SUPERMASSIVE BLACK HOLES IN BULGELESS AND DWARF GALAXIES:
A MULTI-WAVELENGTH INVESTIGATION

by
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A Dissertation
Submitted to the
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In Partial fulfillment of
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Doctor of Philosophy
Physics

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Fall 2014
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Supermassive Black Holes in Bulgeless and Dwarf Galaxies: A Multi-Wavelength Investigation

A dissertation submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy at George Mason University

By

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Dedication

_to my father, who showed me the value of self reliance_
_to my mother, who always knew_
_to my brother, in whom I see the wisdom of an open heart_
_to all of those who yet call into the Void, expecting no reply_
I am deeply indebted to my PhD advisor, Shobita Satyapal, for her invaluable help and guidance in my thesis work. Her kindness and intelligence have made working with her an absolute privilege, and over the years she has not only been a colleague but also a close friend. I know we will continue to collaborate with each other for years to come.

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Abstract

SUPERMASSIVE BLACK HOLES IN BULGELESS AND DWARF GALAXIES: A MULTI-WAVELENGTH INVESTIGATION

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George Mason University, 2014
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Supermassive black holes (SMBHs) are now understood to reside at the centers of nearly all major galaxies in the Universe. From studies of high-redshift quasars, we understand that SMBHs formed very early in the Universe's history, and well-studied correlations between other properties of galaxies, such as their morphologies, star formation rate, and merger history, with their central SMBH shows that SMBHs played a key role in the evolution of galaxies. The fact that the post-Big Bang Universe was extremely uniform and homogeneous presents a major mystery: How did SMBHs millions to billions of times as massive as the Sun form in such a short time? Given the theoretical limit at which a black hole can accrete material, it is not plausible that SMBHs could have formed through the conventional route: the end stage of the lifecycle of a massive star. Rather, there are two major theories for the formation of SMBHs, each with its own prediction for the black hole mass distribution and occupation fraction in the local Universe. Understanding this mass distribution and occupation fraction is therefore imperative to understanding the formation of SMBHs, the quasars that reveal their presence in the early Universe, and ultimately the evolution of galaxies to the present day. While large SMBHs in major, bulge-dominated galaxies are relatively easy to detect and characterize, this population of SMBHs is understood to have
been built up largely through black hole merger events that erase any information about the progenitor black holes’ masses. We must therefore search for SMBHs in late-type, bulgeless, and dwarf galaxies, which are much more likely to have had a relatively quiet, merger-free history, in order to glimpse the properties of the ‘seed’ black holes that led to the buildup of SMBHs during the earliest epoch of the Universe. In this thesis, I will discuss my contributions to the understanding of this question, as well as what questions remain to be answered and the future of research in this field.
Introduction

We now know that supermassive black holes (SMBHs) one million to a few billion times the mass of the sun lurk in the centers of possibly all bulge-dominated galaxies in the local Universe and that their mass $M_{\text{BH}}$ is strongly correlated with the stellar velocity dispersion, $\sigma_*$ of the host bulge (e.g., Ferrarese & Merritt, 2000, Gebhardt et al., 2000, Haehnelt & Kauffmann, 2002). Observations of SMBHs in major, bulge-dominated galaxies have revealed that the evolution of galaxies and their central black holes are fundamentally linked, a finding that can be understood if the galaxy mergers that induce bulge growth simultaneously feed the central SMBHs, as well as if ‘feedback’ from such feeding SMBHs (active galactic nuclei or AGNs) regulates the amount of gas available for nearby star formation (e.g., Fabian, 2012).

While the SMBH and host galaxy properties in the high bulge mass regime have been studied extensively, very little is known about the existence and properties of SMBHs in galaxies with low masses and those with small bulges (for example, see Figure 1 from McConnell & Ma, 2013). This is a significant deficiency because classical bulges are thought to form through mergers (for a review, see Kormendy & Bender, 2012), and so the study of this population allows us to gain an understanding of merger-free pathways to black hole growth. Furthermore, the occupation fraction and properties of SMBHs in galaxies with low masses and in those with no evidence for a bulge provide one of the only observational constraints on the origin and growth efficiency of SMBH seeds, thought to have formed at high redshift (e.g., Volonteri, 2010). Since SMBHs in massive bulge-dominated galaxies have undergone significant accretion through multiple dynamical interactions over cosmic history, any information on the seed population has been lost. In contrast, galaxies that lack
classical bulges have undergone a more secular evolution and therefore the mass distribution and occupation fraction of SMBHs in these galaxies may contain information about the original seed population, allowing us to discriminate between lower mass seeds formed from stellar remnants or massive seeds formed directly out of dense gas (e.g., van Wassenhove et al., 2010). The study of black holes at the low bulge mass regime is therefore crucial to our understanding of both the origin of SMBHs and their growth and connection to galaxy evolution.

Unfortunately, finding and studying the properties of SMBHs in a significant sample of galaxies with low bulge mass is challenging since the black hole mass is expected to be small and therefore impossible to discover dynamically except in the few nearest galaxies. A significant sample of SMBHs in low mass hosts can therefore only be detected if they are accreting. On the basis of optical spectroscopic observations, AGNs are found almost exclusively in massive bulge-dominated hosts, with the fraction of emission line galaxies identified as AGNs dropping steeply below stellar masses of about log(M/M⊙)< 10 (e.g., Kauffmann et al., 2003). Until recently, the only known case of a bulgeless disk galaxy (Hubble type Sd) with an accreting black hole was the well-studied galaxy NGC 4395, which displays a classical Seyfert 1 optical spectrum (Filippenko & Ho, 2003), and was the only late type, bulgeless galaxy identified as a Seyfert from the Palomar optical spectroscopic survey of 486 nearby galaxies (Ho, Filippenko, & Sargent, 1997). Despite the recent advent of the vast amount of optical spectroscopic data available from the Sloan Digital Sky Survey, there still exist only small samples of AGNs discovered by optical surveys in small-bulge galaxies and only a handful with no evidence for any bulge (e.g., Barth et al., 2004, Filippenko & Ho, 2003, Greene & Ho, 2007, Jiang et al., 2011b).

One explanation for the deficit of optically-identified AGNs at low galaxy masses is that, by extrapolating down the M_{BH}-σ relation, a putative nuclear black hole in a galaxy with a minimal bulge is predicted to be small and therefore energetically weak. Also, dusty, late-type star forming galaxies are more likely to host an obscured AGN (e.g., Goulding & Alexander, 2009), and so optical surveys may fail to detect many if not most AGNs.
in this population. These considerations leave open the possibility that there is a hidden population of AGNs in bulgeless and low-mass galaxies, and so a multi-wavelength approach is required to detect them. Because of their high penetrating power, infrared and X-ray observations are ideal probes of possible buried AGN cores. Indeed, recent mid-infrared spectroscopic and X-ray studies aimed at searching for AGNs in small samples of galaxies in the low bulge mass regime suggest that the AGN detection rate in this population is considerably higher than optical studies indicate (Araya Salvo et al., 2012, Desroches & Ho, 2009, Dewangan et al., 2005, Ghosh et al., 2008, Gliozzi et al., 2009, McAlpine et al., 2011, Reines & Deller, 2012, Reines et al., 2013, 2014, 2011, Satyapal et al., 2009, 2014, 2008, 2007, Secrest et al., 2012, 2013, 2014, Shields et al., 2008).

Despite the fact that these studies have been carried out on very small galaxy samples and that there are still only a small number of very low mass or purely bulgeless galaxies with evidence for SMBHs known in the Universe, there are already some interesting correlations, such as the finding that several of the nearby bulgeless disk galaxies with high spatial resolution observations show evidence for prominent nuclear star clusters (NSCs), suggesting an association of SMBHs and NSCs in the complete absence of a bulge (Satyapal et al., 2009). This may not hold true for dwarf galaxies, however, as the dwarf galaxy He 2-10 shows no evidence of a NSC but shows a clear signature of a SMBH as well as clear signs of a recent interaction (Reines et al., 2011). With only a handful of AGN-hosting bulgeless galaxies, and only a few dozen dwarf galaxies with signs of AGN activity, we are not yet equipped to answer statistical questions about this population, such as what fraction of these galaxies hosts AGNs (and relatedly, what the real occupation fraction of SMBHs in these galaxies is), or why a population of galaxies believed to have undergone a mostly secular (merger-free) history should host AGNs while some should not.

In this thesis, I describe our investigations into the presence and characteristics of AGNs in bulgeless and dwarf galaxies using a multi-wavelength approach. This work constitutes a significant contribution to the population of confirmed AGNs in this population of galaxies, which therefore moves this field closer to a statistical understanding of these systems.
Chapters 1 and 2 detail our efforts at characterizing the SMBH in NGC 4178, a late-type, bulgeless disk galaxy we first discovered to produce [Ne V] mid-infrared emission lines, a hallmark of an accreting AGN. Through a detailed Chandra X-ray/VLA radio study, followed by a dynamical as well as spectroscopic Gemini study, we were able to narrow down the mass and the location of the SMBH in NGC 4178 very accurately, revealing possibly the lowest mass SMBH currently known to reside in a bulgeless disk galaxy. In Chapter 3, we describe our X-ray confirmation of a mid-IR AGN in the dwarf galaxy, J1329+3234. This galaxy, despite having no evidence for extreme star formation, is nonetheless bright in the mid-IR, and has a hard X-ray source with properties that confirm the presence of an AGN. J1329+3234 is also one of the lowest mass dwarf galaxies with evidence for an AGN known, with a stellar mass of $M_\star \sim 2.0 \times 10^8 M_\odot$. Finally, in Chapter 4 I detail near-term projects that form a natural continuation of this work.
Chapter 1: The *Chandra* View of NGC 4178: The Lowest Mass Black Hole in a Bulgeless Disk Galaxy?

1.1 Abstract

Using high resolution *Chandra* data, we report the presence of a weak X-ray point source coincident with the nucleus of NGC 4178, a late-type bulgeless disk galaxy known to have high ionization mid-infrared (mid-IR) lines typically associated with active galactic nuclei (AGNs). Although the faintness of this source precludes a direct spectral analysis, we are able to infer its basic spectral properties using hardness ratios. X-ray modeling, combined with the nuclear mid-IR characteristics, suggests that NGC 4178 may host a highly absorbed AGN accreting at a high rate with a bolometric luminosity on order of $10^{43} \text{ ergs s}^{-1}$. The black hole mass estimate, based on our *Chandra* data and archival VLA data using the most recent fundamental plane relations is $\sim 10^4 - 10^5 \, M_\odot$, possibly the lowest mass nuclear black hole currently known. There are also three off-nuclear sources, two with a similar brightness to the nuclear source at 36" and 32" from the center. As with the nuclear source, hardness ratios are used to estimate spectra for these two sources, and both are consistent with a simple power-law model with absorption. These two sources have X-ray luminosities of the order of $\sim 10^{38} \, \text{ergs s}^{-1}$, which place them at the threshold between X-ray binaries and ultra-luminous X-ray sources (ULXs). The third off-nuclear source, located 49" from the center, is the brightest source detected, with an X-ray luminosity of $\sim 10^{40} \, \text{ergs s}^{-1}$. Its spectrum is well-fit with an absorbed power law model, suggesting that it is a ULX. We also fit its spectrum with the Bulk Motion Comptonization (BMC) model and suggest that this source is consistent with an intermediate-mass black hole (IMBH) of mass $(6 \pm 2) \times 10^3 \, M_\odot$. 
1.2 Introduction

There is mounting evidence that a significant fraction of supermassive black holes (SMBHs) reside in late-type galaxies, and that a classical bulge is not a requirement for a SMBH to form and grow (Barth et al., 2004, 2009, Desroches & Ho, 2009, Dewangan et al., 2008, Filippenko & Ho, 2003, Ghosh et al., 2008, Gliozzi et al., 2009, Greene & Ho, 2004, 2007, Jiang et al., 2011a,b, Mathur et al., 2008, McAlpine et al., 2011, Satyapal et al., 2009, 2008, 2007, Shields et al., 2008). In most late-type galaxies that host an AGN, however, the galaxies have a pseudobulge component, characterized by an exponential surface brightness profile. And while classical bulges are believed to form through mergers, pseudobulges are thought to form through secular processes (Kormendy & Kennicutt, 2004). Of the late-type, AGN-hosting galaxies, bulgeless (no evidence even for a pseudobulge) galaxies are by far the rarest. To date, there are only three such bulgeless disk galaxies that are confirmed to host SMBHs: NGC 4395 (Filippenko & Ho, 2003, Peterson et al., 2005, Shih et al., 2003), NGC 1042 (Shields et al., 2008), and NGC 3621 (Barth et al., 2009, Gliozzi et al., 2009, Satyapal et al., 2009, 2007). While very large SMBHs ($\gtrsim 10^6 M_\odot$) likely form through galaxy mergers (e.g., Kauffmann & Haehnelt, 2000), leading to a tight correlation between the black hole mass, $M_{BH}$, and the host galaxy’s bulge velocity dispersion $\sigma$ (e.g., Ferrarese & Merritt, 2000, Gebhardt et al., 2000, Haehnelt & Kauffmann, 2002), it is still unclear how SMBHs form and grow in bulgeless galaxies. Central to this question is how SMBHs affect, or are affected by, their host galaxy properties. It has already been shown that the presence and properties of SMBHs do not correlate with galaxy disks or pseudobulges (e.g., Kormendy et al., 2011). Interestingly, however, all three bulgeless disk galaxies with SMBHs have nuclear star clusters (NSCs), and there is growing evidence that suggests that the mass of SMBHs and NSCs may be correlated in galaxies that possess both (e.g., Graham & Spitler, 2009, Seth et al., 2008).

Given their rarity, determining the properties of SMBHs in bulgeless disk galaxies is crucial to our understanding of the low end of the SMBH mass function and its relation to host
galaxies. Observationally, the only viable method for finding SMBHs in bulgeless galaxies is through the search for AGNs. Since bulgeless galaxies are typically dusty, star-forming galaxies, a putative AGN is likely to be missed by optical surveys. X-ray observations are the ideal tool to search for AGNs in such galaxies since X-rays are generally only produced in the inner nuclear regions of an AGN, and hard X-rays are not substantially affected by absorption.

The goal of this paper is to investigate the X-ray properties of the putative SMBH that lurks at the center of NGC 4178, a bulgeless disk galaxy that was recently found to have prominent mid-IR [NeV] emission associated with the nucleus (Satyapal et al., 2009). While the [NeV] emission strongly suggests the presence of an AGN, the size of the Spitzer InfraRed Spectrograph (IRS) slit (4.7" × 11.3", at 14.3 μm) precludes us from confirming the nuclear origin of the emission. Thus, the presence of a significant X-ray point source counterpart in high-resolution Chandra data would provide a confirmation of a nuclear SMBH, as X-ray emission associated with starburst activity is generally extended (e.g., Dudik et al., 2005, Flohic et al., 2006, González-Martín et al., 2006). If it does have a SMBH, NGC 4178 will be only the fourth known truly bulgeless disk galaxy with a SMBH.

NGC 4178 is a highly-inclined (i ~ 70°), SB(rs)dm galaxy (de Vaucouleurs et al., 1991) located within the Virgo Cluster at a distance of 16.8 Mpc (Tully & Shaya, 1984). Based on its nuclear optical spectrum, it is classified as having an HII nucleus (Ho, Filippenko, & Sargent, 1997), and contains an NSC of ~ 5 × 10⁵ M⊙ (Böker et al., 1999, Satyapal et al., 2009). Other than some asymmetric, locally enhanced Hα emission near the outer parts of the disk, the Hα distribution of NGC 4178 is typical of that found in star-forming galaxies (Koopmann & Kenney, 2004). The HI distribution is more extended than the optical part of the galaxy and shows no evidence of interactions (Cayatte et al., 1990). Apart from our previous Spitzer observations, there is no evidence for an AGN in this galaxy. With these considerations, the presence of a SMBH in this galaxy is highly unexpected.

This paper is structured as follows. In §2, we describe the Chandra observations and data reduction, as well as archival VLA data. We follow with a description of our results,
including X-ray spectral modeling in §3. In §4, we discuss constraints on the nuclear black hole using the bolometric luminosity by presenting an updated $L_{\text{bol}}/L_{\text{[NeV]}}$ correlation. We compute the Eddington mass and compare our findings with mass estimates from other methods. In §5, we compare our results to other bulgeless disk galaxies and give a summary and our main conclusions in §6.

1.3 Observations and Data Reduction

1.3.1 Chandra Data

We observed NGC 4178 with Chandra ACIS-S for 36 ks on 2011 February 19. The data were processed using CIAO v. 4.3 and we retained only events in the energy range 0.2 – 10 keV. We also checked that no background flaring events occurred during the observation.

