample may differ from “normal” Seyferts. Armed with this set, we can investigate whether the unified model is in fact applicable across all AGN black hole masses, or if there is evidence that the structure of AGN at low bolometric luminosities varies from the standard unified model. Using X-ray observations to probe the inner regions of AGN in dwarf galaxies, we hope to determine whether the lack of broad emission lines in low-mass type 2 objects is actually due to absorption, or a fundamentally different morphology.

In the next chapter, I will briefly review the surveys that have been initiated to search for low-mass AGN and describe how our own survey fits into this effort. After explaining the process by which our initial sample of low-mass candidates was chosen, I then outline how our search resulted in a new set of 28 dwarf galaxies containing AGN. Six of these objects were observed by the Chandra X-Ray Observatory; Chapter 3 gives an overview of X-ray astronomy with Chandra, describing the telescope and the science instrument before going on to explain the process of analyzing the data we received. In Chapter 4, I present the results for our six objects as well as the data from a serendipitous ASCA observation of a seventh object from our sample. Based on the observed X-ray fluxes and spectra, we clearly demonstrate evidence for absorption in these objects. Finally, we conclude with a discussion of the implications of our results, and possible future work.
Chapter 2

Defining our Sample

As discussed in the previous chapter, the low accretion luminosity of galaxies containing IMBHs is correlated with less available gas to feed the black hole, and so galaxies with low-mass BHs are typically faint. This makes it relatively difficult to identify IMBH candidates, and it is only in the last decade that astronomers have begun to find larger numbers of IMBHs. In this chapter, I describe the surveys that have been implemented to find these objects and the benefits and limitations of their designs. I then explain the process by which we went about designing our own survey, one that would be less biased and reach to lower-mass galaxies than ever before, and how we implemented this search. Finally, the last section summarizes our findings in the context of the entire sample.

2.1 Surveying for Low-Mass AGN

One of the earliest and most well-known intermediate-mass black hole candidates is in the dwarf galaxy NGC 4395, a bulgeless spiral whose broad emission lines and $10^5 M_\odot$ black hole have been thoroughly characterized since its discovery (Filippenko & Sargent 1989, Filippenko & Ho 2003). The other well-studied example is POX 52, also a Seyfert 1 with very similar BH mass and emission spectra in both the optical and X-ray, but with an elliptical host-galaxy morphology (Barth et al. 2004, Thornton et al. 2008).
More recently, the search for IMBHs has vastly expanded as the Sloan Digital Sky Survey (SDSS) has made it possible to carry out systematic searches for AGN with low-mass black holes. Using spectroscopic data from SDSS, a number of surveys have identified several hundred additional IMBH candidates (Greene & Ho 2004, 2007a; Dong et al. 2007, 2012b; Barth et al. 2008). The surveys carried out by Greene & Ho (2004, 2007a) and Dong et al. (2012b) fit emission-line spectra to cull only broad-line AGN—type 1s were ideal in these cases because their BH masses could be estimated from their broad-line widths and continuum luminosities. BH masses were found using emission from the broad line region, which is located very close to the black hole, as a dynamical tracer. This allowed them to derive velocity dispersion from the Hα line width. The BLR radius, the other piece of information needed to estimate $M_{BH}$, can be inferred from the overall AGN luminosity based on a radius-luminosity relationship. This relationship is derived from prior reverberation mapping of a sample of $\sim 30$ AGN, a method in which the time delay between fluctuations in the AGN’s photoionizing continuum and a corresponding fluctuation in line emission from the BLR (presumably due to light travel time) can be used to measure radius. The black hole masses derived in this way do have a significant amount of uncertainty, as reverberation mapping is susceptible to large systematic errors deriving from the assumptions made about geometry and kinematics. Nevertheless, they have actually been shown to agree quite well with the $M_{BH}-\sigma_*$ relationship, and as such can be taken to yield appropriate approximations for an initial test of black hole masses. Finally, a study that specifically targeted narrow-line AGN was carried out by Barth et al. (2008), hoping to find lower-mass black holes than could be identified with the type 1

\[ M_{BH} = f \cdot R \cdot \frac{v^2}{G}, \]

where $R$ is the radius of the BLR gas, $v$ is its velocity dispersion, and $f$ is some scaling factor to describe the (unknown) geometry of the BLR, assumed by both studies to be spherical (Dong et al. 2012b/a).
AGN searches.

While these surveys successfully demonstrated the existence of IMBHs in a number of low-mass galaxies, the methods by which they identified their targets opened them up to luminosity bias in their samples: the typical luminosities of both the nuclei and the host are large compared to the general population. This bias becomes apparent when we look at the distances of the objects discovered. With a median redshift $z \approx 0.05–0.09$, they are fairly distant, implying that their nuclei must be relatively luminous in order to have been detected. In addition, the host galaxies must be brighter than some detection threshold in order to be included in the spectroscopic follow-up search in the SDSS for broad or narrow line components. Accordingly, objects found by this method (including both the Greene & Ho (2004, 2007a) and Barth et al. (2008) samples) are biased to higher luminosities. Furthermore, since the SDSS is itself flux-limited, such surveys correlate greater distances with higher nuclear luminosities (more luminous objects will rarely be found nearby while faint objects won’t be detected at greater distances).

These limitations are clearly apparent when the IMBH candidates are compared to NGC 4395 and POX 52; these two AGN are still far less luminous. In order to detect either using the surveys’ methodology for targeting AGN, a significantly higher signal-to-noise ratio would be required. This implies that the catalogue of known IMBHs remains incomplete for faint (low mass) host galaxies.

