X-Ray and Ultraviolet Properties of AGNs in Nearby Dwarf Galaxies

Vivienne F. Baldassare1, Amy E. Reines2,4, Elena Gallo1, and Jenny E. Greene3
1 Department of Astronomy, University of Michigan, Ann Arbor, MI 48109, USA
2 National Optical Astronomy Observatory, 950 N. Cherry Ave., Tucson, AZ 85719, USA
3 Department of Astrophysical Sciences, Princeton University, Princeton, NJ 08544, USA

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Abstract

We present new Chandra X-ray Observatory and Hubble Space Telescope observations of eight optically selected broad-line active galactic nucleus (AGN) candidates in nearby dwarf galaxies (z < 0.055). Including archival Chandra observations of three additional sources, our sample contains all 10 galaxies from Reines et al. (2013) with both broad Hα emission and narrow-line AGN ratios (six AGNs, four composites), as well as one low-metallicity dwarf galaxy with broad Hα and narrow-line ratios characteristic of star formation. All 11 galaxies are detected in X-rays. Nuclear X-ray luminosities range from $L_{0.5-7\text{keV}} \approx 5 \times 10^{39}$ to $1 \times 10^{42}$ erg s$^{-1}$. In all cases except for the star-forming galaxy, the nuclear X-ray luminosities are significantly higher than would be expected from X-ray binaries, providing strong confirmation that AGNs and composite dwarf galaxies do indeed host actively accreting black holes (BHs). Using our estimated BH masses (which range from $\sim 7 \times 10^4$ to $1 \times 10^6 M_\odot$), we find inferred Eddington fractions ranging from ~0.1% to 50%, i.e., comparable to massive broad-line quasars at higher redshift. We use the HST imaging to determine the ratio of UV to X-ray emission for these AGNs, finding that they appear to be less X-ray luminous with respect to their UV emission than more massive quasars (i.e., $\alpha_{OX}$ values an average of 0.36 lower than expected based on the relation between $\alpha_{OX}$ and 2500 Å luminosity). Finally, we discuss our results in the context of different accretion models onto nuclear BHs.

Key words: galaxies: active – galaxies: dwarf – quasars: supermassive black holes – ultraviolet: galaxies – X-rays: galaxies

1. Introduction

In the past few years, the number of active galactic nuclei (AGNs) identified in dwarf galaxies (i.e., $M_\star \lesssim 3 \times 10^9 M_\odot$) has grown from a handful of quintessential examples (e.g., NGC 4395; Filippenko & Sargent 1989; POX 52; Barth et al. 2004) to a body of several hundred candidates (see Reines & Comastri 2016, for a review). This has largely been possible thanks to large-scale optical spectroscopic surveys (e.g., the Sloan Digital Sky Survey [SDSS]), which have facilitated the search for AGN signatures in samples of tens of thousands of galaxies (see, e.g., Greene & Ho 2004, 2007; Dong et al. 2012), with the most recent studies concentrating on bona fide dwarf galaxies (Reines et al. 2013; Moran et al. 2014; Sartori et al. 2015). In particular, the most successful searches for AGNs in dwarf galaxies have used narrow emission line diagnostics (e.g., the BPT diagram; Baldwin et al. 1981) to search for photoionized gas consistent with the presence of an AGN (see also Kauffmann et al. 2003; Kewley et al. 2006 for commonly used diagnostics).

For AGNs exhibiting broad Hα emission, assuming that the broad-line region gas is virialized, it is possible to estimate the mass of the central black holes (BHs). Note that, for AGNs in dwarf galaxies, this also relies on the assumption that the scaling relation between BH mass and host stellar velocity dispersion (Ferrarese & Merritt 2000; Gebhardt et al. 2000) holds in this mass regime (Bentz et al. 2016). The velocity of the broad-line region gas is estimated from the width of the Hα line, and the radius to the broad-line region is estimated from the luminosity of the broad emission (Kaspi et al. 2000; Peterson et al. 2004; Greene & Ho 2005; Bentz et al. 2009, 2013). BH masses in dwarf AGNs are typically $\sim 10^5$–$10^6 M_\odot$ (see, e.g., Reines et al. 2013, Baldassare et al. 2016), with the lowest reported mass being just ~50,000$M_\odot$ (Baldassare et al. 2015).

Despite these recent advances in the identification of AGNs in dwarf galaxies, the radiative properties of this population of AGNs as a whole are largely unconstrained. Much work has been done exploring the X-ray properties of $\sim 10^6 M_\odot$ optically selected AGNs from the Greene & Ho samples (Desroches et al. 2009; Dong et al. 2012; Plotkin et al. 2016), but these host galaxies tend to be more massive than the dwarf galaxies considered here. Stacking analyses have been used to detect X-ray emission in dwarf galaxies out to $z \approx 1.5$ (Mezcua et al. 2016; Paggi et al. 2016). Additionally, Pardo et al. (2016) used X-ray observations to search for AGNs in dwarf galaxies at $z < 1$, finding an AGN fraction of ~1%. However, we are concerned with following up individual systems in order to obtain a detailed look at the radiative properties of this relatively unexplored population.

Determining the radiation properties of actively accreting BHs at the cores of dwarf galaxies is important for several reasons. First, the BHs at the centers of dwarf galaxies may provide clues about galaxy nuclei in the early universe, since they are expected to be similar (to first approximation; see, e.g., Bellovary et al. 2011; Habouzit et al. 2016). With current instrumentation, it is not possible to detect $10^6 M_\odot$ BHs in the earliest galaxies. A BH of this size accreting at its Eddington limit has a bolometric luminosity of $\sim 10^{44}$ erg s$^{-1}$. Assuming that it releases ~10% of its energy in hard X-rays, the flux reaching us would be an order of magnitude below the detection limit of the 4 Ms Chandra Deep Field-South (which has a ~2–8 keV flux limit of $5.5 \times 10^{-17}$ erg s$^{-1}$ cm$^{-2}$; Xue et al. 2011). Furthermore, searches for AGNs at high redshift ($z > 6$) find fewer sources than expected based on relations at
lower redshift (Weigel et al. 2015), possibly due to the lower normalization for low-mass galaxies in the BH mass–galaxy stellar mass relation (Reines & Volonteri 2015; Volonteri & Reines 2016). As an alternative, present-day dwarf galaxies can serve as useful local analogs (Jia et al. 2011; Reines et al. 2011, 2014). Present-day dwarf galaxies have likely not undergone any major mergers and are thus relatively undisturbed and “pristine” compared to more massive systems.