We used the XSPEC v. 12.7.0 software package (Arnaud, 1996, Dorman & Arnaud, 2001) for the spectral analysis. For the bright off-nuclear source, we re-binned the spectrum in order to contain at least 15 counts per channel in order to use the $\chi^2$ statistic. To compute the error (90% confidence) on the flux, we used the \texttt{cflux} model component available in XSPEC as a means to estimate fluxes and errors due to model components (Arnaud et al., 2012). For the other sources where low counts ($\lesssim$ 50 counts) prevented a direct spectral fit, we employed X-ray hardness ratios as a rough estimator of spectral state. The hardness ratio we use is defined as:

$$\frac{\text{hard}}{\text{soft}} \equiv \frac{\text{counts}[2-10\text{ keV}]}{\text{counts}[0.2-2\text{ keV}]}$$

1.3.2 Archival VLA data

To search for and constrain the level of radio emission from the detected Chandra X-ray sources in NGC 4178, we utilized archival Very Large Array (VLA)\footnote{The National Radio Astronomy Observatory is operated by Associated Universities, Inc. under a cooperative agreement with the National Science Foundation (NSF).} data. The highest angular resolution VLA dataset available was a 560 sec snapshot obtained in B-array at 4.9
GHz (\(\sim 1.5''\) beam; program AS314) on Feb 1, 1988, and published by Saikia et al. (1994). We used AIPS to calibrate and edit the data using standard procedures. A final image with beam dimensions 1.95'' \(\times\) 1.36'' (position angle = \(-12.5^\circ\)) was produced with the IMAGR task using natural weighting (ROBUST weighting = 2) and 1000 CLEAN iterations.

All coordinates listed in this paper refer to the J2000 epoch.

### 1.4 Results

As can be seen in Figure 1.1, Chandra clearly detects a nuclear X-ray source (source A), which appears to be situated symmetrically between two nearly mirrored infrared lobes and is located at RA=12\(^{\mathrm{h}}\)12\(^{\mathrm{m}}\)46.32, DEC=10\(^{\circ}\)51'54''.61. Centroid analysis reveals that the infrared lobes are at the same distance from the nuclear source, about 7.8'', corresponding to a distance of 1.3 kpc at the distance of NGC 4178. These infrared lobes are likely associated with star formation regions, known from H\(\alpha\) studies to be associated with, and confined to, the bar (e.g., Martin & Kennicutt, 2001). This is supported by the presence of Pa-\(\alpha\) emission coincident with these lobes (Figure 1.2). Two weaker off-nuclear sources (B and C) are located at RA=12\(^{\mathrm{h}}\)12\(^{\mathrm{m}}\)47.33, DEC=10\(^{\circ}\)52'22''.52 32'' and RA=12\(^{\mathrm{h}}\)12\(^{\mathrm{m}}\)48.47, DEC=10\(^{\circ}\)52'11''.03, 35.7'' (5.2 kpc) and 36'' (5.9 kpc) from the nuclear source, respectively. A third, brighter off-nuclear source (D) is located at RA=12\(^{\mathrm{h}}\)12\(^{\mathrm{m}}\)44.51, DEC= 10\(^{\circ}\)51'13''.64, 49'' (8 kpc) from the nuclear source. Only one of the off-nuclear sources, source C, appears to have a counterpart in any other band.

In order to determine if the nuclear X-ray source is consistent with the photocenter of the galaxy, the source coordinates were compared to the 2MASS photocenter. The 2MASS photocenter was found to be at RA=12\(^{\mathrm{h}}\)12\(^{\mathrm{m}}\)46.34, DEC= 10\(^{\circ}\)51'55''.1, 0.6'' \(\pm\) 0.6'' off from the X-ray source coordinates. Thus, we conclude that the nuclear X-ray source is coincident with the 2MASS photocenter, within the astrometric uncertainties. After spatially registering the HST H-band image with the 2MASS H-band image, we find that
the Chandra source is coincident with the NSC (Figure 1.2).

1.4.1 The Nuclear Source

The nuclear X-ray source is shown in Figure 1.3. We detect $37 \pm 7$ (5.3 $\sigma$) X-ray counts (0.2–10 keV) from the source. The nuclear source is strikingly soft, with $31 \pm 6$ counts in the 0.2–2 keV band and $5 \pm 2$ counts in the 2–10 keV band (for low counts, Poisson statistics are used to calculate the uncertainty, as described in the approach of Gehrels (1986), where the error corresponds to the 84.13% confidence limit), yielding a hardness ratio of $0.16^{+0.12}_{-0.08}$. Using a simplified phenomenological power law (PL) model with a Galactic absorption of $1.91 \times 10^{20}$ cm$^{-2}$ (Dickey & Lockman, 1990, Chandra Colden tool), and adopting the global intrinsic absorption for NGC 4178 of $N_H \approx 10^{21}$ cm$^{-2}$ (Cayatte et al., 1994), the observed hardness ratio can be replicated with a photon index $\Gamma = 2.6^{+0.6}_{-0.5}$. Using these parameters, this model predicts an X-ray luminosity of $L_{0.2-10}$ keV $= 4.6^{+3.6}_{-1.4} \times 10^{38}$ ergs s$^{-1}$, and a hard
Figure 1.2: Left: HST NICMOS-3 $H$-band image of NGC 4178 overlaid with the \textit{Chandra} nuclear X-ray extraction region in white and the \textit{Spitzer} 3.6 \(\mu m\) infrared lobes outlined in green. Right: HST Pa-\(\alpha\) image with the same regions. The NSC is marked with an arrow in the \textit{H}-band image.
X-ray luminosity is \( L_{2-10 \text{ keV}} = 7.9^{+9.1}_{-4.9} \times 10^{38} \text{ ergs s}^{-1} \), significantly lower than that implied by the observed [NeV] luminosity.\(^2\) Indeed, the bolometric luminosity inferred by the [NeV] luminosity is \( \sim 10^{43} \text{ ergs s}^{-1} \) (see §1.5.1), 5 orders of magnitude higher than the hard X-ray luminosity predicted by this simplified phenomenological PL model. The bolometric correction factor is \( \kappa_{2-10 \text{ keV}} \sim 10^5 \), much too high for any realistic AGN spectral energy distribution (SED) (Vasudevan & Fabian, 2009).\(^3\)

We therefore postulate that there is highly localized absorption around the central source. Indeed, analysis of data from Chandra Deep Field North has shown that more complex spectra are characteristic of AGNs in local galaxies due to the ubiquity of heavy absorption, and a simple PL cannot reliably be estimated from hardness ratios (Brightman & Nandra, 2012). With a covering fraction of 0.99 and absorption \( N_H = 5 \times 10^{24} \text{ cm}^{-2} \), a partially-absorbed scenario combined with a simple PL can account for the hardness ratio with \( \Gamma = 2.3^{+0.6}_{-0.5} \). With these parameters, the intrinsic X-ray luminosity is \( L_{0.2-10 \text{ keV}} = 3.1^{+1.5}_{-0.5} \times 10^{40} \text{ ergs s}^{-1} \) and the hard X-ray luminosity is \( L_{2-10 \text{ keV}} = 8.6^{+10.4}_{-5.5} \times 10^{39} \text{ ergs s}^{-1} \). The partially-absorbed scenario can be physically interpreted as a strongly-accreting black hole imbedded in a heavy medium in which a few holes have been "punched out" by strong X-ray flux. This is in line with our understanding of black hole accretion, our understanding of the interstellar environment of late-type spiral galaxies, and it is consistent with the bolometric luminosity.

We point out that the observed X-ray luminosity is low, and therefore by itself we cannot exclude the possibility that it is produced by X-ray binaries in the nuclear star cluster. However, the [NeV] luminosity is \( 8.23 \times 10^{37} \text{ ergs s}^{-1} \), which is at the the low

\(^2\)It should be noted that the apparent luminosity \( L_{0.2-10 \text{ keV}} = (2.1 \pm 0.1) \times 10^{36} \text{ ergs s}^{-1} \) is consistent with the upper limit previously established for NGC 4178 based on Einstein observations of \( L_{0.2-4.0 \text{ keV}} \lesssim 2.5 \times 10^{36} \text{ ergs s}^{-1} \) (Fabbiano et al., 1992).

\(^3\)In predicting the bolometric luminosity, we included all of the [NeV] 14.3 \( \mu \text{m} \) flux. In principle, [NeV] emission can be produced by shocked gas associated with a starburst-driven superwind (e.g., Veilleux et al., 2005). However, in the case of NGC 4178, the absence of notable Pa-\( \alpha \) emission near the photocenter (Figure 1.2) suggests that there is no vigorous star formation around the nuclear X-ray source. Moreover, the optical spectrum is typical of an HII region and is not consistent with shocks (Ho, Filippenko, & Sargent, 1997).
end of the range observed in standard optically-identified AGNs (Pereira-Santaella et al., 2010). Indeed, the [NeV] luminosity in NGC 4178 exceeds that of NGC 3621, which has recently been confirmed to have an optical Seyfert 2 spectrum using high resolution Keck observations (Barth et al., 2009). Moreover, the bolometric luminosity implied by the [NeV] luminosity is two orders of magnitude greater than that of NGC 4395, which is indisputably an AGN (Filippenko & Ho, 2003) (see 1.5.1). Therefore, the [NeV] luminosity, combined with our X-ray results, strongly suggests that the X-ray source is due to an AGN.

1.4.2 Off-Nuclear Sources

Source B

We detected $20 \pm 5$ net counts in the $0.2 - 10$ keV range for source B. The hardness ratio is $0.41^{+0.38}_{-0.22}$. At a radial distance of $31.6''$, the known intrinsic absorption for NGC 4178 is $N_H \simeq 10^{21}$ cm$^{-2}$ (Cayatte et al., 1994). With this absorption, source B’s hardness ratio can be reproduced by an absorbed PL model with $\Gamma = 1.7^{+0.7}_{-0.6}$. The corresponding
Figure 1.4: Left: HST NICMOS-3 H-band image of NGC 4178 overlaid with the celldetect X-ray extraction region for source C. Right: Smoothed SDSS g-band image with the same contour. 1" $\simeq$ 80 parsecs.

X-ray luminosity is $L_{0.2-10\text{ keV}} = 2.2^{+1.5}_{-0.5} \times 10^{38}$ ergs s$^{-1}$. In the hard X-ray band, the corresponding luminosity is $L_{2-10\text{ keV}} = 1.2^{+1.7}_{-0.8} \times 10^{38}$ ergs s$^{-1}$.

Source C

The net counts in the 0.2 – 10 keV range for source C are 26 ± 5, with a hardness ratio of 0.20$^{+0.19}_{-0.12}$. This relatively low hardness ratio can be reproduced by an absorbed PL model with $\Gamma = 2.3^{+0.9}_{-0.6}$ and $N_H = 10^{21}$ cm$^{-2}$, giving an X-ray luminosity of $L_{0.2-10\text{ keV}} = 6.2^{+6.8}_{-1.2} \times 10^{38}$ ergs s$^{-1}$ and a hard X-ray luminosity of $L_{2-10\text{ keV}} = 1.7^{+2.4}_{-1.2} \times 10^{38}$ ergs s$^{-1}$. 
Source D

Our brightest X-ray source, source D, had 575 ± 24 total counts in the 0.2 – 10 keV range, enough to directly fit a spectrum. We tested the variability of this source by extracting the light curve in the 0.2 – 10 keV range and applying a $\chi^2$ test, and found that the source flux was likely constant during the observation ($\chi^2$/dof = 22.584/39, $P_{\chi^2} = 0.98$).

The spectrum is well fit ($\chi^2_{\text{red}} = 0.997$ for 33 degrees of freedom) using an absorbed PL model with $\Gamma = 1.24 \pm 0.12$ and setting the intrinsic absorption $N_H = 10^{21}$ cm$^{-2}$. This yields an X-ray luminosity of $L_{0.2-10\text{ keV}} = (7.9 \pm 0.8) \times 10^{39}$ ergs s$^{-1}$ and a hard X-ray luminosity of $L_{2-10\text{ keV}} = (5.9 \pm 0.9) \times 10^{39}$ ergs s$^{-1}$. If we allow the intrinsic absorption to vary, a comparable fit ($\chi^2_{\text{red}} = 1.02$ for 32 degrees of freedom) is achieved with $N_H = 1.5 \pm 0.14 \times 10^{20}$ cm$^2$ and $\Gamma = 1.31 \pm 0.23$, yielding an intrinsic X-ray luminosity $L_{0.2-10\text{ keV}} = (8.0 \pm 1.0) \times 10^{39}$ ergs s$^{-1}$ and a hard X-ray luminosity of $L_{2-10\text{ keV}} = (5.8 \pm 0.7) \times 10^{39}$ ergs s$^{-1}$.

This large luminosity gives us a second method of spectrally characterizing the source. Recent work has shown that the physically motivated Bulk Motion Comptonization (BMC) model may provide an effective means of estimating the mass of accreting black holes (Gliozzi et al., 2009, 2011, Shaposhnikov & Titarchuk, 2009). This technique relies on the self-similarity of black holes and their accretion characteristics to relate the photon index $\Gamma$ with the BMC model normalization $N_{\text{BMC}}$. In short, the BMC model convolves the inverse Comptonization of X-ray photons by thermalized electrons with the inverse Comptonization of X-ray photons by electrons with bulk relativistic motion (see Titarchuk et al., 1997, for details on the BMC model). The BMC model has 4 free parameters: the temperature $kT$, the spectral index $\alpha$, related to the photon index $\Gamma$ by $\alpha = \Gamma - 1$, a parameter $\log A$ related to the fraction of Comptonized seed photons $f$ by $A = f/(f - 1)$, and the model normalization $N_{\text{BMC}}$.

The BMC model gives an excellent fit ($\chi^2_{\text{red}} = 1.00$ for 31 degrees of freedom) with
the intrinsic absorption set to $N_H = 5 \times 10^{20}$ cm$^2$, $kT = 0.48^{+0.08}_{-0.07}$, $\alpha = 0.77^{+0.44}_{-0.25}$, and log $A = 7.1$ (Figure 1.5). The normalization is $N_{\text{BMC}} = 1.39 \times 10^{-6}$. The corresponding X-ray luminosity is $L_{0.2-10 \text{ keV}} = (6.5 \pm 0.4) \times 10^{39}$ ergs s$^{-1}$, and the hard X-ray luminosity is $L_{2-10 \text{ keV}} = (5.1 \pm 0.5) \times 10^{39}$ ergs s$^{-1}$. Five different spectral patterns of Galactic black hole systems with mass and distance well constrained are provided in Gliozzi et al. (2011). These are the reference sources utilized in the X-ray scaling method. To be conservative in the estimate of the black hole mass of Source C, we have used all five reference patterns and computed the average and standard deviation of the five $M_{\text{BH}}$ values, resulting in $\langle M_{\text{BH}} \rangle = (6 \pm 2) \times 10^3$ M$_\odot$.

The Nature of The Off-Nuclear Sources

With the exception of source C, the lack of noticeable counterparts in other bands (see Figure 1.1) suggests that these sources are not foreground objects. Source C is coincident with an extended ($\sim 800 \times 520$ parsecs) region (Figure 1.4), especially evident in high-resolution HST data. This region appears to be an area of extensive star formation, though it is not associated with significant Pa-\(\alpha\) emission. A priori, we cannot rule out that these sources are background AGN that appear to be located within NGC 4178 by chance. With the known hydrogen column density of $\sim 10^{21}$ cm$^{-2}$, a background X-ray source would not be heavily absorbed by NGC 4178, even in the soft band. Using results from the Chandra Deep Field-South (CDF-S), we can calculate the likely number of hard X-ray sources in our field ($\sim 4 \times 10^{-4}$ deg$^{-2}$) for a given flux that could be expected to occur by chance (e.g., Tozzi et al., 2001). For sources B and C, with hard X-ray fluxes on order of $\sim 10^{-15}$ ergs s$^{-1}$ cm$^{-2}$, the expected number of sources is $\sim 5$, so sources B and C may indeed be background objects. However, for source D, with hard X-ray flux on order of $\sim 10^{-13}$ ergs s$^{-1}$ cm$^{-2}$, the expected number of sources is $\sim 0.1$. We therefore conclude that source D is likely local to NGC 4178. Source D has a luminosity of $\sim 10^{40}$ ergs s$^{-1}$, and
is therefore consistent with a ULX (e.g., Berghea et al., 2008, Swartz et al., 2004, Winter et al., 2006). Source D’s spectrum is also well fit by the BMC model, suggesting that it may be an IMBH. VLA observations by Cayatte et al. (1990) of neutral hydrogen in NGC 4178 show a heightened concentration ($N_H = 1.48 \times 10^{22}$ cm$^{-2}$) of neutral hydrogen coincident with source D. Niklas et al. (1995) gives the position of this source as RA $\simeq 12^h12^m43^s$, DEC $\simeq 10^\circ50'59''$. This concentration is very diffuse, however, so it is uncertain that it is related to source D.