In the next section, I will describe our attempt to locate AGN in still fainter galaxies. While we too adopt emission-line diagnostics as a strategy for identifying AGN, we begin with a fundamentally different approach in an effort to lessen the effects of luminosity biases and thus detect weaker AGN. Rather than identifying targets based on spectral characteristics, we instead construct a sample
that includes all galaxies within a particular distance limit that might host AGN. Focusing on the nearest objects allows us to detect IMBHs in the faintest, and therefore least massive, galaxies. Once this sample of all potential host galaxies has been assembled, we then go on to search for spectroscopic evidence of AGN activity. By looking specifically at nearby objects, we are able to detect AGN in the least luminous, and thereby least massive galaxies. While our sample is still not entirely complete, the issues arising from luminosity bias in previous samples are significantly decreased.

2.2 Defining a New, Less-Luminous Sample

As with the previous searches for IMBH candidates, our survey draws from the SDSS. From its seventh data release (DR7), we chose all objects with extragalactic classifications and set a rough distance limit by including only objects with heliocentric recessional velocities below 5,300 km/second. Once done, though, it was critical that these heliocentric velocities be adjusted to account for the movement of the Local Group itself. The relatively low redshift meant that we were able to correct the small deviations from the Hubble flow due to large-scale gravitational attractors by accounting for infall due to first the Virgo Cluster, and then the Great Attractor \cite{Mould2000}. Having applied these corrections, the objects’ adjusted recessional velocities can be used with the Hubble law to find physical distances to our objects. In most cases, our chosen velocity cutoff corresponds to a maximum distance of 80 Mpc. The initial sample included 13,580 objects; after first removing all blank spectra, each object was inspected in order to ensure reliable spectra. We further removed a number of spectra that had either been incorrectly classified as galaxies (generally stars) or whose red-
shifts were clearly miscalculated (quasars or more distant galaxies). This left us with a sample of 9,528 galaxies. Armed with this sample, we next utilized their photometric data from SDSS to determine masses for each galaxy (Moran et al. 2013).

Because photometry is so essential for accurately characterizing the galaxies in our sample, we have removed galaxies with very low redshifts ($z < 0.003$) and those very close to the Virgo cluster; these objects have the greatest potential for error in their distances. Absolute magnitudes and stellar masses can then be calculated as described by Moran et al. (2013). This leaves us with an ideal, distance-limited sample to search for AGN.

To search for evidence of nuclear activity in the galaxies in our sample, we obtained optical spectra of each galaxy from SDSS’s DR7 database. Two steps were required in order to analyze the possible nuclear activity of each object: first, the stellar continuum was subtracted from the raw spectrum; and second, the fluxes of important emission lines present in the residual spectrum were measured. The nuclear regions of galactic spectra are almost always dominated by starlight from the inner regions of the galaxy—the stellar continuum must be subtracted in order to carry out an accurate assessment of the spectral emission lines. Moran et al. (2013) give a complete description of this subtraction process; I will briefly summarize it here.

We used the GANDALF (Gas AND Absorption Line Fitting) algorithm as described in Sarzi et al. (2006)

\footnote{GANDALF was originally developed as a procedure for accurately measuring the stellar and emission-line contributions to the spectra observed by the Spectroscopic Areal Unit for Research on Optical Nebulae (SAURON), in order to derive the kinematics of gas and stars in early-type galaxies (Sarzi et al. 2006).} to perform starlight subtraction on our data. After masking out the locations of strong emission lines, GANDALF uses a combination...
2. Defining our Sample

of starlight templates and a power-law component to model the continuum in each spectrum. It then lifts the masks and fits the emission lines and the continuum simultaneously. This fitted continuum is then subtracted, and we can go on to use the emission line flux ratios to characterize the galactic nuclear activity (Moran et al. 2013).

Although GANDALF automatically calculates emission-line fluxes when it fits the continuum, it relies on a number of assumptions that can be problematic in certain circumstances. For example, we allowed the program to assume Gaussian profiles for the lines; for broad or non-Gaussian lines, there will be errors in the generated fluxes. To reduce these errors, we used an alternate approach as well in our emission-line measurements. After first subtracting the GANDALF fits (including emission lines) from our original spectra, we were able to visually examine the residual spectra for AGN features (or poor fits). Combining the GANDALF results with our own evaluations enabled us to construct a more complete list of AGN candidates. Finally, each of these candidates was inspected individually. For a more complete explanation of this process, see Moran et al. (2013).

2.3 A New Set of AGN in Dwarf Galaxies

Ultimately, we were able to detect 28 AGN in dwarf galaxies with $M_* < 10^{10}M_\odot$. Figures 2.1 and 2.2 show the distributions of magnitude and stellar mass for our entire sample and for the 28 dwarf galaxies in our sample. Interestingly, all but two of our 28 objects were narrow-line AGN. Previous optical surveys have indicated that while type 2s are more common than type 1s, the advantage is not nearly large enough to account for the imbalance in our sample (although with this low sample size there is some possibility that the ratio is not significant).
Figure 2.1: Distribution of magnitudes for the entire sample (black) and the sample of 28 AGN-containing dwarf galaxies (red). The histogram for AGN is inflated by a factor of 35.