Moreover, studying AGNs in dwarf galaxies is useful for understanding the interplay between AGN activity and star formation on all galaxy scales. AGN feedback is expected to have an effect on galaxy-scale star formation, particularly in more massive systems (e.g., King & Pounds 2015). Feedback from massive stars and/or supernovae is expected to be particularly relevant for dwarf galaxies, but it is unclear what (if any) influence AGNs can have on star formation in these smaller systems (Murray et al. 2005; Hopkins et al. 2010, 2014, 2016). Studying radiation from AGNs in dwarf galaxies is also useful for understanding whether BH accretion had any influence on star formation in the earliest galaxies (see, e.g., Alexandroff et al. 2012), as well as for investigating the contribution of low-luminosity AGNs to reionization (Milošavljević et al. 2009; Madau & Haardt 2015).

High-resolution X-ray and UV follow-up of these systems is essential for understanding the accretion properties of AGNs in dwarf galaxies. If detected, sufficiently bright, point-like nuclear UV/X-ray emission provides strong confirmation of the presence of an AGN (e.g., Elvis et al. 1994). Additionally, X-ray studies can be used to determine the distribution of Eddington ratios for AGNs in dwarf galaxies. Furthermore, the relative strength of the UV and X-ray emission is important for learning about the structure and properties of the accretion disk and corona (Tananbaum et al. 1979; Lusso & Risaliti 2016). Finally, studies of the broadband spectra of these objects are necessary for determining the bolometric correction for this class of AGNs.

Reines et al. (2013) identified 151 dwarf galaxies with narrow and/or broad emission line signatures indicating the presence of an AGN. With the above goals in mind, we analyze Chandra X-Ray Observatory observations of a subsample of these objects, focusing on the most promising broad-line AGN candidates. The paper is organized as follows. In Section 2, we discuss our sample, X-ray and UV observations, and data reduction and analysis. In Section 3, we report on properties of the X-ray and UV emission, including the ratio of X-ray to UV emission. In Section 4, we discuss the origin of the X-ray emission and compare the properties of our galaxies to those of more massive quasars.

2. Observations and Analysis

Reines et al. (2013) identified 10 dwarf galaxies with both narrow and broad emission line signatures. Of these, six fall in the “AGN” region of the BPT diagram, and four fall in the “composite” region. Composite objects are expected to have contributions to narrow-line emission from both an AGN and recent star formation. The 10 galaxies include the well-studied NGC 4395 (RGG 21), as well as two objects (RGG 20 and RGG 123) identified in the Greene & Ho (2007) catalog and followed up in Dong et al. (2012) (see Section 2.3). Figure 1 shows the location of our sample on the BPT diagram.

We have obtained new Chandra X-ray Observatory and Hubble Space Telescope (HST) Wide-Field Camera 3 (WFC3) UV observations (Proposal ID: 16700103; PI: Reines) of the remaining seven. Additionally, we observed RGG B, a dwarf galaxy identified by Reines et al. (2013) to have broad Hα emission but narrow-line ratios consistent with photoionization from HII regions. However, this object’s narrow-line ratios place it on the upper left of the star-forming region of the BPT diagram, a regime where it is thought that low-metallicity AGNs can reside (Groves et al. 2006). In all, our full sample comprises 11 objects, three of which have Chandra observations analyzed in the literature, and eight of which have new Chandra/HST observations analyzed in this work. We stress that with our new observations, we complete high-resolution X-ray follow-up for all secure broad-line AGNs identified in Reines et al. (2013).

All targets are nearby (z < 0.055), and stellar masses range from $\sim 1 \times 10^8$ to $3 \times 10^9 M_\odot$ (see Tables 1 and 3 in Reines et al. 2013). Stellar masses are computed using the kcorrect software (Blanton & Roweis 2007) and taken from the NASA-Sloan Atlas. Figures 2–9 show, for each of our eight new targets, the three-color SDSS image, the HST UV image, and the Chandra image.

2.1. Chandra X-Ray Observatory

Chandra observations of our targets were taken with the Advanced CCD Imaging Spectrometer S-array (ACIS-S) between 2014 December and 2016 April (PI: Reines; Cycle 16). See Table 1 for a summary of observations. The data were reprocessed and analyzed with the Chandra Interactive Analysis of Observations software package (CIAO; version 4.8). After reprocessing and restricting our data to the S3 chip, we generated a preliminary source list using CIAO WAVDETECT and corrected the Chandra astrometry by cross-matching our observations with sources in the SDSS catalog.
We checked all sources for background flares; none were found. We then applied an energy filter (0.3–8 or 0.5–7 keV) and reran WAVDETECT using a threshold significance of $10^{-6}$ (equivalent to one false detection over the S3 chip).

We used SRCFLUX to calculate count rates and errors in three energy bands: soft (0.5–2 keV), hard (2–10 keV), and broad (0.5–7 keV). For targets with a WAVDETECT source coincident with the optical nucleus (RGG 9, RGG 32, RGG 48, RGG 119, RGG 127), we extracted counts in a circular source region of radius 2'' centered on the WAVDETECT coordinates. In the absence of a WAVDETECT source (RGG 1, RGG 11, RGG B), we extracted counts in a region of the same size centered on the nominal position of the nucleus as given by SDSS coordinates. We used a background annulus with inner and outer radii of 20 and 30'', respectively. All sources were detected in the soft and broad bands.

Counts were converted to unabsorbed fluxes using the Portable, Interactive Multi-Mission Simulator (PIMMS). We assumed the underlying spectrum to be a power law with $\Gamma = 2.0$, except in the cases of RGG 119 and RGG 127, for which we were able to measure $\Gamma$ directly from the extracted spectra (see below). Galactic H\textsc{i} column density measurements were obtained with the HEASARC nH tool, which uses H\textsc{i} column densities measured by Kalberla et al. (2005). Table 2 presents the counts, unabsorbed fluxes, and luminosities for each target in each wave band.

We took the following steps to account for intrinsic absorption. First, assuming $\Gamma = 2.0$, we used PIMMS to determine the expected 0.5–2 keV count rate based on the count rate in the 2–10 keV band, which is largely unaffected by absorption. If the expected 0.5–2 keV count rate was higher than the observed rate, we determined what intrinsic $n_{\text{H}}$ would be required to produce the observed rate. We then recalculated 0.5–2 and 0.5–7 keV fluxes accounting for both Galactic extinction and intrinsic absorption. Using this methodology, there is evidence for some intrinsic absorption in RGG 1, RGG 11, and RGG 48. Additionally, spectral fitting for RGG 127 suggests a small amount of intrinsic absorption (see below).

Table 3 presents the computed intrinsic $n_{\text{H}}$ for these four systems and updated 0.5–2 keV and 0.5–7 keV fluxes. Extinction-corrected fluxes are used throughout the remainder of this paper. We note that intrinsic $n_{\text{H}}$ values range from $4 \times 10^{20}$ to $9 \times 10^{20}$ cm$^{-2}$ and the extinction-corrected fluxes are within a factor of $\sim2$ of the observed fluxes (and generally within the errors in the observed fluxes).