1.5 Constraints on the Nuclear Black Hole Mass

1.5.1 Bolometric Luminosity and Eddington Mass Limit of the AGN

Our IR and X-ray observations allow us to derive a mass estimate for the nuclear black hole. In our previous work, we showed that the [NeV] luminosity is tightly correlated with the bolometric luminosity of the AGN in a sample of optically identified AGNs. We
can therefore use the [NeV] luminosity to obtain an estimate of the Eddington mass of
the black hole (Satyapal et al., 2007), and therefore set a lower mass limit on the AGN.
Since the publication of our previous work, there have been a number of additional mid-
IR [NeV] fluxes available in the literature. We therefore update our previously published
relation between the [NeV] 14.32 µm luminosity and the AGN bolometric luminosity using
the most up-to-date mid-IR line fluxes of AGNs observed by Spitzer (Armus et al., 2007,
Cleary et al., 2007, Dale et al., 2009, Deo et al., 2007, Dudik et al., 2007, 2009, Gorjian
et al., 2007, Haas et al., 2005, Ogle et al., 2006, Pereira-Santaella et al., 2010, Tommasin
et al., 2008, 2010, Veilleux et al., 2009, Weedman et al., 2005) that have well-characterized
nuclear SEDs. In Figure 1.6, we plot $L_{\text{bol}}$ versus $L_{\text{[NeV]}}$, which shows a strong correlation.
The Spearman rank correlation coefficient is 0.83, with a probability of chance correlation of
$10^{-13}$. The bolometric luminosities for this updated sample ranged from $\sim 5 \times 10^{42}$ ergs s$^{-1}$
to $\sim 5 \times 10^{46}$ ergs s$^{-1}$ and the black hole masses ranged from log $M_{\text{BH}} = 6.15$ to log $M_{\text{BH}} =
9.56$. The best-fit linear relation yields:

$$\log L_{\text{bol}} = 0.615 \log L_{\text{[NeV]}} + 19.647 \text{ ergs s}^{-1}$$

with an RMS scatter of 0.53 dex. Using the known [NeV] 14.32 µm nuclear luminosity for
NGC 4178 of $8.23 \times 10^{37}$ ergs s$^{-1}$ (Satyapal et al., 2009), the predicted nuclear bolometric
luminosity of the AGN is $L_{\text{bol}} = 9.2^{+22}_{-6.5} \times 10^{42}$ ergs s$^{-1}$. The Eddington mass limit for the
nuclear black hole in NGC 4178 is then $M_{\text{BH}} \geq 7.1^{+17}_{-5.0} \times 10^4 M_{\odot}$.

1.5.2 Archival VLA Data and The Fundamental Plane

At the positions of the four Chandra sources, we did not find any significant emission in
the VLA 4.9 GHz image and measured 3 $\sigma$ point source limits of $< 0.23$ (A), $< 0.17$ (B),
$< 0.15$ (C), and $< 0.16$ (D) mJy. These limits are consistent with the original analysis
of Saikia et al. (1994) where no significant radio sources were detected. Interestingly, we
note a local radio maximum in the VLA image that is $1.7''$ to the northeast of the central
Chandra source (A) with a position, RA=$12^{h}12^{m}46^{s}.40$, DEC= $10^{\circ}51'55''$.9. The peak
Figure 1.6: AGN bolometric luminosity as a function of $[\text{NeV}]$ 14.32 $\mu$m luminosity. It is clear that the $[\text{NeV}]$ luminosity is strongly correlated with the bolometric luminosity over a wide range of luminosities.
of 0.184 mJy/beam is 3.4 times the average rms noise measured in adjacent background regions. At 4.9 GHz, the single-dish flux of NGC 4178 is 12 mJy (Vollmer et al., 2004) and this peak could easily be an artifact due to unmodelled diffuse radio emission from the galaxy. The only other VLA datasets available in the archive were obtained at 1.4 GHz, but these lower-resolution data are dominated by the diffuse star forming regions seen in the Effelsberg data and the VLA 1.4 GHz D-array image of Condon (1987).

If we use the radio luminosity as an upper limit, we can use the hard X-ray luminosity to estimate the upper limit on the nuclear black hole mass through the so-called fundamental plane (Falcke et al., 2004, Gültekin et al., 2009, Merloni et al., 2003, 2006), assuming that the relation extends to lower luminosities and black hole masses. Assuming a 5 GHz flux density for the nucleus of 0.2 mJy, the X-ray and radio luminosity would imply a nuclear black hole mass of \( \sim 2.0^{+8.2}_{-1.6} \times 10^5 \, M_\odot \) (the RMS scatter is \( \sim 0.7 \)), consistent with the Eddington mass limit derived in the previous section.\(^4\) The assumed radio flux value corresponds to the local peak seen in the VLA image in close proximity to the X-ray nuclear source, and is consistent with the strict upper limit measured at the X-ray position.

### 1.5.3 Other Considerations

The presence of an NSC in NGC 4178 provides another estimate of the mass of the central black hole. Satyapal et al. (2009) estimated the mass of the NSC to be \( \sim 5 \times 10^5 \, M_\odot \), similar to the NSC mass in NGC 4395. In cases with a known nuclear star cluster and black hole masses, the ratio of the black hole mass to nuclear star cluster mass, \( M_{BH}/M_{NSC} \), generally ranges from 0.1 – 1 (Graham & Spitler, 2009, Seth et al., 2008). The lower limit on the black hole mass is then \( \sim 5 \times 10^4 \, M_\odot \), consistent with the lower limit set by the Eddington mass (although some galaxies have a BH/NSC mass much less than 0.1, such as M33), and the upper limit on the black hole mass is \( \sim 5 \times 10^5 \, M_\odot \), consistent with the upper limit implied by the radio luminosity.

\(^4\)In calculating this mass, we have used the hard X-ray luminosity of \( 8.6^{+10.4}_{-5.5} \times 10^{39} \, \text{ergs s}^{-1} \) from the heavily absorbed scenario. A lower X-ray luminosity would actually increase the upper limit to the black hole mass, according to the fundamental plane.
With the heavily obscured scenario, we can further constrain the black hole mass. Assuming that the NGC 4178 has an X-ray luminosity of \( \sim 10^{40} \) ergs s\(^{-1}\), the bolometric correction factor becomes \( \kappa_{2-10 \text{ keV}} \simeq 10^3 \). This finding can in turn be used to constrain the black hole mass by exploiting the correlation between \( \kappa_{2-10 \text{ keV}} \) and \( L_{\text{bol}}/L_{\text{Edd}} \) (Vasudevan & Fabian, 2009). Using the correlation that for systems with very high bolometric correction factors, \( L_{\text{bol}}/L_{\text{Edd}} \gtrsim 0.2 \), we obtain \( M_{\text{BH}} \simeq 3.8 \times 10^5 \, M_\odot \), consistent with the upper mass limit implied by the radio luminosity.

### 1.6 Comparison to AGN in Other Late-Type, Bulgeless Galaxies

With a solid X-ray source detection at the center of NGC 4178, we can add this galaxy to the growing collection of bulgeless, extremely late-type disk galaxies with confirmed AGN. The best-studied definitively bulgeless disk galaxy with an AGN is NGC 4395, which shows the hallmark signatures of a type 1 AGN (e.g., Filippenko & Ho, 2003, Lira et al., 1999, Moran et al., 1999). The bolometric luminosity of the AGN is \( \sim 10^{40} \) ergs s\(^{-1}\) (Filippenko & Ho, 2003), nearly three orders of magnitude lower than the estimated bolometric luminosity of the AGN in NGC 4178. The black hole mass of NGC 4395, determined by reverberation mapping, is \( M_{\text{BH}} = (3.6 \pm 1.1) \times 10^5 \, M_\odot \), and does not appear to be radiating at a high Eddington ratio (Peterson et al., 2005). The bolometric luminosity of the AGN in NGC 1042, as estimated from H\(\alpha\) measurements, is \( \sim 8 \times 10^{39} \) ergs s\(^{-1}\), and the central black hole is estimated to be between 60 \( M_\odot \) and 3 \( \times 10^6 \, M_\odot \) (Shields et al., 2008). With the updated \( L_{\text{bol}}/L_{[\text{NeV}]} \) relationship, the estimated bolometric luminosity of the AGN in NGC 3621 is \( 6.8^{+16}_{-4.8} \times 10^{42} \) ergs s\(^{-1}\) and the Eddington mass is \( 5.2^{+12}_{-3.7} \times 10^4 \, M_\odot \), making NGC 4178 and NGC 3621 the most luminous AGNs in extremely late-type galaxies currently known. The likelihood that the AGN in NGC 4178 is heavily absorbed, combined with the high photon index, suggests that it is accreting at a high rate. The black hole mass of the
AGN in NGC 4178 is \( \sim 10^4 - 10^5 \) M\(_\odot\), possibly lower than the black hole in NGC 4395.

1.7 Summary and Conclusions

We have analyzed the X-ray characteristics of NGC 4178 from a 36 ks Chandra observation. The X-ray data, combined with considerations from the mid-IR and radio properties of the galaxy, have led us to the following results:

1. There is a faint but statistically significant (5.3 \( \sigma \)), unresolved X-ray source at the center of NGC 4178, confirming the presence of an AGN. The hardness ratio gives some clues about the spectral state, which is consistent with a scenario where the source is accreting at a high rate with \( \Gamma \simeq 2.3 \). The softness of this source, combined with the discrepancy between the [NeV] luminosity and the observed X-ray luminosity, supports the scenario where NGC 4178 hosts an AGN embedded in a heavy absorber, accreting at a high rate.

2. The bolometric luminosity of the AGN in NGC 4178 predicted by our mid-IR results is \( 9.2 \times 10^{42} \) ergs s\(^{-1}\), significantly higher than that found in any other extremely late-type, bulgeless disk galaxy.

3. The updated bolometric luminosity, combined with other lines of evidence such as the fundamental plane and the correlation between the mass of nuclear star clusters and their resident SMBHs, have led us to conclude that the AGN in NGC 4178 is powered by a black hole of \( \sim 10^4 - 10^5 \) M\(_\odot\).

4. Two weak off-nuclear sources found in NGC 4178 have X-ray luminosities consistent with very bright XRBs or ULXs, although we cannot rule out the possibility that they are background objects. A third off-nuclear source is very bright and was directly fit with a PL model, showing that it is a ULX located in NGC 4178 about 8 kpc from the nuclear source. It was also directly fit with a BMC model, suggesting that it may be an IMBH of \( \sim 6 \times 10^3 \) M\(_\odot\).
1.8 Acknowledgements

It is a pleasure to thank Tim Jordan for his invaluable help carefully compiling the fluxes used to construct Figure 1.6. We thank the referee for their very careful review and insightful comments that significantly improved the paper. This research has made use of the NASA/IPAC Extragalactic Database (NED), which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. N. S. and S. S. gratefully acknowledge support by the Chandra Guest Investigator Program under NASA grant G01-12126X. Work by C. C. C. at NRL is supported in part by NASA DPR S-15633-Y.
Chapter 2: A Multi-Wavelength Analysis of NGC 4178: A Bulgeless Galaxy with an Active Galactic Nucleus

2.1 Abstract

We present Gemini longslit optical spectroscopy and VLA radio observations of the nuclear region of NGC 4178, a late-type bulgeless disk galaxy recently confirmed to host an AGN through infrared and X-ray observations. Our observations reveal that the dynamical center of the galaxy is coincident with the location of the Chandra X-ray point source discovered in a previous work, providing further support for the presence of an AGN. While the X-ray and IR observations provide robust evidence for an AGN, the optical spectrum shows no evidence for the AGN, underscoring the need for the penetrative power of mid-IR and X-ray observations in finding buried or weak AGNs in this class of galaxy. Finally, the upper limit to the radio flux, together with our previous X-ray and IR results, is consistent with the scenario in which NGC 4178 harbors a deeply buried AGN accreting at a high rate.

2.2 Introduction

The fact that supermassive black holes (SMBHs, $M_{\text{BH}} \gtrsim 10^6 \, M_\odot$) or intermediate-mass black holes (IMBHs, $10^2 \, M_\odot \lesssim M_{\text{BH}} \lesssim 10^6 \, M_\odot$) can be found in late-type galaxies in which there is no evidence for classical bulge is now on firm empirical ground (Araya Salvo et al., 2012, Barth et al., 2004, 2009, Desroches & Ho, 2009, Dewangan et al., 2008, Filippenko & Ho, 2003, Ghosh et al., 2008, Gliozzi et al., 2009, Greene & Ho, 2004, 2007, Jiang et al., 2011a,b, Mathur et al., 2008, McAlpine et al., 2011, Satyapal et al., 2009, 2008, 2007, Secrest et al., 2012, Shields et al., 2008, Simmons et al., 2013). The presence of such black holes in these galaxies points to a new understanding of the formation mechanisms of large
nuclear black holes. This is further bolstered by the remarkable evidence for the presence of an active galactic nucleus (AGN) in the dwarf galaxy Henize 2-10 (Reines et al., 2011) and the mounting evidence for AGN activity in blue compact dwarf galaxies (Izotov et al., 2007, Izotov & Thuan, 2008, Izotov et al., 2010). It is also likely that the particularly bright ultraluminous X-ray source HLX-1, also an IMBH (Soria et al., 2010, Webb et al., 2012), is the remnant of a dwarf galaxy (Farrell et al., 2012). Central to this new understanding is the black hole occupation fraction, which can provide insights into differentiating whether the first ‘seed’ black holes in the Universe originated from Population III stars, or whether the first seed black holes had a more exotic origin, such as the hypothetical ‘quasistar’ direct-collapse scenario (see Bonoli et al., 2012, and references therein) that may have unfolded in the early Universe due to the extremely low metallicity environment and lack of stellar clumping (for details on how the black hole occupation fraction differs under these two scenarios, see, e.g., van Wassenhove et al., 2010). These bulgeless and dwarf galaxies are of particular importance to this question because classical bulges are thought to form through mergers, which erase information on the progenitor galaxies’ black hole masses after they coalesce, while pseudobulges are thought to form through secular processes (Kormendy & Kennicutt, 2004). Nuclear black holes in these galaxies may thus be thought of as ‘pristine’, having likely gone through only secular growth during the extent of cosmic history, and preserving the characteristics of the seed population from which they originated. While it is not yet technically feasible to obtain an unbiased estimate of the black hole occupation fraction at masses $\lesssim 10^6 M_\odot$ due to limitations on detectability\(^1\), we can nonetheless begin to build a census of AGNs in low mass and bulgeless galaxies that will contribute to our understanding of this subject.

One such galaxy is NGC 4178, a late-type, bulgeless spiral galaxy ($d = 16.8$ Mpc) that was recently confirmed to host an AGN through high-resolution Chandra X-ray observations (Secrest et al., 2012, hereafter S12), with a nuclear black hole mass, inferred through

\(^1\)Although see Greene (2012) for a first-pass estimate, which tentatively finds that the direct-collapse scenario may better explain the (limited) data we currently have on this black hole demographic.
mid-IR and radio/X-ray correlations, between $\sim 10^4 - 10^5 \, M_\odot$. While the presence of an AGN has been confirmed in this object, the optical confirmation of the presence of an AGN in NGC 3621 (Barth et al., 2009), a bulgeless spiral galaxy with highly similar X-ray/mid-IR properties, has motivated us to explore the optical properties of NGC 4178. While an optical spectrum of the nuclear region already exists (Ho et al., 1995), we have determined that it did not actually cover the region containing the nuclear X-ray source, and so it is not known how the ionization of the interstellar medium (ISM) changes near the source, if at all. Furthermore, it is not definitively known whether or not some of the [Ne V] emission from the nucleus (Satyapal et al., 2009) originates in a starburst and/or shocks. If this were true, then it would reduce the inferred bolometric luminosity of the AGN and therefore the lower limit on the mass of the nuclear black hole. By examining the star formation properties of the nuclear region, we can explore this possibility and make the inferred bolometric luminosity more robust.

The aim of this paper is to further characterize the nuclear environment around the AGN in NGC 4178. We used Gemini longslit spectroscopy to derive the dynamical center of the galaxy, explore the ionization state of the circumnuclear ISM, and explore the presence of star formation. We also obtained new Very Large Array (VLA) observations to further constrain the mass of the nuclear black hole. In §2, we describe the Gemini observations and data reduction, as well as the new VLA data. We continue with a description of our results in §3, before discussing the implications of our results in §4. We give a summary and our primary conclusions in §5.

2.3 Observations and Data Reduction

2.3.1 Gemini Spectroscopic Observations

NGC 4178 was observed with the Gemini GMOS-N, long-slit ($1''$), B600-G5307 grating on 2012 February 14th and 21st for 3600 seconds and 2400 seconds (1200 seconds per frame),
respectively (Program ID: GN-2012A-Q-14). The position angle of the slit was 25° east of north so as to align the slit along the major axis of the galaxy. The effective airmass for the observations ranged from 1.016 to 1.041, making differential refraction effects negligible. Upon inspection of the pointing frames, it became apparent that the seeing was considerably worse on the second night and the pointing missed the nucleus. Consequently, we carried out our primary analysis on the three successful observations from the first night.

The data were reduced and calibrated with the Gemini package for IRAF, v. 1.11, following standard procedures. Cosmic rays were cleaned using the gscrspec multi-extension fits wrapper for L.A.Cosmic (van Dokkum, 2001) and using the default parameters. Despite the large (~330") length of the slit, some contamination remained from the galaxy even at the ends. While this was a minor drawback and did not affect the subsequent analysis, it did make full sky line removal impossible. A set of standard spectroscopic star observations were obtained on the same night using the 5" slit mask, and so we found that slit losses through the 1" slit mask were negligible.