Figure 2.2: Distribution of stellar masses for the entire sample (black) and for the sample of 28 AGN-containing dwarf galaxies (red). The histogram for AGN is inflated by a factor of 25.
Table 2.1: X-ray Observed Sources

<table>
<thead>
<tr>
<th>Object</th>
<th>D (Mpc)</th>
<th>z</th>
<th>Mg (mag)</th>
<th>log (M_\text{\textsc{z}})</th>
<th>log(L_{\text{[O III]}}) (erg s^{-1})</th>
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</thead>
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<td>-17.74</td>
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<td>39.12</td>
</tr>
</tbody>
</table>

Note: J1207+4307 is NGC 4117. Distances are corrected for infall. log(L_{\text{[O III]}}) is the optical luminosity of the [O III]λ5007 emission line, which is correlated with intrinsic X-ray luminosity (see Chapter 4).

Perhaps this correlation breaks down for lower-mass galaxies; it is also possible that the broad-line regions in our AGN are obscured. We have obtained X-ray spectra from *Chandra* for six of our objects, which are summarized in Table 2.1.

By allowing us to estimate absorption in our objects, these spectra will provide insight into their nuclear structures.

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3These six galaxies were chosen because they required the shortest exposure times for a robust detection.
2. Defining our Sample

Figure 2.3: Spectra and images of the seven objects in our sample (six observed with Chandra, and the serendipitously-observed NGC 4117 (J1207)). The spectra have been continuum-subtracted using GANDALF. All images are from the SDSS, and are all the same physical size: 12 kpc x 12 kpc on a side.
Chapter 3

Observing with *Chandra*

X-ray astronomy is greatly limited by the opacity of the Earth’s atmosphere at wavelengths shorter than about 300 nm, which makes ground-based observation of astronomical X-ray sources impossible (Burke & Graham-Smith 2010). The atmosphere’s absorption of X-ray radiation means that space telescopes are necessary in order to observe X-ray sources—in order to detect any of these photons, the instrument must be above “all but one millionth” of the atmosphere (Seward & Charles 2010, p. 2).

Because they are designed to detect very high-energy photons, X-ray telescopes are necessarily different from those observing longer wavelengths. The photons can easily pass through less-dense materials, so the mirrors and their housings must be fabricated from elements with high atomic numbers to ensure complete detections and protect against contamination from the harsh radiation environment in space. For this reason, optical mirrors made to reflect visible light at normal angles of incidence work poorly for X-rays, absorbing or transmitting them instead of reflecting. X-rays will, however, reflect from sufficiently smooth surfaces as long as the incidence angle at which they hit is small. The mirrors must therefore be aligned nearly parallel to the incoming X-rays. Since this angle is a critical determinant of both the resolution and high-energy cut-off after which the instrument will not reflect photons, it is important that all the incoming rays
be identically aligned.

![Cross-sectional schematic of the HRMA mirrors and associated structures](Chandra_X-ray_Center_2012)

**Figure 3.1:** Cross-sectional schematic of the HRMA mirrors and associated structures (Chandra X-ray Center 2012).

### 3.1 The *Chandra* Telescope

Our observations were taken by the *Chandra* X-ray Observatory. Orbiting the Earth on a highly elliptical path that reaches over a third of the way to the moon at its semimajor axis, *Chandra* is a NASA-operated X-ray telescope. *Chandra*’s high resolution mirror array (HRMA) consists of four nested parabolic mirrors, followed by four nested hyperboloids, which concentrate the rays onto a $\sim 1^\circ$ focal surface 10 meters away.\footnote{This kind of telescope, consisting of grazing-incidence hyperboloid and paraboloid mirrors, is called a Wolter Type-1 telescope.} The mirrors, made from Zerodur glass and coated in iridium, have incidence angles of less than 0.5 degrees, while collimators ensure that only parallel rays enter the telescope (see Figure 3.1). The grazing
angle at which the beam enters the telescope is extremely significant; because it strikes the mirror at such a small angle of incidence, the scattering effects of microscopic imperfections on the surface of the mirror are drastically compounded. *Chandra*’s high resolution\(^2\) (\(< 0.5\) arcsec), in addition to its large collecting area and sensitivity to higher-energy X-rays, allows for the detection of significantly fainter X-ray sources in more crowded fields than could be studied with previous X-ray imaging instruments.

*Chandra* contains two focal-plane science instruments—the HRC (High Resolution Camera) and the ACIS (Advanced CCD Imaging Spectrometer). The HRC is comprised of a detector with the largest field-of-view on *Chandra* (HRC-I) and a detector optimized for soft X-ray spectroscopy when coupled with the on-board low-energy transmission grating (HRC-S). ACIS, the instrument with which our observations were made, is made up of an array of CCDs, and offers the best combination of spatial resolution, energy resolution, and sensitivity on *Chandra*. For this reason, it is the workhorse instrument on the satellite.