Two sources (RGG 119 and RGG 127) had enough counts (n $\gtrsim$ 100) to warrant spectral analysis (Figure 10). We use the Sherpa fitting package in CIAO to model the extracted spectra using an absorbed power-law model. Since it is possible to have both Galactic absorption and absorption intrinsic to the galaxy itself, we fit the spectra two ways: with $n_{\text{H}}$ frozen to the Galactic value, and with $n_{\text{H}}$ constrained to be at least the Galactic value. We find that the spectrum of RGG 119 has a best-fit power-law index of $\Gamma = 2.25 \pm 0.25$. The models did not prefer an $n_{\text{H}}$ greater than the Galactic value, suggesting little to no intrinsic absorption. RGG 127, however, has a best-fit $n_{\text{H}}$ approximately twice the Galactic value, indicating potential intrinsic absorption. For RGG 127, we find a corresponding best-fit $\Gamma$ of $2.18^{+0.55}_{-0.35}$. If we freeze $n_{\text{H}}$ to the Galactic value, we obtain $\Gamma = 2.03$.

### 2.2. Hubble Space Telescope

\textit{HST} WFC3 images were taken with the UVIS channel and F275W filter. Individual exposures were processed and combined using the standard \textit{HST} AstroDrizzle reduction pipeline. Total exposure times ranged from 747 to 900 s. We detect UV emission from all eight targets.

We use the PHOT task within the STSDAS package for PyRAF to measure UV fluxes. The UV emission associated with the AGN emerges from the unresolved accretion disk. There may also be spatially resolved UV emission on scales larger than the WFC3 point-spread function (PSF). In order to isolate

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5 http://cxc.harvard.edu/toolkit/pimms.jsp

7 http://heasarc.nasa.gov/cgi-bin/Tools/w3nh/w3nh.pl
emission from the AGN, we measure the flux within an aperture with a radius of 3 pixels centered on the brightest pixel, accounting for the HST WFC3/UVIS F275W encircled energy fraction. We try four different background apertures ranging from an annulus immediately surrounding the source (effectively subtracting off any nearby star formation) to a large annulus containing only the sky background. The choice of background aperture does not strongly affect our results, but since we do
expect some UV emission from star formation in addition to any from the AGN, we use the innermost annulus background for our measurements of the UV-to-X-ray flux ratio. Table 4 presents measured count rates for the background and AGN.

2.3. Archival Data

Chandra imaging of RGG 21 (NGC 4395) was analyzed in Moran et al. (2005), and RGG 20 and RGG 123 were analyzed in Dong et al. (2012). We briefly summarize their findings here.
Table 1
New Chandra Observations of Broad-line AGN Candidates

| RGG ID | NSAID | R.A.         | Decl.        | BPT Class | Redshift | Obs. Date | Obs. ID | Exp. Time (ks) |
|--------|-------|--------------|--------------|-----------|-----------|-----------|---------|---------------|
| 1      | 62996 | 02:46:56.39  | -00:33:04.8  | AGN       | 0.0459    | 2015 Jul 12 | 17032   | 17.4          |
| 9      | 10779 | 09:06:13.75  | +56:10:15.5  | AGN       | 0.0466    | 2014 Dec 26 | 17033   | 15.83         |
| 11     | 125318| 09:54:18.14  | +47:17:25.1  | AGN       | 0.0327    | 2016 Apr 06 | 17034   | 10.26         |
| 32     | 15235 | 14:40:12.70  | +02:47:43.5  | AGN       | 0.0299    | 2015 Apr 01 | 17035   | 6.97          |
| 48     | 47066 | 08:51:25.81  | +39:35:41.7  | Composite | 0.041     | 2015 Dec 07 | 17036   | 12.89         |
| 119    | 79874 | 15:26:37.36  | +06:59:41.6  | Composite | 0.0384    | 2015 Feb 10 | 17037   | 10.9          |
| 127    | 99052 | 16:05:31.84  | +17:48:26.1  | Composite | 0.0317    | 2015 Feb 22 | 17038   | 7.75          |
| B      | 15952 | 08:40:29.91  | +47:07:10.4  | Star-forming | 0.0421  | 2015 Jan 05 | 17039   | 12.89         |

Note. Columns (1) and (2) give the IDs assigned by Reines et al. (2013) and the NASA-Sloan Atlas, respectively. Column (5) gives the BPT classification determined using SDSS spectroscopy. Column (7) gives the date of the Chandra observation, column (8) gives the observation ID, and column (9) gives the Chandra exposure time.

RGG 20. RGG 20 (SDSS J122342.82+581446.4) was found to have a 0.5–8 keV luminosity of $L = 6.7 \times 10^{41}$ erg s$^{-1}$. There were a sufficient number of counts to extract a spectrum; the best-fit photon index was $\Gamma = 1.54 \pm 0.10$. The ratio of X-ray to UV emission ($\alpha_{\text{OX}}$; see Section 3.2) is $\alpha_{\text{OX}} = -1.30$.

RGG 21. RGG 21 (NGC 4395; SDSS J122548.86+333248.7) was found to have a 2–10 keV luminosity of $L = 8.0 \times 10^{39}$ erg s$^{-1}$. NGC 4395 displays dramatic spectral variability, with measured power-law indices ranging from $\Gamma = 1.72$ (Iwasawa et al. 2000) to $\Gamma = 0.61$ (Moran et al. 2005) on timescales of several years.

RGG 123. RGG 123 (SDSS J153425.58+040806.6) has a 0.5–8 keV luminosity of $L = 8.5 \times 10^{41}$ erg s$^{-1}$. There were not sufficient counts to extract an X-ray spectrum. The photon index as estimated from the hardness ratio is $\Gamma_{\text{HR}} = 2.57 \pm 0.27$, and $\alpha_{\text{OX}}$ was found to be $-1.22$.

Dong et al. (2012) report count rates for RGG 20 and 123 (as well as fluxes and luminosities) in the 0.5–2 keV and 2–8 keV bands. For uniformity, we convert their 2–8 keV count rates to 2–10 keV fluxes using PIMMS. For RGG 20, we use the photon index of $\Gamma = 1.54$ obtained from the fit to the spectrum. For RGG 123, we follow the same procedure as for our new data and use a photon index of $\Gamma = 2.0$.

3. Results

3.1. Nuclear X-Ray Emission

All 11 targets are detected, i.e., we find a 100% X-ray detection rate for nearby ($z < 0.055$) dwarf galaxies with broad- and narrow-line AGN signatures (i.e., those falling in the AGN or composite region of the BPT diagram). For our eight new targets, we measure count rates in the 0.5–7 keV band ranging from $1.5 \times 10^{-4}$ to $5.2 \times 10^{-2}$ counts s$^{-1}$. Correspondingly, we estimate 0.5–7 keV luminosities ranging from $\sim 5 \times 10^{39}$ to $\sim 1 \times 10^{42}$ erg s$^{-1}$. Distances are estimated using redshifts reported in the NASA-Sloan Atlas and Ned Wright’s cosmology calculator (Wright 2006).