### 2.3.2 VLA Radio Observations

We observed NGC4178 on 2012 July 14-15 with the NRAO Karl G. Jansky VLA (Perley et al., 2011) while in its B-configuration (program AS1114, 12A-093). In the 1.5 hr observing run, a single 18 min scan of the galaxy was obtained at C-band while two 18 min scans were obtained at X-band. The target scans were bracketed with observations of the point source J1224+0330 for phase calibration while 3C 286 was utilized as the primary flux and bandpass calibrator. After basic calibration in AIPS, we produced CLEAN images at C-band split into two 1 GHz wide side-bands centered at 5.0 and 6.0 GHz with off-source rms (1σ) = 11.9 µJy/beam and 12.6 µJy/beam, respectively. The center frequency of the

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2Based on observations obtained at the Gemini Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under a cooperative agreement with the NSF on behalf of the Gemini partnership: the National Science Foundation (United States), the Science and Technology Facilities Council (United Kingdom), the National Research Council (Canada), CONICYT (Chile), the Australian Research Council (Australia), Ministério da Ciência, Tecnologia e Inovação (Brazil) and Ministerio de Ciencia, Tecnología e Innovación Productiva (Argentina)

3The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.
X-band image was 9.0 GHz (2 GHz bandwidth) with an off-source rms of 6.7 $\mu$Jy/beam. The image beamsizes were $1.19'' \times 1.49''$ (5 GHz), $1.03'' \times 1.28''$ (6 GHz), and $0.66'' \times 0.84''$ (9 GHz).

In the VLA images, diffuse steep-spectrum emission from the NGC4178 galaxy was detected but the Chandra detected nucleus (A) and the three off-nuclear X-ray point sources (B, C, and D) reported in S12 were not detected. For the nucleus, we measured 3$\sigma$ point-source upper limits of $< 84.9$ $\mu$Jy (5 GHz), $< 46.8$ $\mu$Jy (6 GHz), and $< 24.9$ $\mu$Jy (9 GHz) at the Chandra X-ray position. These values are larger than the off-source rms due to the presence of the NGC4178 galaxy emission. The corresponding limit from our previous analysis of an archival VLA 5 GHz exposure was $< 230$ $\mu$Jy (S12). For the off-nuclear X-ray sources, we measured (5 GHz, 6 GHz, 9 GHz) $[\mu$Jy] upper limits of ($< 38.7$, $< 55.2$, $< 25.5$) for B, ($< 27.0$, $< 36.6$, $< 17.1$) for C, and ($< 35.7$, $< 31.2$, $< 19.8$) for D. The 5 GHz values are $4.4 - 5.6 \times$ smaller than determined from the archival VLA data (See S12). Note that the diffuse galactic radio emission is resolved in the $\sim$arcsecond resolution VLA image (Figure 2.1) and exhibits a clumpy appearance due to the CLEAN processing of the data with limited $(u, v)$ coverage. In this respect, the local peak (66$\mu$Jy/beam) in the new VLA 5 GHz image of the galaxy that we noted in our previous analysis of a sparser archival VLA dataset (S12) is noticeably offset (about 1.7") from the Chandra nucleus and is likely unrelated to the AGN activity.

### 2.4 Results

The calibrated Gemini spectrum can be seen in Figure 2.2. Emission line and stellar population fitting were done with simplefit (Tremonti et al., 2004) using the stellar population model of Bruzual & Charlot (2003). One set of 1-dimensional (1"") and 2-dimensional spectra were produced by performing sky subtraction using the ends of the slit as the sky sample. The line fluxes for the central 1"") are listed in Table 2.1.
Figure 2.1: VLA 5 GHz image (beam = 1.49'' × 1.19'' at position angle 11.2°) of NGC 4178 showing diffuse emission from the galaxy. The white circle outlines the *Chandra* X-ray source, and the dashed white lines indicate the *Gemini* longslit. 1'' ≃ 80 pc.

<table>
<thead>
<tr>
<th>Line</th>
<th>Flux*</th>
<th>EW(Å)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hβ</td>
<td>0.33 ± 0.02</td>
<td>1.57</td>
</tr>
<tr>
<td>[O III]λ5007</td>
<td>0.18 ± 0.02</td>
<td>0.88</td>
</tr>
<tr>
<td>Hα</td>
<td>1.31 ± 0.01</td>
<td>8.74</td>
</tr>
<tr>
<td>[N II]λ6584</td>
<td>0.41 ± 0.01</td>
<td>2.78</td>
</tr>
<tr>
<td>[S II]λ6717</td>
<td>0.36 ± 0.01</td>
<td>2.48</td>
</tr>
<tr>
<td>[S II]λ6731</td>
<td>0.26 ± 0.01</td>
<td>1.81</td>
</tr>
</tbody>
</table>

* in units of 10^{-15} erg s^{-1} cm^{-2}
2.4.1 The Dynamical Center

To derive a robust rotation curve, we measure the radial velocity as a function of radius in two ways: 1) by cross-correlating the spectrum at each spatial position against galaxy templates to determine the velocity, and 2) by fitting directly for the centroids of the Hα emission line. For each method, we treat each spatial row of the longslit spectrum independently, but we note that the slit width and seeing are both larger than this pixel size, such that neighboring rows are not independent. For our purposes, it is desirable to assess whether emission line ratios which rise and then fall across a small spatial extent indicate an unresolved AGN source, or arise within a larger resolved region.

Under the first method, we follow a similar procedure to that used by SDSS, where the spectrum at each position is transformed into an evenly spaced grid in log wavelength, and then cross-correlated with several similarly-prepared template spectra to determine the redshift (or velocity) of that spectrum with respect to the rest frame. Under the
second method, using the cross-correlation result as a first-guess, we fit and subtract off the absorption component of each spectrum (following the procedure described below), and then measure the centroid of a Gaussian fit to the Hα line. We note that the two methods yielded consistent curves at all radii for this galaxy.

To the raw measured rotation data, we fit a smooth function of the form \( V(R) = V_{\text{MAX}}(R + \Delta R)/((R + \Delta R)^a + R_s^a)^{1/a} + \Delta V \) (Böhm et al., 2004, Moran et al., 2007), where \( R \) is the radius, \( a \) and \( R_s \) are free parameters that govern the shape of the rotation curve and its turn-over, \( \Delta V \) is the offset of the galaxy’s central velocity from the given value \( (z = 0.001248) \), and \( \Delta R \) is the radius offset. Both \( \Delta R \) and \( \Delta V \) are left free to vary in the fit, but are constrained to stay within a reasonable range of values (5 ″ and 75 km s\(^{-1}\), respectively). Notably, we find no evidence that \( \Delta R \) is significantly different from zero (the uncertainty, as estimated from bootstrapping, was better than \( \sim 2'' \), or \( \sim 320 \) pc), implying that the presumed center of the galaxy (the location of the Chandra X-ray source measured in S12) is also consistent with being its rotational center (Figure 2.4). While the error on the location of the dynamical center appears to preclude us from completely ruling out the possibility that the dynamical center is coincident with the local radio peak 1.7 ″ northeast of the Chandra source, there are two reasons why this scenario is unlikely. First, the error in the determination of the dynamical center is along the spatial direction of the slit, which did not cover the local radio peak (See Figure 2.3), so the velocity offset at the location of the radio peak is not known. Second, the Chandra source is coincident with the Two Micron All Sky Survey photocenter, which is coincident with a nuclear star cluster (NSC, see Section 3 in S12), making it a priori more likely that the dynamical center is coincident with the Chandra X-ray source.

After deriving the best-fit rotation curve, we adjust the spectrum at each spatial position to its rest-frame wavelength scale, and perform all further analysis in the rest frame.
Figure 2.3: The *Hubble Space Telescope* H-band image of the nuclear region of NGC 4178 with the *Spitzer* SH slit outlined in green, the *Chandra* X-ray source outlined in blue, and the *Gemini* longslit outlined in dashed white. The white contours are the VLA 5 GHz radio contours. $1'' \sim 80$ pc.
Figure 2.4: The rotation curve of NGC 4178. The red points are the Hα, while the black points are from the absorption line fits. The x axis is defined relative to the Chandra nuclear point source. The uncertainties in the velocities are less than ~10%, or 10-15 km s$^{-1}$ for both $V_{\text{MAX}}$ and $V_{\text{MAX}}$(Hα). 1″ ≃ 80 pc.
2.4.2 The BPT Diagram

We employ a modified version of the simplefit code that fits stellar templates and emission lines for each row of the 2-dimensional longslit data. In order to increase S/N, the spectra were extracted in $1''$ bins along the spatial direction of the slit, with each consecutive bin shifted by 1 row. This had the effect of slightly smoothing the data and reducing the noise. Each extracted spectrum was fit with a linear combination of templates drawn from the Bruzual & Charlot (2003) single stellar population models of varying metallicities, masking out the emission lines. The best-fitting stellar continuum model was then subtracted from the measured spectrum, creating an emission-line only spectrum where the Balmer emission lines can be measured free of contamination from the underlying stellar continuum. We then fit Gaussian functions to the emission lines, with the widths and centers of the Gaussian free to vary.

In addition to the Balmer lines H$\alpha$ and H$\beta$, we also measure the forbidden lines [O III]$\lambda$5007, [N II]$\lambda$6548/6584, and [S II]$\lambda$6717/6731, which are required to measure metallicity and test for the presence of an AGN. To assess the presence of an AGN, we use the Kewley et al. (2001) version of the classic Baldwin, Phillips & Terlevich (BPT, Baldwin et al., 1981), diagnostic, which utilizes the line flux ratios of [O III]$\lambda$5007 to H$\beta$, [N II]$\lambda$6584 to H$\alpha$, and [S II]$\lambda$6717/6731 to H$\alpha$. As a function of radius, we plot these line ratios to assess how rapidly the ionization state of the ISM may change with location in the galaxy Figure 2.5. While the line ratios vary with radius, at all points their location on the BPT diagram is consistent with originating in HII regions.

2.4.3 The Fundamental Plane

In S12, we used a radio upper limit obtained from archival VLA data combined with the Chandra X-ray detection to set an upper limit on the nuclear black hole’s mass using the so-called fundamental plane of black hole activity (Bonchi et al., 2013, Falcke et al., 2004, Gültekin et al., 2009, Li et al., 2008, Merloni et al., 2003, 2006, Miller-Jones et al., 2012, Wang et al., 2006). With the new 5 GHz 3$\sigma$ flux density upper limit of $< 84.9$ $\mu$Jy and the
0.5–10 keV luminosity calculated from the scenario in which the AGN is heavily embedded with only a few non-Compton thick openings in which X-ray flux escapes (see Section 3.1 of S12), we find a predicted black hole mass of $M_{\text{BH}} \lesssim 8.4 \times 10^4 M_\odot$ using the Miller-Jones et al. (2012) relation (1σ scatter = 0.44 dex), which may be more valid than the Gültekin et al. (2009) relation for lower-mass systems because the Gültekin et al. relation was derived for black hole masses greater than $10^6 M_\odot$ (see Section 4.2 of Miller-Jones et al.). This is a considerably lower upper limit than our previous value of $\sim 2 \times 10^5 M_\odot$.

However, it is important to point out that the Miller-Jones et al. relation was derived from the strongly sub-Eddington ($\dot{M}/\dot{M}_{\text{Edd}} < 0.01 - 0.02$) sample of Plotkin et al. (2012), while significant scatter exists for more highly-accreting objects (e.g., Körding et al., 2006), as the AGN in NGC 4178 likely is (S12). We discuss this issue in the next section.
2.5 Discussion

With the confirmation that the dynamical center of NGC 4178 coincides with the location of the Chandra X-ray point source, an important property of the AGN in this galaxy has been confirmed. While bulge-hosting galaxies usually have dynamical centers very clearly aligned with their photocenters, bulgeless galaxies, especially bulgeless galaxies with dusty bars such as NGC 4178, have much less obvious centers, and several sources within the bar of NGC 4178 could be considered candidates for the dynamical center, such as one of the two IR-bright lobes detected by Spitzer (see Figure 1 of S12). This analysis highlights the value of using longslit spectroscopy on this unique class of objects, despite the fact that optical emission lines originating from the narrow line region (NLR) may either be too absorbed or too weak to use as an AGN diagnostic by themselves.

It is not clear from the data alone whether it is heavy absorption that prevents NGC 4178 from being optically classified as an AGN or if it is simply that the AGN is too weak to be detected above surrounding star formation. By comparing the X-ray properties of the AGN with the bolometric luminosity predicted from the [Ne V] 14.3 μm emission, S12 found that the AGN in NGC 4178 is indeed likely to be heavily obscured, and so we should therefore not be surprised that this galaxy shows no signs of an AGN at optical wavelengths. Even with heavy obscuration, we may be able to detect an increase in ionization parameter near the AGN, giving some clues as to degree of absorption involved. One advantage of longslit spectroscopy is that it has allowed us to examine the ionization state of the ISM as a function of radius from the AGN. Of the three ionization parameters used in Kewley et al. (2001), all three appear to rise near the galactic center, but only [O III]/Hβ line flux ratio appears to increase sharply enough at the galactic center to possibly be considered local to the AGN (Figure 2.5). However, the magnitude of the rise in the line flux ratio at the center is comparable to that of the nearby off-nuclear variations. The rise in the line flux ratio at the center cannot alone be considered unambiguous evidence for the AGN.

There is, however, some amount of scatter in the $L_{[NeV]}/L_{bol}$ relation (0.53 dex), and a
portion of this scatter is likely due to \([\text{Ne V}]\) contamination by heavy starburst activity (e.g., Veilleux et al., 2005). In order to explore this possibility, we plot the star formation rate (SFR) as a function of distance from the nuclear source in Figure 2.6 using the Kennicutt (1998) relationship between the \(\text{H}\alpha\) luminosity and the SFR and using the Charlot & Fall law (Charlot & Fall, 2000) to empirically correct for extinction assuming optically-thick (Case B) recombination. The IR-bright lobes detected by \textit{Spitzer} at \(\sim 7''\) away from the AGN are clearly visible as large increases in the SFR. However, within \(\sim 3''\) of the nucleus, the SFR hovers at around \(10^{-3}\ M_\odot\ yr^{-1}\), indicating that there is no significant starburst activity near the nucleus, as is implied by the absence of significant \(\text{Pa-}\alpha\) emission noted by S12, Figure 2 therein. Being an extremely late-type, and therefore very dusty galaxy, it is natural to ask if there might be a deeply buried starburst contributing to the \([\text{Ne V}]\) emission that could be obscured even in the near-IR. To explore this possibility, we used the tight relationship between \(L_{[\text{Ne II}]+[\text{Ne III}]}\) and SFR (Ho & Keto, 2007), which is largely insensitive to differences in metallicity, to calculate the SFR at the nucleus of NGC 4178 under the possible scenario in which the \([\text{Ne II}] + [\text{Ne III}]\) emission is due to a buried starburst and not to the presence of an AGN. Using the best-fit ionization fraction values of Ho & Keto, we derive a SFR of \(\sim 4 \times 10^{-2}\ M_\odot\ yr^{-1}\). As this number is consistent with the rate predicted by the \(\text{H}\alpha\) emission within the margin of error, we conclude that there is not a buried starburst contributing to the \([\text{Ne V}]\) emission in NGC 4178.

The new upper limit to the 5 GHz radio luminosity further constrains the upper limit on the black hole mass to within the same order of magnitude as the Eddington lower mass limit implied by the \([\text{Ne V}]\) luminosity. This would seem to corroborate the scenario of an IMBH deeply embedded in a heavy absorbing material and accreting at a high rate. However, it is important to note that the \textit{Chandra} point source in NGC 4178 is thus inferred to be in the ‘high-soft’ state of black hole X-ray emission (see section 3.1 of S12), and so the radio and X-ray luminosities may be only weakly dependent on the mass of the nuclear black hole (for details, see Li et al., 2008, Wang et al., 2006). The upper limit on the mass implied by the
Figure 2.6: SFR (M⊙ yr⁻¹) as a function of angular distance from the nuclear source. Error bars are 1σ. 1″ ≃ 80 pc.

deeper VLA measurements should therefore be considered tentative (Although see Gliozzi et al., 2010, for an example of an AGN accreting very close to the Eddington limit with a mass accurately predicted by the fundamental plane).

2.6 Summary and Conclusions

We have analyzed Gemini longslit optical spectroscopy of NGC 4178, as well as deeper VLA radio observations. By performing a full spatial spectroscopic characterization of the galaxy, as well as more tightly constraining its radio properties, we have found the following results:

1. The dynamical center of NGC 4178 is coincident with the location of the Chandra X-ray point source discovered by S12, providing further support for the presence of an AGN in this galaxy, as well as confirming that this galaxy contains a nuclear star cluster.
2. While the ionization state of the ISM near the nucleus appears to increase, NGC 4178 remains classified as optically normal, further underscoring the need for the penetrative power of mid-IR and X-ray observations in finding buried or energetically weak AGNs in this class of galaxy.