ACIS consists of two independent chip arrays. One of these arrays is intended to provide the best possible imaging over the widest possible field (ACIS-I), while the other is optimized for spectroscopy when coupled with the on-board high energy transmission grating (ACIS-S). ACIS-I consists of four chips, arranged two by two, while ACIS-S is a linear array of six chips. Two of the CCDs on ACIS-S, S1 and S3, are back-illuminated (BI), while all the other chips are front-illuminated (FI). The chips’ illumination direction leads to different quantum efficiencies as a function of photon energy, which must be taken into account when choosing a detector for science observations ([Chandra X-ray Center 2012](https://cxc.harvard.edu)). A schematic of

\(^2\)Due to the unusual effects of scattering, the point-spread function here is not Gaussian as with an optical telescope. Instead of a full-width at half maximum, then, we refer to the half-energy width (HEW) or half-power diameter (HPD).
3. Observing with Chandra

**ACIS FLIGHT FOCAL PLANE**

![Schematic of the ACIS CCD chips. A key is given on the lower left. Aimpoints are indicated on S3 (the ‘+’) and on I3 (the ‘x’).](Chandra X-ray Center 2012)

**Figure 3.2:** Schematic of the ACIS CCD chips. A key is given on the lower left. Aimpoints are indicated on S3 (the ‘+’) and on I3 (the ‘x’). (Chandra X-ray Center 2012)
the ACIS instrument is given in Figure 3.2.

CCD pixels are defined by a gate structure on one surface of the device. Beneath the gates is a layer of silicon—this is the depletion region in which most of the absorption takes place. When an X-ray is photoelectrically absorbed by the silicon, a number of electrons are freed in proportion to the total energy of the absorbed photon. An electric field confines this charge to within a small area near the site of contact and then moves it up to the surface, where the discrete charges associated with each pixel are passed along to a readout by varying the voltages in the gates. The front-illuminated chips are oriented so that the gate structures face the incident X-ray beam. These FI chips have an inactive substrate layer below the depletion region, which is removed in the two back-illuminated chips. For these, the CCD is reversed, and the silicon is thinned so that the depletion region is exposed facing the beam. Because of this, BI CCDs are unaffected by losses due to interference by the gate structures, and are therefore more sensitive to low-energy photons than the front-illuminated chips. At the same time, though, the thinness of the BI chips means that some high-energy photons will go through the depletion region and will be lost, making them somewhat less sensitive at higher energies (Chandra X-ray Center 2012).

The efficacy of each instrument can be gauged by comparing the effective areas associated with them. The effective area of a telescope is a product of the geometric area of the primary mirror and the square of its reflectivity (to account for the two reflections; reflectivity depends strongly on photon energy as well as grazing angle), and is expressed as a function of energy. The Chandra X-ray Center (CXC) further defines effective area to encompass the effects of vignetting.

Vignetting is an effect created by photons entering at an off-axis angle. The greater the angle, the fewer of the photons entering the telescopes actually reach the focal plane, resulting in a decreasing illumination towards the edges of the chip. Vignetting is a function of energy as
as well as the quantum efficiency of the detector. The total effective area achieved with the BI chips tends to be higher than that of the FI CCDs at lower energies, although it is slightly lower at energies greater than about 7 keV (see Figure 3.3). We decided that the minimal gain in quantum efficiency beyond 7 keV with ACIS-I was not worth the loss at lower energies compared with ACIS-S—particularly considering our interest in observing the effects of absorption, which is best characterized at soft (low) energies. Since the aimpoint for ACIS-S is located on the S3 chip, and this is the only chip that is not tilted, our objects were observed with S3 (Chandra X-ray Center 2012).

One potential hazard when observing X-rays with CCDs is a loss of information due to pileup. This occurs when two or more photons arrive within a single detector region during a single readout time. Because X-ray CCDs can directly translate the number of photoelectrons collected into photon energy, the charge is interpreted as having come from a single, high-energy photon rather than two of lower energy. Pileup was a concern for us since we were particularly interested in gauging the hardness of our X-ray sources. In order to counteract this problem, we used only a 2’ by 8’ subarray of the chip for observations (this can be done by operating only one of the nodes on the chip; see Figure 3.2). Using a subarray significantly decreases the time it takes for the charge to be moved out of the detecting part of the chip, decreasing the chances of pileup (Chandra X-ray Center 2012).
3. Observing with *Chandra*

Figure 3.3: On-axis effective areas for observing a point-source (integrated over the PSF) for front-illuminated ACIS-I chips, back-illuminated ACIS-S chips, and the HRC wide-field imaging detector. The ACIS curves allow for the predicted degradation of ACIS efficiency for observing cycle 14 ([Chandra X-ray Center 2012](#)).
3. Observing with *Chandra*

3.2 Data Analysis Methods with *Chandra*

The data from our observations were processed following the standard *Chandra* ACIS data processing thread for extracting source and background spectra for pointlike sources, using the CXC’s CIAO v4.3 software. First, apertures were selected for the sources and background regions. These apertures were centered at the telescope’s pointing coordinates. The local background region was selected to be a concentric annulus, and its radius was chosen to maximize its area while avoiding including any other irregular regions that appeared to be sources. Once these regions were defined, the CIAO *specextract* command was used to extract spectra for each object. The PHA (a historical term, generally taken to designate pulse height analyzer or pulse height amplitude) files generated contain the spectrum in the form of a histogram of counts stored as an array of bins, or channels. By looking only at specific channels, this file can then be filtered to find the number of counts for the energy ranges of interest. *Specextract* generates PHA files for both source and background, along with their associated ARF (ancillary response file, which describes the effective area and quantum efficiency as a function of energy averaged over time) and RMF files (redistribution matrix file, describing the probability of a photon with a particular energy being detected by a certain channel, as a function of position on the detector).