If we assume that the measured X-ray luminosities are due to accreting BHs (see Section 4.1 for a discussion of the origin of X-ray emission for these sources), we can estimate Eddington fractions, i.e., what percentage of their Eddington luminosities these BHs are accreting. Eddington luminosities are determined using the BH masses from Reines et al. (2013), with the exceptions of RGG 9 and RGG 119, which have updated BH masses given in Baldassare et al. (2016). BH masses for this sample are estimated using the luminosity and FWHM of the broad H$\alpha$ emission line (Kaspi et al. 2000;...
| RGG ID | Counts | Flux (10^{-15} \text{ erg s}^{-1} \text{ cm}^{-2}) | Luminosity (\log(\text{erg s}^{-1})) |
|--------|--------|----------------------------------|----------------------------------|
|        | 0.5–2 keV | 0.5–7 keV | 2–10 keV | 0.5–2 keV | 0.5–7 keV | 2–10 keV | 0.5–2 keV | 0.5–7 keV | 2–10 keV |
| 1      | 2 (0.5, 5.3) | 3 (1.1, 6.7) | 1 (0.1, 3.9) | 0.66 (0.18, 1.76) | 1.42 (0.52, 3.16) | 1.15 (0.20, 4.48) | 39.52 (38.94, 39.95) | 39.85 (39.41, 40.19) | 39.76 (39.00, 40.35) |
| 9      | 15 (10.3, 21.3) | 17 (12.0, 23.6) | 2 (0.5, 5.3) | 5.23 (3.59, 7.42) | 8.57 (6.04, 11.90) | 2.52 (0.67, 6.71) | 40.43 (40.27, 40.58) | 40.65 (40.50, 40.79) | 40.12 (39.54, 40.54) |
| 11     | 2 (0.5, 5.3) | 4 (1.8, 8.0) | 2 (0.5, 5.3) | 1.37 (0.36, 3.64) | 3.97 (1.74, 7.92) | 5.01 (1.33, 13.34) | 39.53 (38.96, 39.96) | 39.99 (39.63, 40.29) | 40.10 (39.52, 40.53) |
| 32     | 8 (4.7, 13.0) | 9 (5.4, 14.2) | 1 (0.1, 3.9) | 6.42 (3.74, 10.43) | 10.41 (6.28, 16.43) | 2.87 (0.30, 11.15) | 40.12 (39.88, 40.33) | 40.33 (40.11, 40.53) | 39.77 (38.79, 40.36) |
| 48     | 48 (39.4, 58.2) | 69 (58.6, 80.9) | 21 (15.4, 28.2) | 20.60 (16.90, 24.97) | 42.81 (36.35, 50.19) | 32.54 (23.83, 43.67) | 40.91 (40.82, 40.99) | 41.23 (41.16, 41.20) | 41.11 (40.98, 41.24) |
| 119    | 457 (429.8, 485.6) | 572 (541.6, 603.9) | 117 (103.4, 132.1) | 244.7 (230.2, 260.0) | 404.10 (382.6, 426.6) | 198.1 (175.0, 223.7) | 41.93 (41.90, 41.96) | 42.15 (42.13, 42.17) | 41.84 (41.79, 41.89) |
| 127    | 111 (97.7, 125.8) | 144 (128.9, 160.6) | 34 (26.8, 42.8) | 82.82 (72.92, 93.84) | 144.6 (129.3, 161.3) | 82.49 (64.96, 103.8) | 41.29 (41.23, 41.34) | 41.53 (41.48, 41.58) | 41.29 (41.19, 41.39) |
| B      | 2 (0.5, 5.3) | 2 (0.5, 5.3) | 0 (0, 2.3) | 0.87 (0.23, 2.30) | 1.25 (0.33, 3.32) | 0 (0, 4.1) | 39.56 (38.98, 39.98) | 39.72 (39.14, 40.15) | <40.18 |

**Note.** Columns (2)–(4) give the total counts in the 0.5–2, 0.5–7, and 2–10 keV ranges, respectively, with lower and upper limits in parentheses, as computed by SRCFLUX. Errors on the counts were estimated using the 90% confidence limits given in Gehrels (1986). Columns (6)–(8) give the corresponding fluxes (corrected for galactic extinction only), and columns (10)–(12) present corresponding luminosities.
Table 3
Extinction-corrected X-Ray Fluxes

| RGG ID | Galactic $N_H$ (cm$^{-2}$) | Intrinsic $N_H$ (cm$^{-2}$) | Flux ($10^{-15}$ erg s$^{-1}$ cm$^{-2}$) |
|--------|---------------------------|---------------------------|---------------------------------|
|        | (1)                       | (2)                       | (3)                             | (4) | (5) |
| 1      | $4.25 \times 10^{20}$     | $2.5 \times 10^{21}$      | 1.03                            | 0.52 keV | 1.97 |
| 11     | $1.6 \times 10^{20}$     | $9.2 \times 10^{21}$      | 4.96                            | 2 keV | 9.51 |
| 48     | $2.43 \times 10^{20}$     | $1.70 \times 10^{21}$      | 28.8                           | 2 keV | 55.1 |
| 127    | $3.30 \times 10^{20}$     | $4.1 \times 10^{20}$      | 95.3                           | 0.52 keV | 156 | 174 |

Note. Column (2) gives the galactic H I column density. Column (3) gives the intrinsic column density ("redshifted $N_H^\alpha"$ in PIMMS), computed as described in Section 2.1. Columns (4) and (5) give the corrected 0.5–2 and 0.5–7 keV fluxes, with upper and lower limits in parentheses.

3.2. UV-to-X-Ray Flux Ratios

We measure $\alpha_{OX}$ in order to quantify the relative power output in the UV and in X-rays (Tananbaum et al. 1979). The quantity $\alpha_{OX}$ is defined as $\alpha_{OX} = -0.383 \log(l_{2500}/l_{2keV})$, where $l_{2500}$ is the luminosity density at 2500 Å and $l_{2keV}$ is the unabsorbed luminosity density at 2 keV. We measure the 2500 Å UV flux density directly from the HST F275W imaging (the peak of the filter output is close to 2600 Å, i.e., $\sim$2500 Å for a galaxy at $z = 0.04$). We use PIMMS and the appropriate power-law index ($\Gamma = 2.0$, except when measured directly from spectral fitting) to determine the 2 keV luminosity.

We find $\alpha_{OX}$ values ranging from $-2.13$ to $-0.95$ (Figure 11). Values of $\alpha_{OX}$ are reported for each galaxy in Table 5. These values are consistent with those found by Dong et al. (2012) and Plotkin et al. (2016) for low-mass AGNs with BH masses of $\sim 10^5 M_\odot$. Though we have a very limited sample size, broadly speaking, the highest-$L_{bol}/L_{Edd}$ objects have the least negative $\alpha_{OX}$ values, i.e., are more X-ray luminous relative to their UV emission.