3. From new, deeper constraints on the 5 GHz radio luminosity, the upper limit on the nuclear black hole’s mass appears to be near the Eddington limit implied by its mid-IR properties, lending support to the notion that this object is deeply embedded and accreting at a high rate. The uncertainty in applying the fundamental plane to highly-accreting black holes, however, means that we should consider this to be a tentative result.

2.7 Acknowledgements

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3.1 Abstract

Supermassive black holes are found ubiquitously in large, bulge-dominated galaxies throughout the local Universe, yet little is known about their presence and properties in bulgeless and low mass galaxies. This is a significant deficiency, since the mass distribution and occupation fraction of non-stellar black holes provide important observational constraints on supermassive black hole seed formation theories and many dwarf galaxies have not undergone major mergers that would erase information on their original black hole population. Using data from the Wide-field Infrared Survey Explorer, we discovered hundreds of bulgeless and dwarf galaxies that display mid-infrared signatures of extremely hot dust highly suggestive of powerful accreting massive black holes, despite having no signatures of black hole activity at optical wavelengths. Here we report, in our first follow-up X-ray investigation of this population, that the irregular dwarf galaxy J132932.41+323417.0 (z = 0.0156) contains a hard, unresolved X-ray source detected by XMM-Newton with luminosity $L_{2-10 \text{ keV}} = 2.4 \times 10^{40}$ erg s$^{-1}$, over two orders of magnitude greater than that expected from star formation, providing confirmation of the presence of an accreting massive black hole. While enhanced X-ray emission and hot dust can be produced in extremely low metallicity environments, J132932.41+323417.0 is not extremely metal poor ($\approx 40\%$ solar). With a stellar mass of $2.0 \times 10^8$ $M_\odot$, this galaxy is similar in mass to the Small Magellanic Cloud, and is one of the lowest mass galaxies with evidence for a massive nuclear black hole currently known. If future follow-up X-ray observations of this newly discovered population yield similar results, then a key and striking result from this study is that there
resides a population of optically-hidden AGNs in the lowest mass galaxies that significantly
outnumbers optically-identifiable AGNs.

3.2 Introduction

It is well known that supermassive black holes (SMBHs) are ubiquitous in massive bulge
dominated galaxies. In contrast, for decades, less than a handful of SMBHs were known
in either low mass, or bulgeless galaxies (e.g., Barth et al., 2004, Filippenko & Ho, 2003).
Identifying such a population and constraining their occupation fraction is crucial to our
understanding of the origins of SMBHs and the secular pathways for their growth (e.g., van
Wassenhove et al., 2010, Volonteri, 2010). In recent years, there have been a number of
discoveries of active SMBHs in the low bulge mass regime (e.g., Araya Salvo et al., 2012,
Bizzocchi et al., 2014, Coelho et al., 2013, Desroches & Ho, 2009, Dewangan et al., 2005,
Dong et al., 2012, Ghosh et al., 2008, Gliozzi et al., 2009, Izotov & Thuan, 2008, Maksym
the list of active galactic nuclei (AGNs) in low mass or bulgeless galaxies may be steadily
growing, optically identified AGNs likely represent a small fraction of the total number
of AGNs in this population. AGNs identified by their optical spectra are preferentially
found in massive bulge-dominated hosts, with the fraction of galaxies with optical signs of
accretion dropping dramatically at stellar masses log $M_*/M_\odot < 10$ (e.g., Kauffmann et al.,
2003). For example, Reines et al. (2013) find that out of 25,974 low-mass (log $M_*/M_\odot < 9.5$)
galaxies with high signal-to-noise optical spectra, only 151 show any optical signatures of
AGN activity (0.6%) and only 35 (0.1%) are unambiguously identified as AGNs on the BPT
diagram. While a combination of obscuration, energetically weak AGNs, and contamination
by star formation all limit optical AGN selection in late-type galaxies, optical AGN selection
in lower mass galaxies may also be affected by their lower metallicities, reducing their
[N II]/H$\alpha$ emission line ratios and shifting AGN-hosting galaxies into the HII region of the
BPT diagram (see Izotov & Thuan, 2008, and references therein), and even unobscured AGNs may nonetheless fail to be discerned optically (e.g., Pons & Watson, 2014). The use of optical AGN diagnostics in low mass galaxies is further complicated in practice by the non-uniform nature of SDSS spectroscopic targeting, which preferentially targets more luminous galaxies (i.e., not dwarfs; see also the discussion in Greene & Ho, 2007).

Motivated by the possibility that optical studies miss a significant fraction of AGNs in bulgeless and low mass galaxies, we used the all-sky Wide-field Infrared Survey Explorer (WISE) to search for optically hidden AGNs in a large sample of bulgeless galaxies (Satyapal et al., 2014). Remarkably, we discovered several hundred optically normal bulgeless galaxies, many with low stellar masses, that display extreme red mid-infrared colors ([3.4\mu m]-[4.6\mu m]; hereafter W1-W2) suggestive of dominant AGNs that may outnumber optically-identified AGNs by as much as a factor of \( \approx 6 \). Astonishingly, the vast majority of these galaxies have no signs of accretion at optical wavelengths. Moreover, based on their red WISE color, not only do these galaxies possibly harbor AGNs, but the AGNs must dominate the mid-IR luminosities of their galaxies, since in typical low redshift sources, it is very difficult to replicate the observed WISE colors from star formation alone (e.g., Assef et al., 2013).

While the red mid-IR colors discovered by WISE are highly suggestive of accretion activity, there are cases when red W1-W2 colors indicate hot dust due to extreme star formation, especially when associated with red W2-W3 ([4.6\mu m]-[12\mu m]) colors. Indeed, there have been a handful of low metallicity blue compact dwarfs (BCDs) with extreme mid-infrared colors (e.g., Griffith et al., 2011, Izotov et al., 2014) raising the possibility that there is a similar origin for such mid-IR colors in bulgeless galaxies. It is impossible to confirm the putative AGN in this population of galaxies with the infrared observations alone. Follow up X-ray observations are required, since the detection of a hard, luminous nuclear X-ray source coincident with the nucleus provides unambiguous confirmation of the existence of accreting black holes.

In this paper, we present the first follow-up X-ray observations obtained with XMM-Newton of the bulgeless galaxy SDSS J132932.41+323417.0 (SDSS “objectID”=1237665126939754596;
hereafter J1329+3234). J1329+3234 is a blue, irregular dwarf galaxy (log $M_*/M_\odot$=8.3) with a metallicity of $Z/Z_\odot$=0.4, at a redshift of $z=0.0156$ that hosts a bright, unresolved mid-IR source with WISE colors suggestive of the presence of an AGN ($W1-W2=0.73$ mag.; $W2-W3=2.59$ mag.). Based on the optical emission line ratios from the SDSS spectrum, there is no evidence for an AGN ($\log$ [OIII]$_{\lambda 5007}/$H$\beta$ = 0.25, $\log$ [NII]$_{\lambda 6584}/$H$\alpha$ = −1.05).

We adopt a standard ΛCDM cosmology with $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_M = 0.3$, and $\Omega_\Lambda = 0.7$.

### 3.3 Observations and Data Reduction

#### 3.3.1 XMM Observations

We obtained X-ray observations of J1329+3234 on 2013 June 12, as part of a broader XMM-Newton program searching for AGN X-ray signatures in bulgeless galaxies (Secrest et al. 2015, in prep.). We acquired three full-frame event files with the EPIC pn, MOS1, and MOS2 CCDs, in an effective energy range of 0.3-10 keV, with effective exposure times of 30.0 ks for pn and 34.8 ks for the two MOS detectors. We reduced the data with the XMM-Newton Science Analysis Software (SAS), version 13.0.0, using the most up to date calibration files. We checked our reduced event files for hard X-ray background flares ($> 10$ keV), but no significant flaring occurred during the exposure.

Of the 135 EPIC sources detected in the 30' field of view of our observation, we found one source coincident with J1329+3234 (hereafter S1) and one source $\sim 20''$ to the SW of J1329+3234 (hereafter S2) on-axis with an angular resolution of 6''. In Figure 3.1, we show the 2-10 keV pn image of J1329+3234. Neither source shows any evidence of being extended, as confirmed by the automated XMM-Newton pipeline.

#### 3.3.2 Large Binocular Telescope Observations

Since there are two X-ray sources detected in our XMM-Newton observations, we obtained an optical spectrum of our target that includes S1 and S2 on UT Feb 17, 2014 using the
Multi-Object Double Spectrograph 1 (MODS-1; Pogge et al., 2006, 2010) mounted on one of the two 11.8 meter mirrors of the Large Binocular Telescope (LBT). MODS-1 is a low-medium resolution two channel (blue & red) spectrograph mounted on the f/15 Gregorian focus of the SX (left) mirror of the LBT. In two channel mode MODS-1 can simultaneously observe the wavelength range 0.3-1.0$\mu$m. The observations were obtained using only the red arm of MODS-1, which covers 0.49-1.00$\mu$m. The spatial scale of the red arm is 0\,"123 pixel$^{-1}$. A 1\,"2 wide segmented longslit mask was used. The mask contains 5 longslit segments, each 60\," in length. A single segment was sufficient to span S1 and S2. The observations were obtained under thin clouds and in near full moon conditions, for a total of 2400 seconds (2x1200 second exposures). The spectrophotometric standard Feige 67 was observed using the same instrumental setup as our science observations. Slitless pixel flats were obtained to correct for the detector response. Ar, Xe, Kr, Ne and Hg lamps were observed for wavelength calibration and to measure the spectral resolution. The slit was centered on S2 with RA=13h29m31s.269, Decl.=+32\degree33\arcmin59\arcsec.91, and a position angle of 227\degree. Note that while the slit covers much of J1329+3234, we did not center it on J1329+3234, as we did not want to our optical spectrum to overlap with the spectrum from SDSS. Instead, we oriented the slit such that it would cover the K-band concentration possibly associated with S1 in Figure 3.2 (see §3.4.1).

The data were first reduced using Version 0.3 of the modsCCDRed collection of Python scripts. These perform basic 2D reduction including: bias subtraction, removing the over-scan regions, constructing flat fields from the slitless pixel flats, fixing bad columns and flipping the red arm data so that wavelength increases from left to right along the x-axis. Further processing was performed using customized IRAF scripts developed by B. R. Cosmic rays were removed using the task CRUTIL. Two dimensional spectra were extracted in strip mode for the central longslit segment using the task APALL. MODS-1 spectra are tilted along both the spectral (x-axis) and spatial (x-axis) dimensions. The spectra for both exposures were simultaneously corrected in both axes using the arc lines and the IRAF tasks ID, REID, FITC, and TRANSFORM. MODS-1 data are very sensitive to the polynomial
order used to wavelength calibrate the data. A 4th order Legendre polynomial produces the smallest residuals and avoids introducing low-order noise into the 2D spectra. From the arc lamps, the dispersion was measured to be $0.84 \, \text{Å \ pixels}^{-1}$. Measurements of the arc lines yielded a final spectral resolution of $6.77 \, \text{Å}$ for the $1''2$ slitwidth. This corresponds to $R \sim 740-1380$ over the observed wavelength range. Once the 2D spectra were rectified and wavelength calibrated, the background was subtracted in each exposure by fitting a 3rd order Chebyshev polynomial to the columns (spatial axis) using the IRAF task `BACKGROUND`. The two exposures were then combined and flux calibrated using the spectro-photometric standard Feige 67. This step also removes the instrumental signature.

Finally, the data were corrected for atmospheric extinction and galactic reddening assuming $R_V = 3.1$ and a value of $A_V = 0.020$ (Schlafly & Finkbeiner, 2011). A 1D spectra of S1 was extracted from the combined 2D rectified and background subtracted image in an aperture of width 100 pixels or $12''3$ to maximize signal-to-noise, using the task `APALL`. A 1D spectra of S2 was extracted in the same fashion, but using an aperture of width 10 pixels or $1''23$. The 1D spectra were then flux calibrated (removing the instrumental response), corrected for atmospheric extinction, and corrected for galactic reddening using the same values as above.

### 3.3.3 Astrometry

The EPIC X-ray event files for J1329+3234 were not astrometrically corrected. This introduced a $\sim 4''$ offset between the location of nearby X-ray sources (including S2) and their putative optical counterparts in the SDSS field. We manually inspected the *XMM-Newton* pipeline astrometric solution of the optical monitor $B$-band image by blinking it with the SDSS $g$ image, and found it to be sufficient to apply to our X-ray event files. This astrometric solution applies an offset of $\Delta RA = -3.2''$ and $\DeltaDecl. = 3.4''$. The astrometry corrected EPIC data confirms that the position of S1 does coincide with the position of the red *WISE* source (Figure 3.1). The *XMM-Newton* pipeline formal astrometric uncertainties (the astrometric uncertainty after correction) is $0.47''$ and $0.51''$ for S1 and S2, respectively.
Figure 3.1: Smoothed pn 2-10 keV image with WISE 4.6\(\mu\)m source contours overlaid in white. The pn image was binned by a factor of 32 and smoothed with a Gaussian kernel of 4 pixels. The green circles represent the centroids of S1 to the NE and S2 to the SW, with radii representing their 1\(\sigma\) formal astrometric uncertainties.

While J1329+3234 is not bright enough to have been detected by 2MASS, it was detected in the UKIDSS survey\(^1\), enabling us to examine the near-infrared \(K\) band (Figure 3.2). J1329+3234 in the \(K\) band displays an irregular, clumpy structure, with no discernible photo center. Optically, J1329+3234 also presents an irregular structure, with no unambiguous photo center (Figure 3.3). The location of S2 is consistent with an optical concentration with no obvious association with J1329+3234, and S2 likely a background AGN (see §3.4.2). This optical concentration source does not appear in any QSO catalogs and does not appear to have been studied before in any way.

\(^1\)www.ukidss.org/
Figure 3.2: UKIDSS $K$ band image of J1329+3234 with the (unresolved) WISE 4.6$\mu$m source overlaid as contours. The UKIDSS and WISE astrometric accuracies are $0.1''$ and $0.2''$, respectively. The green circles represent the centroids of S1 to the NE and S2 to the SW, with radii representing their 1$\sigma$ formal astrometric uncertainties. The position of the LBT slit is outlined in dashed line, with the apertures used for S1 and S2 solid ($12.3''$ and $1.2''$, respectively). The red arrow marks the possible near-IR counterpart to S1.
Figure 3.3: Smoothed SDSS $ugr$ image of J1329+3234 with $WISE$ 4.6$\mu m$ source contours overlaid. The green circles represent the centroids of S1 to the NE and S2 to the SW, with radii representing their $1\sigma$ formal astrometric uncertainties.
3.3.4 X-ray Analysis

We extracted X-ray spectra for both sources following standard procedures, and grouping the spectra by a minimum of 15 counts per channel for the $\chi^2$ statistic. Due to the projected proximity of the sources ($\sim 20''$), we extracted spectra using apertures that corresponded to the half-energy diameter of an on-axis point-source ($\sim 15''$ for pn) in order to minimize cross-contamination. We performed spectral analysis on the binned spectra using XSPEC version 12.7.0 (Arnaud, 1996) and using the online Chandra Colden\(^2\) tool to find the Galactic neutral hydrogen column density for J1329+3234, which we account for in our spectral analysis as a fixed photo-electric absorption multiplicative component ($wabs$). We do not explicitly state the inclusion of this spectral model later in the paper, because it is included in all our X-ray spectral modeling, and has a value of $N_H = 1.08 \times 10^{20}$ cm$^{-2}$. While we primarily focused our spectral analysis on the higher signal-to-noise pn data, we also performed simultaneous spectral fitting on the data from all three detectors by multiplying each spectrum by a separate constant that was free to vary, holding the values of the spectral parameters identical between spectra. This allowed inter-detector sensitivity variability to be accounted for without compromising the overall spectral fit. The value of this constant was generally close to unity. To derive fluxes and errors, we appended the $cflux$ convolution model, holding the model normalization fixed. All errors in this work are $1\sigma$.

3.4 Results

3.4.1 S1

We fit the X-ray spectrum for S1 with a simple power-law spectrum, achieving a good fit ($\chi^2$/degrees of freedom (d.o.f.) = 11/10 = 1.1) with $\Gamma = 1.3 \pm 0.1$. We achieve a comparable fit with the addition of an intrinsic absorber ($zwabs$, $\chi^2$/d.o.f. = 8.6/9 = 0.96), but we do not find the fit to be sensitive to this addition due to low counts. In Figure 3.4, we show the best-fit spectrum for S1. We derive unabsorbed full and hard band X-ray fluxes

\(^2\)cxc.harvard.edu/toolkit/colden.jsp
of log $F_{0.3-10\text{ keV}} = -13.3 \pm 0.1$ erg cm$^{-2}$ s$^{-1}$ and log $F_{2-10\text{ keV}} = -13.4 \pm 0.1$ erg cm$^{-2}$ s$^{-1}$, translating to a full band luminosity of $L_{0.3-10\text{ keV}} = (3.0 \pm 0.7) \times 10^{40}$ erg s$^{-1}$ and a hard X-ray luminosity of $L_{2-10\text{ keV}} = (2.4 \pm 0.6) \times 10^{40}$ erg s$^{-1}$, similar to the hard X-ray luminosities found in LINERS and low-luminosity Seyferts (e.g., Terashima et al., 2002).