From the PHA file for each source, I found the counts only for the channels with energies between 0.5-8.0 keV—the range over which *Chandra* is most sensitive. Excluding the channels that are outside of this range, and therefore will not contain much useful data, allows us to significantly reduce the impact of the background by removing counts that are highly likely to be noise. The corresponding files for the background regions give the number of background counts
for the same energy range. Multiplying the background counts by the ratio of the source aperture’s area to the background area then gives the expected number of background counts in the source aperture. We subtract the expected counts from the actual counts to get a background-subtracted count-rate value for each object.
### Table 3.1: Object Summary

<table>
<thead>
<tr>
<th>ID</th>
<th>D  (Mpc)</th>
<th>ACIS-S exp time (s)</th>
<th>Net Counts</th>
<th>Expected BackgroundCounts</th>
<th>S/H</th>
<th>Count Rate (10^{-4} s^{-1})</th>
<th>Detected?</th>
</tr>
</thead>
<tbody>
<tr>
<td>J0811+2328</td>
<td>67.4</td>
<td>22890</td>
<td>10</td>
<td>0.47</td>
<td>2.33</td>
<td>4.2±1.3</td>
<td>yes</td>
</tr>
<tr>
<td>J0840+1818</td>
<td>64.9</td>
<td>22850</td>
<td>2</td>
<td>1.3</td>
<td>0/2</td>
<td>&lt; 0.29</td>
<td>no</td>
</tr>
<tr>
<td>J0949+3213</td>
<td>26.2</td>
<td>9570</td>
<td>1</td>
<td>0.90</td>
<td>1/0</td>
<td>&lt; 0.20</td>
<td>no</td>
</tr>
<tr>
<td>J1005+1257</td>
<td>43.3</td>
<td>9570</td>
<td>41</td>
<td>0.18</td>
<td>2.15</td>
<td>43±6.7</td>
<td>yes</td>
</tr>
<tr>
<td>J1009+2656</td>
<td>64.1</td>
<td>9101</td>
<td>3</td>
<td>0.28</td>
<td>3/0</td>
<td>3.0±1.8</td>
<td>yes</td>
</tr>
<tr>
<td>J1151+5009</td>
<td>18.7</td>
<td>14130</td>
<td>11</td>
<td>0.31</td>
<td>2.67</td>
<td>7.6±2.3</td>
<td>yes</td>
</tr>
</tbody>
</table>

Notes: (1) The object name from SDSS. (2) Infall-corrected distance. (4) The total counts detected by the source aperture. (5) The number of background counts we expect the source aperture to receive, calculated by multiplying the counts detected within the background aperture by the ratio of the area of the source aperture to the area of the background aperture. (6) The ratio of the soft counts (0.5-2 keV) to hard counts (2-8 keV) detected. (7) The counts detected per second. Error is calculated as the square root of the counts over time.
Using the same method, I could then separately extract the soft (0.5 to 2 keV) and hard (2–8 keV) components of each spectrum. Then, I found the number of background counts that would be expected in the central aperture if no source were actually present by multiplying the background counts by the ratio of the source aperture area to that of the background aperture. Finally, I subtracted this value from the measured count number for the source to get a final number of source counts. These final counts are recorded in Table 3.1.

The expected number of background counts was also crucial for evaluating the significance of my results. It was important to ensure that the detections of my sources were statistically significant, particularly for the sources with very few counts. Because our source data did consist of so few counts, we relied on Poisson statistics in making our statistical interpretation rather than a Gaussian distribution, which is only strictly applicable in the high-count regime. To determine which detections were significant, I found the number of counts corresponding to an equivalent 3σ Gaussian deviation for each object; those objects for which the actual number of detected counts was greater than this 3σ deviation were considered significant \(^4\) (see column 9 in Table 3.1). Four galaxies did indeed meet this criterion, while two were shown to be non-significant detections (see Table 3.1).

\[^4\] The Poisson probability distribution is given by \(p(x) = \frac{e^{-\mu} \mu^x}{x!}\), where \(x\) is a discrete number of counts and \(\mu\) is the counts that we expect the source aperture to detect if no source is actually present (col. (5) in Table 3.1). The probability of getting a 3-sigma deviation by chance is 0.0027 (1 - 0.9973), so by integrating the Poisson distribution from 0 until a value > 0.9973 is obtained, we find the \(x\) value that is approximately equivalent to a 3σ deviation. This \(x\), indicating a number of counts, was then used to evaluate the significance of our detections.
demonstrate the significance of the detections.

In general, our sources had too few counts to allow us to model their spectra. Instead of using modeling to determine spectral parameters and fluxes associated with each galaxy, we turned to the PIMMS tool created by NASA’s High Energy Astrophysics Science Archive Research Center (HEASARC). PIMMS, the Portable, Interactive Multi-Mission Simulator, is an interactive program developed as a proposal planning toolkit for a range of HEASARC missions. It is freely available online as both downloadable software and through a web interface. Among its possible uses, PIMMS allows an observer to convert observed count rates to absorbed or unabsorbed fluxes, given assumed values for photon index ($\Gamma$) and the Galactic neutral hydrogen column density ($n_H$).