In Figure 12, we compare our $\alpha_{OX}$ values to expected values based on the relationship between $\alpha_{OX}$ and $l_{2500}$ found by Just et al. (2007). We find that our targets tend to have $\alpha_{OX}$ lower than expected based on the $\alpha_{OX}$–$l_{2500}$ relation (the $\alpha_{OX}$ values range from $\sim 0.1$ to $1$ below the expected values). Despite the general trend, RGG 119 and RGG 127, i.e., the two objects with the highest $L_{bol}/L_{Edd}$, have $\alpha_{OX}$ consistent with their "expected" values. The large dispersion in $\alpha_{OX}$ values for BHs with $M_{BH} \lesssim 10^6 M_\odot$, as well as their tendency to appear X-ray weak relative to the $\alpha_{OX}$ – $l_{2500}$ relation, is also observed by Dong et al. (2012) and Plotkin et al. (2016). This is further discussed in Section 4.2.

We note that it is very difficult to distinguish emission from the AGN from emission from star formation. If a significant fraction of the UV emission is from star formation, then $\alpha_{OX}$ values would appear lower (i.e., more negative) than they are.

3.3. X-Ray Hardness Ratio

Hardness ratios can yield information about the spectral shape for sources with too few counts to extract a spectrum. We compute hardness ratios for our targets using the Bayesian Estimation of Hardness Ratios code (BEHR; Park et al. 2006). Hardness ratio is defined as $(H - S)/(H + S)$, where $H$ and $S$ are the number of counts in the hard and soft bands, respectively. Here, we use 0.5–2 keV as our soft band and 2–7 keV as the hard band. BEHR treats counts as independent Poisson random variables and can be used even if the source is undetected in one of the bands (as is the case for RGG B).

We find hardness ratios ranging from $-0.75$ to $-0.02$, with a median hardness ratio of $-0.57$ (see Figure 13). For reference, we compute expected hard- and soft-band counts for power-law spectra with varying $\Gamma$; a hardness ratio of $\sim 0.4$ is characteristic of an unabsorbed power-law spectrum with $\Gamma = 2.0$, while an unabsorbed power-law spectrum with $\Gamma = 2.5$ produces a hardness ratio of $\sim 0.6$.

The hardness ratios for RGG 119 and RGG 127 are consistent with the expected hardness ratios for $\Gamma \approx 2.0$–2.5; these are in turn consistent with the $\Gamma$ that best fit the extracted X-ray spectra (2.25 and 2.18 for RGG 119 and RGG 127, respectively).

4. Discussion

4.1. Origin of X-Ray Emission

The Eddington luminosity for a $10^5 M_\odot$ BH is $\sim 10^{39}$ erg s$^{-1}$. Therefore, the X-ray luminosities of Eddington-limited X-ray binaries can be comparable to the luminosities of sub-Eddington AGNs in our BH mass range of interest. Here, we carefully consider the origin of the detected X-ray emission in our targets.

The expected X-ray luminosity due to high-mass X-ray binaries (HMXBs) scales with the star formation rate of the galaxy (Grimm et al. 2003), while the X-ray luminosity due to low-mass X-ray binaries (LMXBs) scales with stellar mass (Gilfanov 2004). As shown in Gilfanov (2004), for a galaxy with $M_\star \sim 10^9 M_\odot$, we expect LMXBs to contribute $L_X < 10^{38}$ erg s$^{-1}$; our X-ray sources are all more luminous by at least a factor of 10, making LMXBs an unlikely source of the nuclear X-ray emission. Additionally, while the fairly soft best-fit spectral indices for RGG 119 and RGG 127 are typical...
of quasars, they are also typical of HMXBs, particularly in the steep power law and high/soft states (Remillard & McClintock 2006). Thus, we consider HMXBs our most likely alternative source of X-ray emission. We estimate the expected luminosity contributed from HMXBs below.

Using the extinction-corrected luminosity of the narrow Hα emission from Reines et al. (2013) and the relation in Kennicutt & Evans (2012), we compute upper limits on the SFR for each galaxy by assuming that all the narrow Hα emission within the SDSS fiber is due to star formation. Note that for objects that fall in the composite or AGN region of the BPT diagram, we consider HMXBs our most likely source of the nuclear X-ray emission. RGG B, which falls in the star-forming region of the BPT diagram, has a 0.5–8 keV X-ray luminosity consistent with that expected from star formation.

Using 2–10 keV luminosities and the relation given by Lehmer et al. (2010), we find that most targets have X-ray luminosities greater than would be expected from star formation (1σ–9σ higher), with the exception of RGG 32, which has a hard X-ray luminosity consistent with the estimated contribution from HMXBs, and RGG B, which is not detected in the 2–10 keV band (see right panel of Figure 14). We stress again that the SFRs used are conservative upper limits, and that the actual star formation rates are lower for objects falling in the composite or AGN region of the BPT diagram.

With the exception of RGG B (and RGG 32 in the hard band), the X-ray luminosities of our targets are higher than would be expected from star formation. For our seven targets with broad and narrow emission line signatures of an AGN, we consider an AGN the most likely source of the nuclear X-ray emission. RGG B, which falls in the star-forming region of the BPT diagram, has the lowest X-ray luminosity and, moreover, a 0.5–8 keV X-ray luminosity consistent with that which would be expected from star formation. Optical spectroscopy of RGG B was also analyzed in Baldassare et al. (2016), who carried

Table 4

| RGG ID | Exp Time | Count Rate (counts s⁻¹) | f_LX000 (erg s⁻¹ cm⁻² Hz⁻¹) | f_LX000 (erg s⁻¹ Hz⁻¹) |
|--------|----------|-------------------------|-----------------------------|------------------------|
|        | (1)      | Total (3)               | Background (4)              | AGN (5)                | (6)                    | (7)                    |
| 1      | 747      | 1.32                    | 0.37                        | 0.95                   | 8.18 × 10⁻⁰           | 4.10 × 10⁻²          |
| 9      | 900      | 6.31                    | 3.19                        | 3.12                   | 2.69 × 10⁻⁸           | 1.39 × 10⁻⁹          |
| 11     | 882      | 32.86                   | 12.59                       | 20.27                  | 1.75 × 10⁻⁷           | 4.35 × 10⁻⁸          |
| 32     | 747      | 37.40                   | 20.33                       | 17.07                  | 1.47 × 10⁻⁷           | 3.06 × 10⁻⁸          |
| 48     | 801      | 5.50                    | 2.66                        | 2.84                   | 2.44 × 10⁻⁶           | 9.71 × 10⁻⁷          |
| 119    | 747      | 29.79                   | 7.63                        | 22.17                  | 1.91 × 10⁻⁶           | 6.62 × 10⁻⁷          |
| 127    | 756      | 5.07                    | 1.38                        | 3.69                   | 3.17 × 10⁻⁷           | 7.44 × 10⁻⁸          |
| B      | 789      | 90.14                   | 35.20                       | 54.94                  | 4.73 × 10⁻⁶           | 1.99 × 10⁻⁷          |