Given the vicinity of S2 to S1, we extracted the S1 light curves from a circular region with a radius of 11$''$ and the background light curve from a larger nearby region without X-ray sources. We extracted light curves in the soft (0.3-2 keV), hard (2-10 keV), and total (0.3-10 keV) energy bands, and tried different time bins (from 250s to 1000s) to investigate the presence of variability based on a $\chi^2$ test. Only the hard light curves shows evidence for variability irrespective of the time bin used. However, a closer look at the hard background-subtracted light curves reveals the presence of spurious negative values (they are about one order of magnitude smaller that the average count rate), which can be explained by statistical fluctuations of the background light curve combined with the low count rate of the source. Once these spurious data points are removed, only the 1000s
light curve shows some suggestive evidence for variability. Specifically, using the “lcstats” routine from Xronos\(^3\) we got the following results: for the 2-10 keV light curve with 25 data points \(\chi^2=34.7\) with a corresponding probability of constancy \(P_{\chi^2}=0.07\); for the 0.3-10 keV light curve with 34 data points \(\chi^2=33.9\) and \(P_{\chi^2}=0.42\); whereas for the soft 0.3-2 keV light curve with 33 data points \(\chi^2=35.8\) and \(P_{\chi^2}=0.29\). We therefore conclude that only the hard light curve is not consistent with the hypothesis of constancy. In Figure 3.5, we show the 2-10 keV background-subtracted light curve (filled red circles) along with the background light curve (open diamonds, which does not show any significant variability: \(\chi^2=16\) for 25 degrees of freedom and \(P_{\chi^2}=0.91\)) where the time bins are 1000s.

**Near-IR Counterpart of S1**

While there is no obvious optical counterpart for S1, the UKIDSS dataset reveals a possible counterpart in the near-IR. The source, marked with a red arrow in Figure 3.2, is unresolved (median seeing \(\sim 0.5''\)), and corresponds to “sourceID”=433793068380 in the

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\(^3\)https://heasarc.gsfc.nasa.gov/xanadu/xronos/xronos.html
\(^4\)www.ukidss.org/sciencecase/proposal/proposal.wfcam.html
UKIDSSDR9PLUS database, at RA=13^h29^m32^s.39, Decl.+32°34′13″.1. The near-IR Y, H, and K magnitudes for this source are 20.3 ± 0.2, 18.5 ± 0.1, and 17.0 ± 0.1, respectively. The J band magnitude was not measured successfully. This source possibly corresponds to SDSS “objectID”=1237665126939754597, which has a very faint r band magnitude of 23.2 ± 0.3, but this source’s photometry suffers from flux interpolation and deblending problems, so this magnitude value should be considered tentative.

**Optical Spectrum of S1**

The position of the LBT slit overlapped with the position of the near-IR counterpart to S1 described above, as well as the position of S2. In Figure 3.6, we plot the 1D optical spectrum corresponding to the position of this near-IR counterpart. While we detect an H\(_\alpha\) line at \(\lambda=6665.5\) Å (\(z=0.0156\)), we do not detect any other lines at a significant level. The RMS for the H\(\beta\) and [O III]5007Å lines is \(\approx 8 \times 10^{-18}\) erg cm\(^{-2}\) s\(^{-1}\) and \(\approx 7 \times 10^{-18}\) erg cm\(^{-2}\) s\(^{-1}\) for the [N II]6584Å line. The total H\(\alpha\) flux within the 12.3″ aperture is \(F_{\text{H}\alpha}=(5.92 \pm 0.37) \times 10^{-16}\) erg cm\(^{-2}\) s\(^{-1}\). The optical spectrum for this region therefore shows no signatures of an AGN, as optically-identified AGNs typically have [N II]/H\(\alpha\) line ratios between \(\approx 0.6-1.2\).

**3.4.2 S2**

We fit the X-ray spectrum for S2 using all three detectors, and found that the source can best be fit by a simple power law with \(\Gamma = 1.6 \pm 0.1\) (Figure 3.7), although the spectra are still slightly over-fit even with a simple power law (\(\chi^2/\text{d.o.f.}=6.4/11=0.6\)). We derive unabsorbed full and hard band X-ray fluxes of \(\log F_{0.3-10\ \text{keV}} = -13.4 \pm 0.1\) [erg cm\(^{-2}\) s\(^{-1}\)] and \(\log F_{2.0-10\ \text{keV}} = -13.6 \pm 0.1\) [erg cm\(^{-2}\) s\(^{-1}\)], translating to full and hard X-ray luminosities of \(L_{0.3-10\ \text{keV}} = (1.2 \pm 0.3) \times 10^{42}\) erg s\(^{-1}\) and \(L_{2.0-10\ \text{keV}} = (7.3 \pm 1.7) \times 10^{41}\) erg s\(^{-1}\) given its redshift (See §3.4.2). We do not find evidence for variability in any energy band.
Figure 3.6: The LBT optical spectrum of the S1 counterpart. The red line denotes the fit to the continuum and H$\alpha$ line, while the gray denotes the RMS noise. The dotted lines on the left denote where H$\beta$ and [O III]5007 Å would be if they were detected. The apparent structure between 7600 Å and 8200 Å is due to noise and is not real. At $\lambda >$ 8100 Å the night-sky lines for these observations subtracted out rather poorly, yielding noisy data.

Figure 3.7: Best fit spectral model for S2. The black line represents the pn data and the green and red line represent the data from the two MOS detectors.
Optical Spectrum of S2

Figure 3.8 shows the final 1D spectrum corresponding to S2 covering the wavelength range from 5300-9100Å. At $\lambda > 8100$Å the night-sky lines for these observations subtracted out rather poorly, yielding noisy data (see for example the noise spike at 8930Å in Figure 3.8). Only one emission line is detected in the spectrum at $6.7\sigma$. Although a confirmed redshift cannot be ascertained from this data, we can constrain a likely redshift based on the assumption that the detected line is H\(\alpha\). Given the broad wavelength range shown, if the line were H\(\beta\), then we would see H\(\alpha\) in the same window, assuming Case B recombination (Osterbrock, 1989), at least 2.86 times as strong as H\(\beta\). We can also eliminate the possibility that the line is Lyman-\(\alpha\) because there is strong continuum detected significantly blueward of the expected Lyman limit; there are no strong emission lines corresponding to CIV or CIII (all of which would fall within the wavelength range of our observations), and the flux associated with both the line and the XMM-Newton observations would be uncharacteristically bright for the required redshift of $z \sim 5$. The absence of H\(\beta\), or rather, the failure to detect H\(\beta\) is not unexpected if the H\(\alpha\) from S2 arises from a Broad Line Region (BLR) in a radio galaxy or Seyfert 1.8/1.9, where the Balmer decrement can be up to a factor of 10 (e.g., Crenshaw et al., 1988, Osterbrock, 1981, Osterbrock et al., 1976). If the object is a QSO or Seyfert 1 the decrement could be up to a factor of 5 (e.g., Dong et al., 2005, Osterbrock, 1977). All of these scenarios would place the H\(\beta\) line beyond the detection limits of the MODS-1 observations. Thus, assuming the detected emission line is H\(\alpha\), S2 would therefore be a background AGN at $z = 0.108$ and not associated with J1329+3234. The total H\(\alpha\) flux within the 1.2" aperture is $F_{\text{H}\alpha} = (8.1 \pm 1.2) \times 10^{-16}$ erg cm$^{-2}$ s$^{-1}$.

3.5 Discussion

3.5.1 X-ray Emission from X-ray Binaries

Since the X-ray luminosity of J1329+3234 is low compared to powerful AGNs, we investigated the possibility that the observed X-ray emission is due to the integrated emission
from a population of low mass and high mass X-ray binaries (LMXRBs and HMXRBs). Numerous studies of galaxies without AGNs have show that non-AGN X-ray emission is a function of the star formation rate (SFR) and the stellar mass of the host galaxy (e.g., Boroson et al., 2011, Lehmer et al., 2010, Ranalli et al., 2003). Because of the large difference between the SDSS fiber area and the X-ray extraction aperture (7 arcsec$^2$ vs. 180 arcsec$^2$), applying a simple geometric aperture correction to the extinction-corrected H$\alpha$ luminosity introduces too much uncertainty into the estimate for the star formation rate. We therefore use the SFR from the Max Planck Institut fur Astrophysik/Johns Hopkins University (MPIA/JHU) collaboration$^5$, which follows Brinchmann et al. (2004) with photometric corrections following Salim et al. (2007). In short, for galaxies without optical line emission evidence for AGN activity, fiber SFRs are “aperture corrected” by fitting stellar population models to photometry outside of the fiber and then calculating the galaxy-wide SFRs.

We note, however, that this represents the full, galaxy-wide SFR, and so somewhat

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$^5$www.mpa-garching.mpg.de/SDSS/
Figure 3.9: X-ray luminosity expected from the combined emission from X-ray binaries as a function of star formation rate from Lehmer et al. (2010) together with the observed $L_{2-10\text{ keV}}$ luminosity of J1329+3234. The gray shading indicates the 1σ scatter on the Lehmer et al. (2010) relation (0.34 dex).

It is important to note, however, that the galaxies used in the sample of Lehmer et al. (2010) were massive, luminous infrared galaxies (LIRGs), and so it may not be the case that the calibration factors presented therein are accurate for a dwarf galaxy such as J1329+3234. Indeed, recent studies (e.g., Kaaret et al., 2011, Mapelli et al., 2010, Prestwich et al., 2013) have reported enhanced production of X-ray emission from XRBs in extremely low-metallicity galaxies relative to the star formation rate, presumably as a result of the
presence of more massive stars and an enhancement of the accretion rates in low metallicity environments. While J1329+3234 is not an extremely metal poor dwarf galaxy for its mass ($\approx 40\%$ solar) we nonetheless estimated the X-ray emission produced by star formation assuming the relation found in extremely metal poor dwarfs. Using a sample of BCDs with $Z/Z_{\odot} < 0.1$, Brorby et al. (2014) find that the X-ray emission produced for a given SFR is approximately an order of magnitude larger than that found in near solar metallicity galaxies (see also Kaaret et al., 2011). Even if we combine this calibration factor with the $3\sigma$ upper limit to the hard X-ray luminosity due to the galaxy-wide SFR, the X-ray emission predicted from star formation ($L_{2-10\text{ keV}} = 1.4 \times 10^{40} \text{ erg s}^{-1}$) is still about half the value that we observe.

As a further check on the possibility of HMXRB contamination, we explored the possibility that there may be heavily obscured star formation that would not reveal itself using traditional optical diagnostics. To obtain an extinction-insensitive upper limit on the SFR, we used the source lower sensitivity limit at 1.4 GHz derived from the Karl G. Jansky Very Large Array (VLA$^6$) NVSS survey, in which J1329+3234 is not detected, which has a typical lower flux density limit for detected sources of 2.5 mJy. We derive a non-detection 1.4 GHz luminosity upper limit of $L_{1.4\text{ GHz}} < 1.5 \times 10^{21} \text{ W Hz}^{-1}$. Combining this luminosity limit with Eq. 23 from Condon (1992) for the 1.4 GHz thermal free-free emission due to star formation, we derive an upper limit to the star formation rate of $\text{SFR}(M > 5 M_{\odot}) < 2.8 M_{\odot} \text{ yr}^{-1}$. Propagating this through the Lehmer et al. (2010) relation, we find an upper limit to the HMXRB X-ray luminosity of $\log L_{2-10\text{ keV}} < 39.7$, still nearly an order of magnitude less than what we measure, and less than what we measure at the $+2\sigma$ level on the Lehmer et al. (2010) relation. Furthermore, the angular resolution limit of the NVSS survey is $\sim 45''$, encompassing all of J1329+3234 and is considerably more than the angular resolution of \textit{XMM-Newton}, and so this upper limit on the SFR should be considered very conservative.

Finally, we note that the likely variability of S1 (See §3.4.1), indicates that the X-ray

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$^6$The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.
emission is originating from a single source, further making it unlikely that a population of XRBs is responsible for the emission.

### 3.5.2 ULX Origin for the X-ray emission

Given the relatively low X-ray luminosity of S1, we investigated the possibility that the X-ray source in J1329+3234 is an ultraluminous X-ray source (ULX). ULXs are off-nuclear X-ray sources with luminosities in excess of $10^{39}$ erg cm$^{-1}$, which is the Eddington luminosity of a 10 $M_\odot$ stellar mass black hole. The luminosities of ULXs can be produced either by anisotropic emission (beaming) or super Eddington accretion from a stellar sized black hole or by accretion onto intermediate mass black holes (IMBHs), the latter scenario still being the subject of significant controversy (for a recent review see Feng & Soria, 2011).

ULXs are generally rare; however they are preferentially found in regions of enhanced star formation (e.g., Gao et al., 2003, Mapelli et al., 2008) and low metallicity (e.g., Prestwich et al., 2013, Thuan et al., 2014), and the occurrence rate per unit galaxy mass is higher in dwarfs than more massive galaxies (Swartz et al., 2008). Recently Somers et al. (2013) found 16 ULXs in 8 bulgeless galaxies, some with luminosities in excess of $10^{40}$ erg cm$^{-1}$. This raises the possibility that the X-ray source in J1329+3234 is a ULX, and therefore possibly consistent with a stellar sized black hole.

We investigated the possibility that the X-ray source in J1329+3234 is a ULX by comparing the X-ray and mid-infrared properties of J1329+3234 with those of definitive AGNs and ULXs that are cleanly separated from their galaxies’ nucleus. In AGNs, the hard X-ray emission and the mid-infrared continuum emission is strongly correlated (Lutz et al., 2004). This is expected because the hard X-ray emission provides a direct view of the central engine, and the nuclear infrared continuum is dominated by thermally reprocessed radiation from the AGN. We derived our sample of AGNs in the following manner: We cross-matched the final WISE all-sky data release catalog (AllWISE)\(^7\) with the 3XMM-DR4 catalog to within

\(^7\)wise2.ipac.caltech.edu/docs/release/allsky/
less than $< 1''$, and obtained redshifts from SDSS DR10\(^8\) in a similar manner. We required that the WISE W1, W2, and W3 band fluxes have a signal-to-noise ratio greater than or equal to $\geq 5$, and that there be no photometric quality or source extent flags. We similarly required that the XMM-Newton hard band “SC_EP4_FLUX” and “SC_EP5_FLUX” values have a combined signal-to-noise ratio greater than or equal to $\geq 5$, and that there be no high background level (flaring) flags. We further required that the X-ray sources show no sign of spatial extent by requiring the “SC_EXTENT” flag be equal to 0, and that the source observation off-axis angles be less than $< 5'$ to minimize off-axis aberrations. We finally required redshifts greater than $z \geq 0.01$ to reduce distance errors. This selection yielded 184 AGNs with 2-10 keV luminosities between $\log L_{2-10 \text{ keV}} = 42.1\text{-}46.7$ and W2 luminosities between $\log L_{W2} = 42.2\text{-}46.5 \text{ [erg s}^{-1}]$. The mean mid-IR colors of these 184 AGNs are $W1-W2 = 1.01$ mag. and $W2-W3 = 2.98$ mag., with standard deviations of 0.29 mag. and 0.35 mag., respectively. We estimated the linear regression fit between $L_{2-10 \text{ keV}}$ and $L_{W2}$ by drawing $10^5$ random samples with replacement (bootstrapping) of our 184 AGNs, finding a strong correlation (Pearson $r = 0.91$) with:

$$\log L_{2-10 \text{ keV}} = (0.93 \pm 0.03) \cdot \log L_{W2} + (3.26 \pm 1.25)$$

with a standard deviation of $\sigma = 0.40$ dex in the $\log L_{2-10 \text{ keV}}$ direction and the units of luminosity used being erg s$^{-1}$. For comparison, we fit the 6$\mu$m continuum/2-10 keV X-ray luminosity data used for a sample of Sy 1 and Sy 2 galaxies in Lutz et al. (2004), and found good agreement, with a slope of $0.95 \pm 0.08$, intercept of $1.63 \pm 3.50$, and $\sigma=0.43$ dex.

In order to compare the mid-IR and X-ray properties of these AGNs with those of ULXs, we used the most recent and comprehensive catalog of ULXs by Walton et al. (2011), which consists of 470 ULX candidates, located in 238 nearby galaxies, generated by cross-correlating the 2XMM Serendipitous Survey (Watson et al., 2009) with the Third Reference Catalogue of Bright Galaxies. We crossmatched this catalog with AllWISE to within less

\footnote{www.sdss3.org/dr10/}
than $< 1''$ and find that 228 ULXs are associated with WISE sources. Of these, only 57 had WISE photometry with W1, W2, and W3 detections with signal-to-noise greater than 3σ, and all are extended in the WISE bands, suggesting that these ULXs are not being detected in the mid-IR themselves, but rather are simply associated with large-scale, extended emission from star formation. In Figure 3.10, we plot the hard X-ray luminosity versus the W2 band luminosity for AGNs, ULXs, and J1329+3234, along with the linear regression derived above. As can be seen, J1329+3234 has mid-IR and X-ray properties completely consistent with AGNs, while ULXs do not. We further note in Figure 3.10 that NGC 4395, the archetypical bulgeless dwarf Seyfert 1 galaxy, also follows this trend derived from much brighter AGNs, implying that AGNs do not deviate significantly from this relationship for a wide range of X-ray luminosities.