**Table 3.2: X-Ray Detections**

<table>
<thead>
<tr>
<th>Object</th>
<th>$n_H$</th>
<th>Flux</th>
<th>$\log(L_X)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>J0811+2328</td>
<td>4.25</td>
<td>3.23±1.05</td>
<td>39.24±0.12</td>
</tr>
<tr>
<td>J0840+1818</td>
<td>2.55</td>
<td>&lt;2.30</td>
<td>&lt;39.06</td>
</tr>
<tr>
<td>J0949+3213</td>
<td>1.55</td>
<td>&lt;4.62</td>
<td>&lt;39.58</td>
</tr>
<tr>
<td>J1005+1257</td>
<td>3.55</td>
<td>32.7±5.12</td>
<td>39.86±0.063</td>
</tr>
<tr>
<td>J1009+2656</td>
<td>2.63</td>
<td>2.25±1.37</td>
<td>39.04±0.21</td>
</tr>
<tr>
<td>J1151+5009</td>
<td>1.84</td>
<td>5.61±1.72</td>
<td>38.37±0.12</td>
</tr>
</tbody>
</table>

Notes: $n_H$ is the Galactic neutral hydrogen column density, found for each object using the HEASARC $n_H$ calculator tool. X-ray flux in the 0.5-8 keV range is calculated using the PIMMS tool, assuming $\Gamma=2$ and the calculated $n_H$. $L_X$ is the 0.5-8 keV X-ray luminosity. For the two non-detections, J0840 and J0949, upper limits for the flux and luminosities are based on count rates corresponding with the 3$\sigma$ upper limits, calculated as described in the text.

I found a Galactic $n_H$ for each object using HEASARC’s $n_H$ tool (which calculates the total Galactic H I column density for given coordinates); these were about a few $\times10^{20}$ atoms cm$^{-2}$. I used these $n_H$s along with a typical photon
3. Observing with Chandra

index for Seyfert galaxies in these conversions. Nandra & Pounds (1994) found that the mean X-ray continuum for Seyferts is best modeled by a $\Gamma \approx 2$, and this index has since become accepted as typical; we therefore assume a $\Gamma = 2$ (e.g. Peterson (1997)). From these values, PIMMS calculated an intrinsic X-ray flux. Finally, I converted the fluxes to luminosity using the infall-corrected distances determined by Moran et al. (2013) (see Table 3.2).
Chapter 4

Results and Discussion

4.1 X-ray Luminosity and Absorption

There is a well-studied relationship between the optical luminosity of the $[\text{O} \text{III}] \lambda 5007$ emission line and the intrinsic X-ray luminosity ($L_X$) for type 1 and type 2 Seyfert galaxies. Heckman et al. (2005) found that for both Seyfert 1 and 2 galaxies, this correlation holds as long as the $L_X$ of the Seyfert 2s are corrected for absorption, with only minimal uncertainty added as a result of the corrections. Because of this correspondence between the easily-observed optical $[\text{O} \text{III}]$ luminosity and the intrinsic, unabsorbed X-ray luminosity, $[\text{O} \text{III}]$ luminosities can be used to estimate the amount of absorption seen in the X-ray. Panessa et al. (2006) present a sample of quasars and Seyferts of both type 1 and type 2, showing that the correlation remains consistent over a greater luminosity range. Following this study, Thornton et al. (2009) used the sample created by Panessa et al. to test for obscuration at the centers of their sample of low-mass Seyfert 2s. Based on X-ray observations from $XMM-Newton$, they plotted their objects on the same plot as Panessa et al.’s unobscured objects, and evaluated them according to the best fit line correlating $L_{[\text{O} \text{III}]}$ and $L_X$ and the $1\sigma$ boundaries (represented by dotted lines) as calculated by Panessa et al. Objects that fell below the lower $1\sigma$ limit, then, were taken to be absorbed (see Fig. 4.1).
4. Results and Discussion

Figure 4.1: Plot of $L_{\text{[O III]}}$ vs. $L_{2-10\text{keV}}$. Our sample is denoted by red filled circles. NGC 4117’s intrinsic luminosity was found by modeling its spectra with XSPEC; the lower limit indicates the absorbed luminosity. For the two nondetected objects, J0840 and J0949, we plot upper limits based on the count rate necessary for a 3σ detection. The Seyfert 2s from Thornton et al. (2009) are plotted with orange asterisks. Filled black squares indicate the Panessa et al. (2006) sample of X-ray absorption-corrected quasars, Seyfert 1s, and Seyfert 2s. Open symbols represent NGC 4395 (green circle), POX 52 (green triangle), and low-mass Seyfert 1s (blue squares). The solid line indicates the least-squares fit of the Panessa et al. sample, and the two dotted lines represent the 1σ scatter from Panessa et al. (2006).
Following the example set by Thornton et al. (2009), we test for absorption by plotting the \( L_X \) vs \( L_{\text{[O III]}} \) for each of our objects over the plot made by Panessa et al. and added to by Thornton et al. (hereafter referred to as Panessa and Thornton). Because the Panessa and Thornton samples reported X-ray luminosities for the 2-10 keV range, we needed to recalculate our objects’ luminosities for this range before the samples could be compared. To do this, I again used PIMMS to find fluxes for each of our objects, using the same \( \Gamma = 2 \) and values for \( n_{\text{H}} \) as before. This time, however, I wanted to find an output flux of 2-10 keV instead of the original 0.5-8 keV. Because our objects were so soft, with the majority of counts in the 0.5-2 keV range, we worried that including these soft counts would lead to an inaccurate conversion to the harder 2-10 keV range. For this reason, I used only the count rate associated with the 2-8 keV subsection of our known range to input into PIMMS. The 2-10 keV flux calculated when the soft counts were excluded (i.e. using an input count rate for 2-8 keV) was indeed slightly higher than that found by inputting the count rate for the entire 0.5-8 keV range. Not only was the second calculation less problematic, but because it gives a somewhat higher luminosity it is the better choice for proving the presence of absorption.