Note. Column (2) gives the HST exposure time. Columns (3)–(5) give HST count rates. The total count rate refers to the total count rate in an aperture with a radius of 3″ centered on the UV source. The background count rate refers to the count rate in the annulus immediately surrounding the inner aperture and is intended to account for any extended star formation in the galaxy. The AGN count rate is the total count rate minus the background count rate. Columns (6) and (7) give the flux and luminosity densities at 2500 Å, respectively.
Table 5: Summary of Galaxy and AGN Properties

| RGG ID | log($M_\ast/M_\odot$) | log($L_{H_\alpha}$) (log(erg s\(^{-1}\))) | FWHM\(_{H_\alpha}\) (km s\(^{-1}\)) | $A_V$ (mag) | $N_H$ 10\(^{20}\) cm\(^{-2}\) | log($L_{X,S}$) (log(erg s\(^{-1}\))) | log($L_{X,H}$) (log(erg s\(^{-1}\))) | log($M_{BH}/M_\ast$) | $L_{BH}/L_{R_{BLD}}$ | $\alpha_{OX}$ |
|--------|-----------------|-----------------|-----------------|--------|-----------------|-----------------|-----------------|-----------------|-----------------|---------|
| 1      | 9.41            | 39.38           | 1577            | 0.103  | 4.25            | 39.71           | 39.85           | 5.7             | 0.001           | -1.43±0.22 |
| 9      | 9.36            | 40.15           | 703             | 0.066  | 2.30            | 40.43           | 40.65           | 5.6\(^a\)       | 0.003           | -1.36±0.06  |
| 11     | 9.12            | 39.41           | 636             | 0.026  | 1.60            | 40.09           | 39.99           | 4.9             | 0.013           | -1.68±0.22  |
| 20     | 9.47            | 40.13           | 1526            | 0.037  | 1.23            | 41.45\(^b\)     | 41.72\(^b\)     | 6.1             | 0.070           | -1.3\(^b\)  |
| 21     | 9.10            | 38.15           | 1288            | 0.046  | 1.35            | ...             | ...             | 5.0\(^c\)       | 0.007           | ...        |
| 32     | 9.46            | 39.73           | 747             | 0.101  | 2.84            | 40.12           | 40.33           | 5.2             | 0.003           | -1.60±0.05  |
| 48     | 9.41            | 39.67           | 894             | 0.085  | 2.43            | 41.06           | 41.23           | 5.4             | 0.043           | -1.06±0.03  |
| 119    | 9.33            | 40.16           | 1043            | 0.129  | 3.41            | 41.93           | 42.15           | 5.5\(^a\)       | 0.197           | -1.08±0.01  |
| 123    | 9.12            | 39.82           | 634             | 0.122  | 4.24            | 41.77\(^n\)     | 41.41\(^b\)     | 5.1             | 0.543           | -1.22\(^b\) |
| 127    | 9.24            | 39.45           | 792             | 0.135  | 3.30            | 41.35           | 41.53           | 5.2             | 0.102           | -0.92±0.01  |
| B      | 8.11            | 40.67           | 1245            | 0.070  | 2.80            | 39.56           | 39.72           | 6.1             | ...             | -2.13±0.15  |

Notes. Values in columns (2)–(4) are from Reines et al. (2013). Column (5) gives $A_V$ values from the NASA/IPAC Infrared Science Archive using measurements from Schlafly & Finkbeiner (2011). Column (6) gives values from the HEASARC nH tool (see Section 2.1). Soft X-ray luminosities are in the 0.5–2 keV energy range. Hard X-ray luminosities for objects analyzed in this paper are in the 2–7 keV band, while those reported from Dong et al. (2012) are in the 2–8 keV band.

\(^a\) BH mass from Baldassare et al. (2016), calculated from the average of several single-epoch spectroscopic BH mass measurements.

\(^b\) Value taken from Dong et al. (2012).

\(^n\) RGG 21 (NGC 4395) has several BH mass estimates reported in the literature. For consistency, we use the value quoted in Reines et al. (2013) based on the broad H\(_\alpha\) emission, but note that the most recent estimate comes from den Brok et al. (2015), which finds a mass of $4.4\pm3 \times 10^5 M_\odot$ based on gas dynamical modeling.
out multiepoch spectroscopy of star-forming dwarf galaxies with broad Hα. They found that the broad Hα faded in most, indicating that the broad emission was likely produced by a transient stellar process for those targets. RGG B was classified as ambiguous with respect to the presence of broad Hα in spectra taken several years following the SDSS spectrum. However, even if the broad emission in the SDSS spectrum of RGG B is produced by an AGN, we cannot say with certainty that the observed nuclear X-ray emission is not associated with an HMXB.

We emphasize that more than one-third of our sample falls in the composite region of the BPT diagram. Though BPT star-forming objects with broad Hα are not necessarily AGNs, this work provides strong evidence to suggest that the composite objects do indeed host AGNs.

4.2. Comparison to More Massive AGNs

Below, we compare the properties of the AGN considered in this paper to the properties of more massive quasars, as well as to the properties of the Desroches et al. (2009) and Dong et al. (2012) samples of low-mass AGNs (i.e., $M_{\text{BH}} \approx 10^5 - 10^6 M_\odot$). Just et al. (2007) explore the UV and X-ray properties of luminous quasars in SDSS from $z = 1.5$ to 4.5. They find a mean photon index of $\Gamma = 1.92_{-0.08}^{+0.09}$, with measured values ranging from $\Gamma = 1.3$ to 2.3. Our measured values of $\Gamma$ (2.25 and 2.18 for RGG 119 and RGG 127, respectively) are consistent with these. Moreover, it is predicted that objects accreting at higher Eddington fractions will have lower (i.e., more negative) photon indices (Brightman et al. 2013). Just et al. (2007) also measure $\alpha_{\text{OX}}$ values ranging from $-2.2$ to $-1.5$ and find a tight relation between $l_{2500}$ and $\alpha_{\text{OX}}$. While our measured $\alpha_{\text{OX}}$ also fall in this range, based on the $l_{2500} - \alpha_{\text{OX}}$ relation, we expect values closer to $-1.0$. We note that our two brightest, highest-$l_{2500}$ targets (RGG 119 and RGG 127) have $\alpha_{\text{OX}} \approx -1$, consistent with the Just et al. (2007) relation.