The ULXs are also associated with significantly different mid-IR colors than AGNs. The average W1-W2 color associated with these 57 ULX sources detected by WISE is 0.07, with a maximum of 0.57. In Figure 3.11, we plot the W1-W2 versus W2-W3 colors of the ULXs, our AGN sample from above, J1329+3234, normal galaxies from SDSS, and the 3-band AGN demarcation region from Jarrett et al. (2011). As can be seen, the ULXs are clearly separated from J1329+3234, which falls well within the AGN region of the color-color diagram, as do the majority of our sample AGNs. Even amongst the most extreme ULXs ($L_{2-10 \text{ keV}} > 10^{40} \text{ erg s}^{-1}$) in this catalog (Sutton et al., 2012), all of which are well separated from the galaxy nuclei and are unlikely to be background AGNs, only 3 are associated with WISE sources, all of which are resolved and none have red WISE colors.

### 3.5.3 Red WISE Colors in Low Mass Starburst Galaxies

Given the above considerations, the only plausible explanation for the mid-IR and X-ray properties of J1329+3234 is the presence of an AGN. We note, however, that J1329+3234 is certainly not the only dwarf galaxy with extreme or unusual mid-IR colors. For example, Izotov et al. (2011) find, from a sample of $\sim 5000$ SDSS galaxies with WISE colors, 4 dwarf galaxies with extreme WISE colors $W1-W2 > 2$ mag. Like J1329+3234, these galaxies
Figure 3.10: The observed 2-10 keV luminosity versus the W2 luminosity for our sample of AGNs, ULXs, and J1329+3234. For comparison, we also plot NGC 4395, the archetypical bulgeless dwarf Seyfert 1 galaxy. The dashed line represents the linear regression described in §3.5.2 with the $1\sigma$ scatter in gray.
Figure 3.11: $W_1$-$W_2$ color versus the $W_2$-$W_3$ color for AGNs, ULXs, and J1329+3234, with NGC 4395 included for comparison. The AGN region from Jarrett et al. (2011) is also shown as the dashed line, and the typical uncertainty for the AGN colors is given by the black cross at the top right.
are in the mass range of $M_* \sim 10^{8-9} M_\odot$, and like J1329+3234, these galaxies are not particularly metal-poor dwarfs, with $Z/Z_\odot=0.2-0.5$. However, these four galaxies occupy a completely different region of mid-IR color space than J1329+3234, not only with $W1-W2=2.13-2.37$, but most notably with $W2-W3=3.58-4.76$, indicating considerably more emission at longer wavelengths from dust heating due to starbursts. Indeed, the SFRs of these four galaxies are in the range of 5.8 to 26.5 $M_\odot$ yr$^{-1}$, at least two orders of magnitude higher than J1329+3234. Finally, there exists a single Chandra observation of one of the four galaxies from Izotov et al. (2011), J1457+2232, observed 2007 March 23 with ACIS-I for 7.2 ks (ObsID 7709; PI: Garmire). The galaxy is not detected, with a $3\sigma$ upper limit to the 2-10 keV flux of $\sim 3 \times 10^{-15}$ erg cm$^{-2}$ s$^{-1}$, assuming a similar X-ray spectrum to J1329+3234. Given this galaxy’s relatively high mid-IR luminosity of $L_{W2} = 5.0 \times 10^{42}$ erg s$^{-1}$, this galaxy is at least two orders of magnitude underluminous in the hard X-rays compared to AGN-hosting galaxies (see §3.5.2), with a $3\sigma$ hard X-ray upper luminosity limit of $L_{2-10 \text{ keV}} < 2.0 \times 10^{41}$ erg s$^{-1}$. Thus, we conclude that the colors of J1329+3234, along with the SFR and the X-ray luminosity, are not consistent with a population of low-mass starburst galaxies.

3.5.4 Black Hole Mass

Because the ratio of the hard X-ray luminosity to the mid-IR luminosity is consistent with what is seen in AGNs, it is unlikely that we are seeing beamed X-ray emission. With this in mind, we can immediately calculate the Eddington lower mass limit. Using a conservative bolometric correction factor of $\kappa := L_{\text{bol.}}/L_{2-10 \text{ keV}} = 15$ (Vasudevan & Fabian, 2007, 2009), we get a lower mass limit of $M_{\text{BH}} > 2.9 \times 10^3 M_\odot$. More realistically, the black hole is not radiating at its theoretical upper limit. If the black hole is accreting at a rate similar to that found for the sample of low-mass black holes from Greene & Ho (2007), then $L_{\text{bol.}}/L_{\text{Edd.}} \sim 0.4$ and the black hole mass is $M_{\text{BH}} = 7.3 \times 10^3 M_\odot$. There is considerable spread in their sample, however, and several low-mass black holes radiate as low as $L_{\text{bol.}}/L_{2-10 \text{ keV}} \sim 0.02$. In this case, the $M_{\text{BH}}$ in J1329+3234 has a mass of about $M_{\text{BH}} \sim 1.5 \times 10^5 M_\odot$. 

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3.5.5 Host Galaxy Properties

J1329+3234 is a very low luminosity dwarf. The absolute $g$ band magnitude is -16.3, almost two magnitudes fainter than the LMC (Tollerud et al., 2011), and approximately 2 magnitudes fainter than the mean magnitude of the host galaxies in the sample of dwarfs with optical AGNs from Reines et al. (2013), which are in turn considerably fainter than previous samples of low mass optically identified AGNs (e.g., Dong et al., 2012, Greene & Ho, 2007). Based on the SDSS images, the host galaxy reveals an irregular clumpy morphology in the optical, typical of irregular dwarf galaxies. J1329+3234 is slightly extended for a galaxy in its mass range, with a Petrosian half-light radius $r_{50} = 1.82$ kpc, which is more extended than about $\sim 75\%$ of the galaxies in the mass range $\log M_{\star}/M_\odot = 8.1 - 8.3$, and somewhat more extended than the original definition of a blue compact dwarf galaxy (BCD; Thuan & Martin (1981)). We used the two dimensional parametric fitting program galfit (Peng et al., 2010) to model the $g$ band image of J1329+3234. The best fit model consists of a single Sersic with $n = 0.9$, consistent with an exponential disk and two off-nuclear clumpy structures. There is no evidence for a bulge component based on the SDSS images and no clear spiral structure apparent in the SDSS bands. While AGNs are found in disk galaxies, the fraction of optically selected AGNs even within low mass galaxies is higher in galaxies with higher Sersic indices (e.g., Reines et al., 2013). The $g - r$ color of J1329+3234 is -0.5 mag., comparable to the median color of the dwarfs studied by Reines et al. (2013).

The stellar mass of J1329+3234 from the NASA-Sloan Atlas (NSA)\(^9\) is $\log M_{\star}/M_\odot = 8.3$, similar in mass to the SMC (e.g., Skibba et al., 2012), and less massive than any of the 35 optically-identified AGNs dwarf galaxies from Reines et al. (2013). If more galaxies in this mass range are confirmed to host AGNs through X-ray observations, then a key result from this study is that the fraction of AGNs at low stellar masses, revealed by WISE, may be much higher than the fraction of AGNs revealed optically (Satyapal et al., 2014). This is in direct contrast with results from optical spectroscopic surveys, which show that the

\(^9\hspace{1em}www.nsatlas.org\)
AGN fraction approaches nearly 100% for all emission line galaxies at the highest masses and drops dramatically with decreasing stellar mass (see Figure 5, solid histogram in top panel, in Kauffmann et al., 2003).

3.6 Summary and Conclusions

We have conducted our first follow-up X-ray observations of a newly discovered population of low mass and bulgeless galaxies that display extremely red mid-infrared colors highly suggestive of a dominant AGN despite having no optical signatures of accretion activity. Our main results can be summarized as follows:

1. Using XMM-Newton observations, we have confirmed the presence of a hard X-ray point source consistent with AGN activity in J1329+3234, an optically normal dwarf galaxy with red infrared colors obtained from WISE.

2. The X-ray luminosity of J1329+3234 is $L_{2-10\text{ keV}} \sim 2.4 \times 10^{40} \text{ erg s}^{-1}$. Assuming that the black hole is radiating at the Eddington limit and using a conservative bolometric correction factor of $\kappa := 15$, this corresponds to a lower limit on the black hole mass of $M_{\text{BH}} > 2.9 \times 10^{3} \, M_{\odot}$.

3. From multi-wavelength considerations, the X-ray/mid-IR activity of J1329+3234 is consistent with the presence of an AGN, and it is unlikely that the X-ray source in J1329+3234 is due to X-ray binary activity or is a ULX.

4. With a stellar mass of $\sim 2.0 \times 10^{8} \, M_{\odot}$, J1329+3234 is among the lowest mass dwarf galaxies with evidence for AGN activity currently known.
3.7 Acknowledgements

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Chapter 4: Future Work

In this chapter, I will elaborate on the status of a number of near-term projects that form a natural continuation of this work.

4.1 Archival X-ray Selected Dwarf Galaxies

4.1.1 Background

Given the rarity of AGNs in the low mass regime, a systematic approach to finding them is required to increase the number of confirmed cases, and to obtain a statistically meaningful understanding of the SMBH population and occupation fraction at low masses. Using data from the all-sky Wide-field Infrared Survey Explorer (WISE), we recently discovered several hundred optically normal bulgeless galaxies with extreme mid-IR colors suggestive of the presence of an AGN (Satyapal et al., 2014). This is because hot dust surrounding AGNs produces a strong mid-infrared continuum and infrared spectral energy distribution that is clearly distinguishable from star forming galaxies in both obscured and unobscured AGNs (e.g., Jarrett et al., 2011, Stern et al., 2012). In particular, at low redshift, a simple color cut of $W1-W2 > 0.8$ picks out AGNs at a reliability of 95% (see Figures 5 and 6 in Stern et al. 2012 and Figure 1 in Assef et al. 2013).

While mid-IR selection has been shown to be a promising method for differentiating AGNs from starbursts, as well as picking out Compton-thick ($N_H \gtrsim 10^{24} \text{ cm}^{-2}$) AGNs (see, for example, Donley et al., 2012), no one wavelength band is optimum for picking out AGNs completely. X-ray selection, while ineffective for Compton-thick AGNs, has the advantage of being able to distinguish weakly-accreting AGNs from surrounding star formation through the presence of hard ($\gtrsim 2 \text{ keV}$) X-ray photons created via inverse Compton up-scattering in
a highly energetic corona surrounding the innermost accretion region of an AGN. Where the standard BPT diagnostics may fail due to contamination by star formation of the harder optical line ratios arising from the NRL, very few astrophysical phenomena other than AGNs produce hard X-rays in abundance.

In our recent XMM program, we followed up on our WISE discovery of low-mass, optically normal galaxies and confirmed the presence of AGNs in one of two bulgeless galaxies observed (Secrest et al., 2014, see Chapter 3)\(^1\). The most X-ray bright of these two galaxies, J1329+3234, is a diffuse, irregular optically quiescent dwarf galaxy similar in morphology to He 2-10, but a factor of ten less massive and a factor of ten more luminous in the X-rays, suggesting that WISE may be able to reveal rapidly accreting, buried AGNs in the lowest mass dwarf galaxies. These XMM observations have discovered an AGN in one of the lowest mass dwarf galaxies known in the Universe. Based on the red \(W1-W2\) color, not only does this galaxy harbor an AGN, but the AGN must dominate the bolometric luminosity of the galaxy, since in low redshift sources, it is difficult to replicate the observed colors without an energetically dominant AGN (Assef et al., 2013). This was the only dwarf in our previous XMM program. With only one example of such objects, it is impossible to know if this object is an anomaly or if it represents a remarkable as yet undiscovered population. Follow up observations are critical to determine the fraction of these red WISE dwarfs that are indeed AGNs and to address important questions such as: Why do some dwarf galaxies host SMBHs and some do not? How do optically identified AGNs differ from the obscured population? Is the presence and properties of the black hole related in any way to the properties of the host galaxies in the extreme low mass regime? A statistically significant sample of dwarf galaxies with confirmed SMBHs is crucially needed in order to make significant progress in the study of SMBH formation, growth and the connection with galaxy evolution.

To this end, we turn our sights to searching for AGNs in dwarf galaxies through an

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\(^1\)There were originally three bulgeless galaxies observed in our XMM program; however, one of the three was revealed to not actually have red \(W1-W2\) colors in the final data release from WISE (AllWISE). The second bulgeless galaxy may have a more complicated SED and is still under study.
independent search for optically-obscured AGNs through archival X-ray data, which will make up the bulk of this work. For the purposes of this project, we define a dwarf galaxy as any galaxy with \( \log(M/M_\odot) < 10 \), which is the mass cutoff below which almost no optically-identified AGNs are found (see, for example, Figure 5 of Kauffmann et al., 2003). We assume a \( \Lambda \)CDM cosmology with \( H_0 = 71 \text{ km s}^{-1} \text{ Mpc}^{-1} \), \( \Omega_M = 0.3 \), and \( \Omega_\Lambda = 0.7 \).

4.1.2 Galaxy Selection and Archival Data

We select dwarf galaxies from the NASA-Sloan Atlas (NSA), which contains about 145,000 galaxies selected from the Sloan Digital Sky Survey (SDSS), data release 8 (Aihara et al., 2011), out to a redshift of about \( z \lesssim 0.06 \). The NSA contains photometric measurements using the technique of Blanton et al. (2011), which gives better background subtraction and more accurate flux measurements of galaxies over the standard SDSS photometric pipeline, as well as redshifts, K-corrections, masses, line fluxes, and Sérsic profile fits. The masses are given in units of \( h^{-2}M_\odot \) and were derived using the \texttt{kcorrect} code (Blanton & Roweis, 2007), which fits spectral energy distribution models primarily from Bruzual & Charlot (2003) to the SDSS photometry. We adopt \( h = 0.71 \). We obtain 79,548 galaxies with \( \log(M/M_\odot) < 10 \).

Using TOPCAT (Taylor, 2005), we crossmatched these dwarf galaxies to both The \textit{Chandra} Source Catalog (CSC), release 1.1 (Evans et al., 2010), which contains all sources serendipitously detected by \textit{Chandra} up to 2009 December, and the \textit{XMM-Newton} Serendipitous Source Catalog (3XMM-DR4)\(^2\), which contains all X-ray sources detected by \textit{XMM-Newton} between 2000 February 3 and 2012 December 8.

X-ray Source Catalogs

We crossmatched our dwarf galaxy sample with the CSC by matching all sources using the 95% astrometric confidence ellipses provided by the catalog, and requiring the ACIS B-band (“f\_aper\_b”, 0.5-7.0 keV) signal-to-noise be \( \geq 3 \). Similarly, we crossmatched the galaxies

\(^2\)\url{http://xmmssc-www.star.le.ac.uk/Catalogue/xcat_public_3XMM-DR4.html}
with 3XMMi-DR4 by matching all sources within the 95% confidence radius calculated from the “POSERR” column value for each individual source in the 3XMM-DR4 catalog, and requiring that the band-8 EPIC weighted mean camera flux ("EP_8_FLUX", 0.2-12 keV) signal-to-noise be greater than or equal to 3. In this manner we obtained 145 unique dwarf galaxies with X-ray data.

**AGN Selection Criteria**

Where other authors have elected to use a simple X-ray luminosity cutoff (e.g., Goulding et al., 2014, Lira et al., 2002, Moran et al., 1999), we have elected to use a variable luminosity cutoff that selects galaxies with X-ray emission significantly in excess of that expected from star formation from the host galaxy. Using a randomly selected sample of 32 nearby ($D < 30$ Mpc) NGC and Messier galaxies observed by Chandra and having a wide range of star formation rates, masses, and morphologies, Colbert et al. (2004) explored the relationship between the wide-band (0.3-8.0 keV) X-ray point-source luminosity of galaxies and their luminosities in several optical, infrared, and ultraviolet bands and found that galaxies’ total X-ray point-source luminosities are strongly correlated ($r = 0.90$) with their $B$-band luminosities. This correlation is due to the $B$-band luminosity of a galaxy being a proxy for the galaxy’s total mass and SFR, and therefore the galaxy’s population of low-mass X-ray binaries (LMXBs), high-mass X-ray binaries (HMXBs), and ultraluminous X-ray sources (ULXs).