This conversion was not possible for all the galaxies; for two of the objects no counts were detected above 2 keV at all, so for these we used PIMMS to convert directly from the 0.5-8 keV count rate to a 2-10 keV flux. We also considered the effects of using a much higher photon index (\( \Gamma \approx 4 \)) in these direct conversions, but this yielded lower luminosities than for the standard \( \Gamma = 2 \) and we wanted to use the method that gave us the highest luminosity. Due to the standard power-law model used by PIMMS to calculate these fluxes, the 2-10 keV luminosities are lower than those found for the 0.5-8 keV range by a factor of 0.58. As be-
fore, the infall-corrected distances were used to calculate each detected object’s unabsorbed luminosity from the measured flux. The [O III] luminosities for the detected objects are given in Table 2.1. Fig. 4.1 shows our five objects plotted over the Panessa and Thornton samples.

In comparing our objects with those plotted by Panessa et al., all but one reside significantly below the lower 1σ line. NGC 4117 stands out by actually falling well above the best-fit line, almost reaching the 1σ line—we will reserve our discussion of NGC 4117 for the next section. For all of the objects observed with Chandra, though, their locations relative to the unabsorbed galaxies on the diagram clearly demonstrate absorption. Three of the objects—J0811, J1005, and J1151— are about evenly displaced below the lower 1σ line, indicating that even though the galaxies may be absorbed, the correlation between $L_X$ and $L_{[\text{O III}]}$ does not completely disappear. Since [O III] emission lines arise from X-ray flux, it is entirely logical that this relationship should remain despite the obscuration. The Seyfert 2 galaxies from Thornton et al. (2009), represented by orange asterisks, seem to behave similarly to our objects as well. J1009 is the outlier, with apparently not only more associated absorption than the other galaxies in our sample, but perhaps even the greatest displacement from the best-fit line of any galaxy on the plot. Of our seven objects, J1009 has both the lowest stellar mass and the faintest magnitude (see Table 2.1); it is also quite distant at 64.11 Mpc. Its location on the plot strongly implies that as AGN-containing galaxies become fainter, they are indeed becoming increasingly more absorbed.
4. Results and Discussion

4.2 NGC 4117

We were able to obtain X-ray spectra for a seventh object, NGC 4117, serendipitously detected by ASCA during an unrelated observation. ASCA, the Advanced Satellite for Cosmology and Astrophysics, is a Japanese X-ray satellite carrying four identical X-ray telescopes. Launched in 1993, ASCA was the first mission to use CCDs for X-ray astronomy and was jointly available to observers in Japan and the United States until 2000, when a geomagnetic storm caused a malfunction in altitude control and brought scientific operations to a halt. While Chandra used nested Wolter Type-1 telescopes, ASCA’s mirrors were conical, and constructed of light foil. Designed for their flexibility and lightness, these mirrors still give a fair approximation to the Wolter design. NGC 4117 was observed with ASCA’s Gas Imaging Spectrometer (GIS), a proportional counter that used a gas cell of xenon and helium to detect X-ray photons. Although the angular resolution that ASCA could achieve was significantly lower than that of Chandra (2.9 arcmin HPD), its four telescopes allowed it a large effective area and field of view for its time.

NGC 4117 was the only object in our sample with enough counts for spectral fitting, and we hoped that by modeling its spectrum we would be able to confirm the absorption implied by the Panessa plot in the previous section. As described in Chapter 1, a dense obscuring region surrounding the central AGN source would presumably obscure the broad line regions as well. Such a material would heavily absorb softer X-ray fluxes; therefore, evidence of heavy absorption in the soft X-ray band of Seyfert 2s ($n_H \sim 10^{23} - 10^{24}$ cm$^{-2}$) would support the existence of an opaque torus blocking the high-energy continuum emission and broad-line region.

1Angular resolution for X-ray telescopes is expressed in half power diameter (HPD), the diameter in which half of the focused X-ray is contained (see section 3.1).
of the AGN from our view (Cardamone et al. 2007).

![Figure 4.2](image)

**Figure 4.2:** Spectrum of NGC 4117 modeled as the sum of two absorbed power laws, with Galactic absorption $n_H = 1.3 \times 10^{20}$ cm$^{-2}$, $\Gamma=1.7$, and a strong second absorption component $n_H = 39 \times 10^{23}$ cm$^{-2}$.

We analyzed NGC 4117’s spectrum using XSPEC. First, we tried fitting a simple absorbed power law. Beginning with a typical Seyfert photon index of 2 and an absorption column density $n_H = 1.3 \times 10^{20}$ cm$^{-2}$ (the Galactic absorption in the direction of NGC 4117), we first allowed both the photon index and the absorption to vary freely (Cardamone et al. 2007). This gave a very poor fit, producing a model with an unrealistic $\Gamma=-0.6$ and very low column density. While this first model fit the very hard end of the spectrum well, it completely discounted the rise on the low-energy end. This makes the fit particularly problematic, as the
soft component is often interpreted as arising from scattered emission from the central regions of the nucleus. While material in our line of sight may obscure the central source, a medium lying above the black hole may interact with the AGN continuum coming through the hole in the torus, scattering it back towards the observer (George & Fabian 1991). As proposed by Antonucci & Miller (1985), the presence of such a medium would allow us to see evidence of the broad line region even in heavily absorbed type 2 AGN. Although the low-energy component of the spectrum could also arise fully or partially from other sources in the host galaxy, such as binaries, diffuse hot gas, or supernova remnants, we model it here as though it is primarily representative of this scattered emission (Cardamone et al. 2007; Thornton et al. 2009).