As discussed at length in Dong et al. (2012), there are several factors that can influence $\alpha_{\text{OX}}$. In the disk, UV photons are inverse-Compton scattered into an X-ray corona. The temperature of the disk therefore influences how much disk energy is reprocessed in this manner. If the disk extends to the innermost stable circular orbit, the peak disk temperature is dependent on BH mass such that smaller BHs have hotter disks. The disk temperature can also be dependent on the accretion rate. Additionally, the structure of the disk, i.e., whether the disk is thin or slim, can influence $\alpha_{\text{OX}}$. Finally, absorption can lead to suppressed UV emission and a harder overall spectrum.

Dong et al. (2012) combine their sample of low-mass AGNs with more massive AGNs in order to explore trends between $\alpha_{\text{OX}}$, $L_{\text{bol}}/L_{\text{Edd}}$, and $M_{\text{BH}}$. They find that $\alpha_{\text{OX}}$ is not correlated at all with $L_{\text{bol}}/L_{\text{Edd}}$. However, they find a potential trend between $\alpha_{\text{OX}}$ and $M_{\text{BH}}$ such that the mean $\alpha_{\text{OX}}$ decreases (becomes more negative) with increasing $M_{\text{BH}}$. This is expected to be due to the blackbody temperature of the accretion disk increasing with decreasing BH mass (for a given mass accretion rate; see Done et al. 2012). The accretion disk temperature is also expected to rise with increasing mass accretion rate. The mean $\alpha_{\text{OX}}$ for our targets with $M_{\text{BH}} \approx 10^5 - 10^6 M_\odot$ does not follow the trend noted by Dong et al. (2012),
i.e., the mean $\alpha_{\text{OX}}$ is more negative than for the objects with $M_{\text{BH}} \approx 10^6$–$10^7 M_\odot$ (though we reiterate that our sample size is small). Additionally, there appears to be a potential trend between $\alpha_{\text{OX}}$ and $L_{\text{bol}}/L_{\text{Edd}}$ for our sample; the objects with the highest Eddington fractions also have the least negative $\alpha_{\text{OX}}$ values (see Figure 11). A larger sample size would aid in determining whether the disk properties of AGNs in dwarf galaxies are indeed distinct from those of more massive objects.

Desroches et al. (2009) find that their five detected objects (out of eight total) show evidence for slim disk accretion (Abramowicz et al. 1988). This accretion mode is expected to be relevant at high Eddington fractions ($L_{\text{bol}}/L_{\text{Edd}} \geq 0.3$). In this regime, the disk puffs up at small radii, and accretion becomes radiatively inefficient owing to photon trapping. The result is that X-ray emission appears enhanced relative to optical/UV emission. Three AGNs considered here show evidence for slim disk accretion. Using a bolometric correction of 10, we find that RGG 119, RGG 123, and RGG 127 are accreting at high fractions of their Eddington luminosities (20%, 54%, and 10%, respectively). Moreover, they all have relatively flat $\alpha_{\text{OX}}$ values close to $-1.0$; Desroches et al. (2009) find similar values. However, the remaining targets are estimated to be accreting at lower Eddington fractions and have $\alpha_{\text{OX}}$ values closer to $-1.5$.

Dong et al. (2012) explore whether their sample follows the relation between $[\text{O III}]$ $\lambda$5007 luminosity and 2–10 keV luminosity. There is a very tight correlation between these quantities for unobscured AGNs (Panessa et al. 2006), since $[\text{O III}]$ is thought to be a good indicator of the power output of the central engine. While the Dong et al. (2012) objects do not cluster around this relation, they find that their sample tends to scatter below it, i.e., they are relatively X-ray weak compared to the $[\text{O III}]$ luminosity. This behavior is similar to the Compton-thick sample from Panessa et al. (2006), making local absorption a possible explanation for this trend. We observe this behavior for our target AGNs in dwarf galaxies (Figure 15). However, while we do find evidence for some intrinsic absorption in our sample, the H$\alpha$ column densities we find

are in the range of $10^{21}$–$10^{22}$ cm$^{-2}$, much lower than those for Compton-thick sources ($>10^{24}$ cm$^{-2}$).

Finally, Panessa et al. (2006) also find a correlation between the 2–10 keV luminosity and the H$\alpha$ luminosity. We show where our sample lies relative to this correlation in Figure 16. Our targets sit close to the relation, though four out of seven seem to scatter to slightly lower $L_X$ at fixed $L_{\text{H}\alpha}$ relative to more luminous systems. Panessa et al. (2006) suggest that such behavior could be due to intrinsic X-ray absorption (in Compton-thick systems), or contributions to H$\alpha$ from star formation. Additionally, there could be differences in the spectral energy distributions of AGNs in dwarf galaxies, as compared to AGNs in more massive systems.

**5. Conclusions**

We analyze Chandra X-ray Observatory observations of 11 broad-line AGN candidates in dwarf galaxies identified in Reines et al. (2013). These include all 10 objects with broad and narrow emission line AGN signatures (six BPT AGNs, four BPT composites), plus one low-metallicity dwarf galaxy with broad H$\alpha$ but narrow emission lines dominated by star formation. Three out of 11 objects had Chandra observations analyzed in the literature. We analyze new Chandra observations of the remaining eight, supplemented by joint HST/WFC3 F275W imaging.

Nuclear X-ray emission is detected in all galaxies, i.e., we find a 100% detection rate. We also find the following.

1. The detected X-ray nuclei are bright, with $L_{0.5-7\text{keV}} \approx 5 \times 10^{39} - 1 \times 10^{42}$ erg s$^{-1}$. Galaxies in our sample have BH masses in the range of $\sim10^5$–$10^6 M_\odot$; we infer Eddington fractions ranging from $\sim0.1$% to 50%, i.e., consistent with the range of Eddington fractions found for massive broad-line quasars.

2. The observed X-ray emission in broad-line objects falling in either the AGN or composite region of the BPT diagram is brighter than would be expected from HMXBs. We conclude that an AGN is the most likely source of the detected X-ray emission.
3. We emphasize that the observations presented here provide strong evidence that the BPT composite objects (i.e., those thought to have contributions to the narrow-line flux from both star formation and an AGN) do indeed host actively accreting BHs.

4. Our targets tend to have $\alpha_{OX}$ values lower than expected based on relationships defined by classical quasars. If the measured UV emission is not significantly enhanced by nuclear star formation, AGNs in dwarf galaxies seem to be X-ray weak relative to their UV emission.