We can therefore use our galaxies’ $B$-band luminosity to calculate the expected X-ray luminosity from non-AGN objects and select galaxies that significantly exceed this luminosity. Using the high-quality $ugriz$ photometry available in the NSA catalog, we calculate the $B$-band luminosities of our galaxies using the transformation equations of Lupton (2005), which have a scatter of $\sim 0.01$ mag. We calculate the 0.3-8.0 keV luminosities of our targets by assuming a simple power law X-ray spectrum with $\Gamma = 1.8$, typical of AGN spectra, and multiplying the ACIS B-band and XMM-Newton band-8 fluxes by 1.2 and 0.8, respectively,
to correct for the slightly different energy ranges, using the Portable, Interactive Multi-Mission Simulator (PIMMS, Mukai, 1993) and a typical Galactic neutral hydrogen column density $N_H \sim 10^{20} \text{ cm}^{-2}$.

In order to pick out galaxies with significantly higher X-ray emission than what is expected from their masses and SFR, we pick galaxies with 0.3-8.0 keV luminosities higher than the predicted value at the 95% significance level. We also require that there be no evidence for spatial extent of the X-ray source ('extent_flag' = 0 and 'SC_EXTENT' = 0 for CSC and 3XMM-DR4, respectively). These requirements yielded a sample of 33 dwarf galaxies with unusually high X-ray luminosities possibly indicative of the presence of an AGN.

**Other Considerations**

Where high signal-to-noise line fluxes ($S/N \geq 3.0$) are available, we optically classify our targets as either star forming (SF), composite, or AGN using the Baldwin, Phillips, & Terlevich (BPT, Baldwin et al., 1981) composite demarcation of Stasińska et al. (2006) and the AGN demarcation of Kewley et al. (2001) (Figure 4.1). Using these selection criteria, our sample is composed of 10 AGNs, 5 composites, 9 HII galaxies, and 9 unclassified galaxies.

The all-sky *Wide-Field Infrared Survey Explorer* (WISE, Wright et al., 2010) has allowed for the mid-IR characterization of most galaxies identified in the SDSS. We explore the mid-IR properties of our galaxies using *WISE* data and characterize them based on evidence for AGNs. Based on the 3-color AGN diagnostics discussed in Jarrett et al. (2011), 5 out of our 33 dwarf galaxies show evidence for an AGN from their infrared emission alone.$^3$ We plot their mid-IR colors in Figure 4.2.

**4.1.3 Preliminary Results**

We plot our dwarf galaxy sample in Figure 4.3. While optically-identified AGNs/composites extend to much higher X-ray luminosities, we identify several optically-normal galaxies with

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$^3$Mid-IR AGN diagnostics are *reliable* (see Stern et al., 2012) but *not complete*.
Figure 4.1: BPT diagram of our sample. The dashed line is the composite demarcation of Stasińska et al. (2006) while the solid line is the AGN demarcation of Kewley et al. (2001). The black cross at the upper left is the typical error margin for our sample. The gray dots are the full NSA catalog for objects with high signal-to-noise emission line measurements, for comparison.
Figure 4.2: WISE mid-IR colors of our sample. The dashed box is the 3-color AGN diagnostic criteria of Jarrett et al. (2011). For comparison, we also plot J1329+3234 from Secrest et al. (2014), as well as a larger sample of galaxies taken from SDSS as gray dots. Note that in our sample selection we have recovered NGC 4395, which would have been missed by more traditional AGN X-ray diagnostics, since its hard X-ray luminosity is only $\sim 10^{40}$ erg s$^{-1}$. 
Figure 4.3: Plot of our dwarf galaxy sample 0.3-8.0 keV luminosity as a function of $B$-band luminosity. Red squares are optically-identified AGNs, green triangles are optically-identified composites, blue circles are optically normal HII galaxies, and gray diamonds are galaxies without sufficient signal-to-noise for a BPT classification. The solid black line is the Colbert et al. (2004) prediction for non-AGN produced X-ray emission with a scatter of $\sim 0.3$ dex as shaded gray. The small black cross on the lower right is the typical error margin for our sample.

X-ray luminosities more than an order of magnitude higher than what could be expected from X-ray binaries or ULX activity.

As a further check on our method, we also compare the X-ray luminosities of our targets from the expected X-ray luminosity from HMXBs given the UV-calculated SFRs of the galaxies. We use the SFRs and corresponding X-ray luminosities of Mineo et al. (2012), who use the near-UV (NUV) luminosities derived from the Galaxy Evolution Explorer (GALEX) for a sample of 38 late-type, starburst galaxies, predicted from the NUV GALEX absolute magnitudes provided in the NSA (Figure 4.4). Despite the larger scatter in the Mineo et al. relation, all our dwarfs are considerably more X-ray bright than what might be expected if their luminosities were attributable solely to HMXB activity.
Figure 4.4: Plot of our dwarf galaxy sample 0.3-8.0 keV luminosity as a function of NUV-derived SFR. Red squares are optically-identified AGNs, green triangles are optically-identified composites, blue circles are optically normal HII galaxies, and gray diamonds are galaxies without sufficient signal-to-noise for a BPT classification. The dashed black line is the Mineo et al. (2012) prediction for HMXB-produced X-ray emission with a scatter of $\sim 0.4$ dex as shaded gray. The small black cross on the lower right is the typical error margin for our sample.
4.2 Discussion

While these results are preliminary, they are highly suggestive of AGN activity in the low mass regime at a higher fraction than what is seen in optical studies. For example, Reines et al. (2013) find, out of a population of 25,974 dwarf galaxies with masses between \( \log M/M_\odot = 8.5-9.5 \) that have high signal-to-noise (S/N\( \geq 3 \)) SDSS spectra, 151 (0.58%) with any evidence for an AGN. Of those, 35 (0.13%) are BPT AGNs, following the Kewley et al. (2001) demarcation, and 101 (0.39%) are BPT composites, following the Kauffmann et al. (2003) demarcation.

If we limit our sample to the same mass range as the sample of Reines et al. (2013), we have 55 galaxies with X-ray detections in the CSC or 3XMM-DR4 catalog. Of those, 10 (18%) have unusually high X-ray luminosities indicative of possible AGN activity. Even with low count statistics taken into consideration, the percentage of X-ray detected dwarfs (18% ± 6%) is still much higher than the percentage of emission-line dwarfs with evidence for AGN activity. We note that the X-ray luminosities we have calculated have not been corrected for intrinsic absorption, and any Compton-thick AGNs \( (N_H > 10^{24} \text{ cm}^{-2}) \) would not have been detected by \textit{XMM-Newton}, so the fraction of AGNs discovered in this manner is likely a lower limit. In Figure 4.5, we plot the fraction of emission line galaxies with X-ray detections from 3XMM-DR4 that are identified as AGNs using the above method versus mass, as well as optically-identified AGNs using the Kewley et al. (2001) diagnostic for comparison. As can be seen, the fraction of emission line galaxies that are optical AGNs approaches 100% at high stellar mass, in agreement with the finding of Kauffmann et al. (2003), and conversely almost no emission line galaxies at low stellar masses are optically-identified AGNs. However, the fraction that are identified as AGN candidates using our method is considerably higher at lower masses, suggesting that this method could be potentially very powerful at discerning AGNs in low mass galaxies. We note that we limited our sample to 3XMM-DR4 for this comparison because of the off-axis angle column in the catalog, which we limit to \( \theta > 0.5' \) to remove any pointed observations, since they
Figure 4.5: 

**Green:** Fraction of emission line galaxies that are optically-identified AGNs; 
**Red:** Fraction of emission line galaxies qualifying as AGN candidates using our method. While the scatter at lower masses due to low bin counts is considerable, there is a clear trend towards a higher AGN occupation fraction when excess X-ray emission is taken into account.

bias the sample, likely towards large galaxies with bright AGNs. The fraction of AGNs identified using our method does, however, drop off at higher masses, in contradiction with optically-identified AGNs. While we do not yet know the reason for this, it may be related to the sample used in Colbert et al. (2004), which is $\sim$ 80% disk/starforming galaxies, and so our cutoff may be too strict for massive galaxies, which tend to be early-type ellipticals. Finally, we note that X-ray emission due to non-AGN activity may be enhanced as much as a factor of $\sim 10$ in low metallicity dwarf galaxies (see, for example, Brorby et al., 2014), and so extra care should be taken to discern the possible role of metallicity in the enhanced X-ray emission we are seeing. We emphasize that these results are highly preliminary.
4.3 Remaining Work

These results, while promising, require further work. Below I list a tentative plan for the completion of this study:

1. Because we have 33 dwarf galaxies with excess X-ray emission, it is possible to analyze their X-ray data individually. This means re-processing their event files, determining their exact X-ray source positions, and (where possible) extracting and characterizing their X-ray spectra.

2. 17 of the 33 dwarf galaxies have radio data. Using the Fundamental Plane of black hole activity (e.g., Gültekin et al., 2009), constrain the mass of their putative SMBHs.

3. 4 of the 33 dwarf galaxies show evidence of variability. Using the “Excess Variance” method described in Ponti et al. (2012), set mass constraints on their putative SMBHs.

4. Using the more refined results in items 1 and 2, set constraints on the AGN fraction at lower masses that are independent of optical diagnostics.

4.4 XMM-Newton Follow-up Proposal

While the contributions to the understanding of SMBHs in bulgeless and dwarf galaxies made in Secrest et al. (2012), Secrest et al. (2013), and Secrest et al. (2014) have demonstrated the importance of a multi-wavelength approach in the discovery and characterization of such systems, there is much follow-up work to be done. In Secrest et al. (2014), we see that with the X-ray confirmation of an AGN in J1329+3234, WISE pre-selection may prove to be a viable means of discerning AGN activity in dwarf galaxies. This was a pilot study, of course, so we cannot yet make any statistical statements about this population. Nonetheless, we see in §4.1 tantalizing evidence that there may indeed be a population of X-ray selected AGNs that show that the percentage of AGN-hosting dwarf galaxies is much higher than optical studies alone indicate. To bolster these results, we have submitted an XMM-Newton follow-up investigation for AO-14 of 10 bulgeless galaxies with red WISE colors.
indicative of AGN activity.

This sample was constructed by selecting 10 galaxies from the bulgeless sample presented in Satyapal et al. (2014), that meet the most stringent mid-infrared color criteria from Jarrett et al. (2011), which employs the first three *WISE* bands, and show no optical evidence for an AGN. To predict the X-ray luminosities of our targets, we used the tight relationship (Pearson \( r=0.91, \sigma=0.4 \) dex) between \( W2 \) luminosity and 2-10 keV luminosity found for the sample of 184 AGNs described in Secrest et al. (2014). Using this relationship, we predict 2-10 keV luminosities between \( \log L_{2-10 \text{ keV}} = 42.3 - 43.5 \) for our 10 targets (See Figure 4.6). To predict the full band (0.3-10 keV) count rate, we conservatively use the 2-10 keV flux derived from the \(-2\sigma\) lower luminosities derived from the above relation, and we estimate the 0.3-10 keV count rate using *PIMMS*, calculating the count rate for EPIC pn assuming typical absorption \( (N_H=10^{21} \text{ cm}^{-2}) \) and a typical AGN power-law X-ray spectrum with index \( \Gamma=1.8 \). This yields count rates between 0.01 cnt s\(^{-1}\) and 0.05 cnt s\(^{-1}\). As a check on our method, we independently estimated the 0.3-10 keV count rates by using the relationship between the measured 2-10 keV flux and the measured 0.3-10 keV count rate from 3XMM-DR4 for our 184 sample AGNs. This method yielded count rates between 0.04 cnt s\(^{-1}\) and 0.06 cnt s\(^{-1}\) for our 10 targets, in good agreement. We applied for enough exposure time to give at least \( \sim 300 \) counts per target, which is enough to characterize their X-ray spectra using *XSPEC*. \( \sim 300 \) counts per target is enough to be able to distinguish between the presence or non-presence of an AGN in these galaxies, and even a non-detection is scientifically valuable. We also plan to use different filters available for the Optical Monitor, in order to set stringent constraints on the simultaneous SED of our sources.

In order to quantify the level of possible contamination to our targets’ X-ray luminosities by non-AGN sources such as high-mass X-ray binaries (HMXBs), we calculated the expected contamination using the relationship derived by Lehmer et al. (2010) in which the total 2-10 keV luminosity of a galaxy due to HMXBs is derived as a function of star formation rate and galaxy mass. Even using the conservative 95% lower confidence predicted X-ray
Figure 4.6:  **Left panel:** Predicted hard X-ray luminosities of our targets, assuming they are AGNs, given their $W_2$ luminosities and the relationship found in Secrest et al. (2014). Along with our targets and the 184 robustly identified AGNs from Secrest et al., we also plot J1329+3234 from Secrest et al. (2014) and the prototypical dwarf Seyfert 1 NGC 4395, for comparison. The shaded grey area represents ±1σ. We also show the predicted X-ray luminosity of our targets due to XRBs, using the relation from Lehmer et al. (2010). All of our targets have predicted AGN X-ray luminosities orders of magnitude higher than what is attributable to XRBs. In the insert, we display the XMM image of J1329+3245. **Right panel:** Mid-IR color-color diagram of our 10 targets, with the Jarrett et al. (2011) AGN demarcation in dashed line. We have plotted the 184 comparison AGNs discussed in the technical justification.

Luminosities for our targets, if our targets are AGNs, their predicted X-ray luminosities are well in excess of that predicted by star formation, as can be seen in Figure 1 (left panel). Our study is therefore designed to robustly confirm whether or not the proposed targets do contain AGNs. We therefore stress that non-detections in this study are equally as significant: If these galaxies do not turn out to host AGNs, a non-AGN origin of their mid-infrared SEDs would itself be an extraordinary discovery, and will have an impact on the use and reliability of WISE color selection of AGN in other surveys. We summarize our targets in Table 4.1.
<table>
<thead>
<tr>
<th>Name (SDSS)</th>
<th>Distance (Mpc)</th>
<th>W1-W2</th>
<th>W2-W3</th>
<th>log $L_X$ [erg s$^{-1}$]</th>
<th>Count Rate (cnt s$^{-1}$)</th>
<th>Exposure (ks)</th>
</tr>
</thead>
<tbody>
<tr>
<td>J131442.33+353135.8</td>
<td>780</td>
<td>1.01</td>
<td>3.11</td>
<td>43.5</td>
<td>0.038</td>
<td>8</td>
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<tr>
<td>J142847.54+324436.8</td>
<td>950</td>
<td>0.88</td>
<td>3.45</td>
<td>43.3</td>
<td>0.014</td>
<td>22</td>
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<tr>
<td>J154940.85+321330.1</td>
<td>450</td>
<td>1.32</td>
<td>3.57</td>
<td>43.1</td>
<td>0.046</td>
<td>7</td>
</tr>
<tr>
<td>J155409.08+145703.5</td>
<td>640</td>
<td>1.07</td>
<td>3.58</td>
<td>43.1</td>
<td>0.022</td>
<td>14</td>
</tr>
<tr>
<td>J154435.4+420917.7</td>
<td>590</td>
<td>0.83</td>
<td>3.23</td>
<td>43.1</td>
<td>0.022</td>
<td>14</td>
</tr>
<tr>
<td>J232020.09+150420.5</td>
<td>700</td>
<td>0.90</td>
<td>3.65</td>
<td>43.0</td>
<td>0.015</td>
<td>21</td>
</tr>
<tr>
<td>J130131.53+212748.7</td>
<td>400</td>
<td>0.92</td>
<td>2.89</td>
<td>42.8</td>
<td>0.026</td>
<td>12</td>
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<tr>
<td>J164413.51+224927.1</td>
<td>530</td>
<td>1.01</td>
<td>3.54</td>
<td>42.7</td>
<td>0.012</td>
<td>25</td>
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<tr>
<td>J120443.76+050543.8</td>
<td>510</td>
<td>0.80</td>
<td>3.79</td>
<td>42.6</td>
<td>0.010</td>
<td>29</td>
</tr>
<tr>
<td>J123304.57+002347.1</td>
<td>310</td>
<td>1.00</td>
<td>3.64</td>
<td>42.3</td>
<td>0.014</td>
<td>22</td>
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Biography

Nathan Secrest graduated from Walt Whitman High School in Bethesda, Maryland, in 2003. He transferred from Montgomery College, Rockville, to The University of Hawai‘i at Hilo in 2006 to study astronomy. In Hawaii, he worked at the NASA Infrared Telescope Facility and the University of Hawai‘i 2.2-meter telescope, and he worked and volunteered extensively as both an interpretive guide and an astrophotographer at the Onizuka Center for International Astronomy Visitor Information Station on Mauna Kea. He also volunteered to help implement the Variable Young Stellar Objects Survey on Mauna Loa, and the Pacific International Space Center for Exploration Systems on Mauna Kea. He graduated with his Bachelor of Science in astronomy in 2009 and entered the physics PhD program at George Mason University in 2011. He has three first-author publications and one second-author publication in The Astrophysical Journal from his studies in GMU, and he also co-authored a paper in Nature on Kuiper Belt Objects in 2010. He regularly gives public talks and professional colloquia, and has mentored several undergraduate students during his studies at GMU. He is now working as a postdoctoral fellow at the United States Naval Observatory in Washington, DC. In his free time, he enjoys scuba diving, classical guitar, and working on his Mazda MX-5.