Next, we added a second absorbed power-law component to our model, as it was clear that a single power law would not give us a good fit. By combining two components, we were able to account for both the hard and soft ends of our spectra without discounting either the large dip in energy around 3 keV or the low-energy peak (see Figures 4.2 and 4.3). For this model, we froze the Galactic column density at its known value and initialized the second absorbing column density at $5 \times 10^{23}$ cm$^{-2}$. The $\Gamma$s were tied together, based on the assumption that the soft component comes from scattering of the AGN continuum emission, but were allowed to vary as an identical pair. This model resulted in a fit with a reduced $\chi^2=0.535$ for 31 degrees of freedom, for which $\Gamma=1.36$ and the absorbing column density added for this fit was $n_H = 39 \times 10^{23}$ cm$^{-2}$. This value of $n_H$, significantly above the galactic value, strongly implies that NGC 4117 is indeed heavily absorbed.

Although our model is somewhat simple in deference to the low resolution of our data, this kind of multi-component power law, combining a weak and a
strong absorption, has been used to model luminous Seyfert 2 galaxies as well (e.g. Cardamone et al. (2007)). Such similarities between Seyfert 2s at both low and high luminosities may indicate a shared intrinsic structure that does not significantly change for low-mass galaxies.

Fig. 4.2 shows the data with the folded model (this refers to the model after it has been “folded” through the instrument’s response, making it possible to compare them statistically). The residuals for our model are plotted as well. In Fig. 4.3 the unfolded spectrum is plotted, as is our model (indicated by the dotted line). Although this plot does not have the statistical significance of the folded spectrum, it reveals how essential the inclusion of a second, strong absorption

\[
\text{Photons cm}^{-2} \text{s}^{-1} \text{keV}^{-1}
\]

\[
10^{-7} \quad 10^{-6} \quad 2 \times 10^{-6} \quad 5 \times 10^{-6}
\]

\[
\text{Energy (keV)}
\]

Figure 4.3: The unfolded model fit to our data for NGC 4117. The dotted line indicates the model. We can see that the two-component model gives a much better fit than would a single power law.
4. Results and Discussion

Figure 4.4: $\chi^2$ contour plot for $\Gamma$ vs. $n_H$. Each contour line indicates a confidence level: the black line denotes 68% confidence, the red 90%, and the green 99%.

component was for getting a good fit.

To demonstrate the significance of this finding, we plot the $\chi^2$ values on a contour plot (Fig. 4.4) showing the confidence levels for $\Gamma$ and absorbing $n_H$. Although $\Gamma$ is not particularly well-constrained, we see that a range of $\sim 1 < \Gamma < 2$ is within the 90% confidence contour. More significant, however, are the implications for $n_H$: within a 99% confidence interval, $n_H$ lies between about $2 \times 10^{23}$ and $6.5 \times 10^{23}$ cm$^{-2}$. At the central contour line, marking a 68% confidence, $n_H$ is even more tightly constrained on this order of magnitude—given column densities this high, we can be quite confident that some of the emission from the AGN’s central
regions is being obscured.

### 4.3 Implications and Conclusions

Intermediate mass black holes represent a compelling opportunity to probe further back into the history and coevolution of supermassive black holes and their host galaxies. While correlations between black hole mass and various properties of the galactic bulge have been well established, models for exactly how these processes occurred are still poorly constrained. Although surveys of low-mass galaxies are handicapped by their low luminosities, recent years have seen more and more AGN identified in dwarf galaxies. Observing less massive galaxies allows us to look back down the evolutionary chain simply by looking down the mass scale; by inference, if certain relationships break down at low masses, it may indicate certain evolutionary constraints.

Through a survey for AGN in the local universe, we have identified a sample of 28 of the least luminous known active galaxies. Six of these were observed with the Chandra X-ray Observatory, and another was fortuitously observed by ASCA. Interestingly, all but two of our 28 objects, and all of those observed in X-ray, were Seyfert 2s. This was surprising considering that for luminous Seyferts, type 1s have been observed at least twice as frequently as type 2s. Further, the unification model for AGN posits that the only differences between the different varieties of Seyferts arise from the obscuring effects of an opaque torus at certain inclinations. Indeed, our findings strongly support this model; by comparing the X-ray luminosities of our target galaxies to their optical [O III] luminosities, we see clear signs of absorption. Despite its deviation from the others on the Panessa plot in Fig. 4.1, spectral modeling clearly shows absorption in NCG 4117 as well.
As discussed in section 4.1, such an unusually large X-ray luminosity to $L_{\text{[O} \text{III}]\lambda 5007}$ ratio may be anomalous, but it is not illogical considering the dependence of the [O III]λ5007 line on the X-ray continuum radiation. However, if our findings do strongly support the unification model, it remains unclear why such a large fraction of our sample is type 2.

Yet, the fact that the unification model seems to hold for these low-luminosity objects gives us new information about the internal mechanisms driving AGN. The evidence that our targets are heavily absorbed, as well as the estimates made of their large associated column densities, can now be used to limit the role of luminosity in modeling their internal structures. As future studies continue to search for AGN at the most extreme ends of the mass and luminosity scales, the continuation or breakdown of these established relationships will move us forward in our understanding of their structures, histories, and origins.
Bibliography


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