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References

Abramowicz, M. A., Czerny, B., Lasota, J. P., & Szuszkiewicz, E. 1988, ApJ, 332, 646
Alexandroff, R., Overzier, R. A., Paragi, Z., et al. 2012, MNRAS, 423, 1325
Baldassare, V. F., Reines, A. E., Gallo, E., et al. 2016, ApJ, 829, L7
Baldassare, V. F., Reines, A. E., Gallo, E., & Greene, J. E. 2015, ApJL, 809, L14
Baldwin, J. A., Phillips, M. M., & Terlevich, R. 1981, PASP, 93, 5
Barth, A. J., Ho, L. C., Rutledge, R. E., & Sargent, W. L. W. 2004, ApJ, 607, 90
Bellovary, J., Volonteri, M., Governato, F., et al. 2011, ApJ, 742, 13
Bentz, M. C., Buitste, M., Seals, J., et al. 2016, ApJ, 830, 136
Bentz, M. C., Denney, K. D., Grier, C. J., et al. 2013, ApJ, 767, 149
Bentz, M. C., Walsh, J. L., Barth, M. A., et al. 2009, ApJ, 705, 199
Blanton, M. R., & Roweis, S. 2007, AJ, 133, 734
Brightman, M., Silverman, J. D., Mainieri, V., et al. 2013, MNRAS, 433, 2485
den Brok, M., Seth, A. C., Barth, A. J., et al. 2015, ApJ, 809, 101
Desroches, L.-B., Greene, J. E., & Ho, L. C. 2009, ApJ, 698, 1515
Done, C., Davis, S. W., Jin, C., Blaes, O., & Ward, M. 2012, MNRAS, 420, 1848
Dong, R., Greene, J. E., & Ho, L. C. 2012, ApJ, 761, 73
Elvis, M., Wilkes, B. J., McDowell, J. C., et al. 1994, ApJS, 95, 1
Ferrarese, L., & Merritt, D. 2000, ApJL, 539, L9
Filippenko, A. V., & Sargent, W. L. W. 1989, ApJL, 342, L1
Gebhardt, K., Bender, R., Bower, G., et al. 2000, ApJL, 539, L13
Gehrels, N. 1986, ApJ, 333, 336
Gillfanov, M. 2004, MNRAS, 349, 146
Greene, J. E., & Ho, L. C. 2004, ApJ, 610, 722
Greene, J. E., & Ho, L. C. 2005, ApJ, 630, 122
Greene, J. E., & Ho, L. C. 2007, ApJ, 670, 92
Grüm, H.-J., Gillfanov, M., & Sunyaev, R. 2003, MNRAS, 339, 793
Groves, B. A., Heckman, T. M., & Kauffmann, G. 2006, MNRAS, 371, 1559
Haboubiz, M., Volonteri, M., & Dubois, Y. 2016, arXiv:1605.09394
Hopkins, P. F., Kereš, D., Olofsson, J., et al. 2014, MNRAS, 445, 581
Hopkins, P. F., Murray, N., Quataert, E., & Thompson, T. A. 2010, MNRAS, 401, L19
Hopkins, P. F., Torrey, P., Faucher-Giguère, C.-A., Quataert, E., & Murray, N. 2016, MNRAS, 458, 1816
Iwasawa, K., Fabian, A. C., Almaini, O., et al. 2000, MNRAS, 318, 879
Jia, J., Ptak, A., Heckman, T. M., et al. 2011, ApJ, 731, 55
Just, D. W., Brandt, W. N., Shemmer, O., et al. 2007, ApJ, 665, 1004
Kalberla, P. M. W., Burton, W. B., Hartmann, D., et al. 2005, A&A, 440, 775
Kaspi, S., Smith, P. S., Netzer, H., et al. 2000, ApJ, 533, 631
Kauffmann, G., Heckman, T. M., Tremonti, C., et al. 2003, MNRAS, 346, 1055
Kelly, B. C., Vestergaard, M., Fan, X., et al. 2010, ApJ, 719, 1315
Kennicutt, R. C., & Evans, N. J. 2012, ARA&A, 50, 531
Kewley, L. J., Groves, B., Kauffmann, G., & Heckman, T. 2006, MNRAS, 372, 961
King, A., & Pounds, K. 2015, ARA&A, 53, 115
Lehmer, B. D., Alexander, D. M., Bauer, F. E., et al. 2010, ApJ, 724, 559
Lehly, K. M., Seth, A. C., Barth, A. J., et al. 2015, ApJ, 809, 101
Lusso, E., & Risaliti, G. 2016, ApJ, 819, 20
Madau, P., & Haardt, F. 2015, ApJL, 2015, L8
Marconi, A., Risaliti, G., Gilli, R., et al. 2004, MNRAS, 351, 169
Mezcua, M., Civano, F., Fabbiano, G., Miyaji, T., & Marchesi, S. 2016, ApJ, 817, 20
Mihosavljević, M., Bromm, V., Couch, S. M., & Oh, S. P. 2009, ApJ, 698, 766
Mineo, S., Gillfanov, M., & Sunyaev, R. 2012, MNRAS, 419, 2095
Moran, E. C., Eracleous, M., Leighly, K. M., et al. 2005, AJ, 129, 2108
Moran, E. C., Shahinyan, K., Sugarman, H. R., Vélez, D. O., & Eracleous, M. 2014, AJ, 148, 136
Murray, N., Quataert, E., & Thompson, T. A. 2005, ApJ, 618, 569
Paggi, A., Fabbiano, G., Civano, F., et al. 2016, ApJ, 823, 112
Panessa, F., Bassani, L., Cappi, M., et al. 2006, A&A, 455, 173
Pardo, K., Goulding, A. D., Greene, J. E., et al. 2016, ApJ, 831, 203
Park, T., Kashyap, V. L., Siemiginowska, A., et al. 2006, ApJ, 652, 610
Peterson, B. M., Ferrarese, L., Gilbert, K. M., et al. 2004, ApJ, 613, 682
Plotkin, R. M., Gallo, E., Haardt, F., et al. 2016, ApJ, 825, 139
Reines, A., & Comastri, A. 2016, PASA, 33, 54
Reines, A. E., Greene, J. E., & Geha, M. 2013, ApJ, 775, 116
Reines, A. E., Plotkin, R. M., Russell, T. D., et al. 2014, ApJL, 787, L30
Reines, A. E., Sivakoff, G. R., Johnson, K. E., & Brogan, C. L. 2011, Natur, 470, 66
Reines, A. E., & Volonteri, M. 2015, ApJ, 813, 82
Remillard, R. A., & McClintock, J. E. 2006, ARA&A, 44, 49
Sartori, L. F., Schawinski, K., Treister, E., et al. 2015, MNRAS, 454, 3722
Schlafly, E. F., & Finkbeiner, D. P. 2011, ApJ, 737, 103
Shen, Y., & Kelly, B. C. 2012, ApJ, 746, 169
Shen, Y., & Liu, X. 2012, ApJ, 753, 125
Tananabaum, H., Avni, Y., Branduardi, G., et al. 1979, ApJL, 234, L9
Volonteri, M., & Reines, A. E. 2016, ApJL, 820, L6
Weigel, A. K., Schawinski, K., Treister, E., et al. 2015, MNRAS, 448, 3167
Wright, E. L. 2006, PASP, 118, 1711
Xue, Y. Q., Luo, B., Brandt, W. N., et al. 2011, ApJS, 195, 10