Massive Black Hole Formation in Dense Stellar Environments: Enhanced X-Ray Detection Rates in High-velocity Dispersion Nuclear Star Clusters

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Abstract

We analyze Chandra X-ray Observatory imaging of 108 galaxies hosting nuclear star clusters (NSCs) to search for signatures of massive black holes (BHs). NSCs are extremely dense stellar environments with conditions that can theoretically facilitate massive BH formation. Recent work by Stone et al. finds that sufficiently dense NSCs should be unstable to the runaway growth of a stellar-mass BH into a massive BH via tidal captures. Furthermore, there is a velocity dispersion threshold (40 km s$^{-1}$) above which NSCs should inevitably form a massive BH. To provide an observational test of these theories, we measure X-ray emission from NSCs and compare it to the measured velocity dispersion and tidal capture runaway timescale. We find that NSCs above the 40 km s$^{-1}$ threshold are X-ray detected at roughly twice the rate of those below (after accounting for contamination from X-ray binaries). These results are consistent with a scenario in which dense, high-velocity NSCs can form massive BHs, providing a formation pathway that does not rely on conditions found only at high redshift.

Unified Astronomy Thesaurus concepts: Nucleated dwarf galaxies (1130); Intermediate-mass black holes (816); Astrophysical black holes (98); Low-luminosity active galactic nuclei (2033)

Supporting material: machine-readable tables

1. Introduction

Every galaxy with stellar mass above $\sim 10^{10} M_\odot$ seems to host a massive black hole (BH; $M_{BH} > 10^6 M_\odot$) at its center (Kormendy & Ho 2013). It remains unclear when and how these massive BHs form, although some sort of exotic high-mass seed formation mechanism may be required by the existence of the brightest high-redshift quasars (Haiman & Loeb 2001; Lodato & Natarajan 2007; Volonteri 2010; Inayoshi et al. 2020; Kroupa et al. 2020). Formation channels for massive BH seeds can be divided into two categories: those that operate only at high redshift, and channels that continue to produce massive BHs throughout cosmic time (Natarajan 2014).

High-redshift formation channels include the deaths of Population III stars (Madau & Rees 2001; Whalen & Fryer 2012) and direct-collapse BHs (Loeb & Rasio 1994; Belgian et al. 2006; Lodato & Natarajan 2006; Mayer et al. 2010; Latif et al. 2013). Both require the low-metallicity conditions found only in the early universe. Channels in the latter category tend to invoke a gravitational runaway process which requires a dense star cluster (Portegies Zwart & McMillan 2002; Gürkan et al. 2004; Portegies Zwart et al. 2004). Because they are dynamically driven, they can operate at any redshift. These channels are of particular interest for their promise in forming intermediate-mass BHs ($M_{BH} \approx 10^2-10^3 M_\odot$). Recent theoretical works have illustrated the promise of dense young star clusters for forming BHs in the pair-instability mass gap from $\sim 50-100 M_\odot$ (Di Carlo et al. 2020; Kremer et al. 2020; González et al. 2021).

Nuclear star clusters (NSCs) have emerged as a promising stellar environment for facilitating the formation and/or growth of intermediate-mass BHs. NSCs reside at the centers of most galaxies with stellar masses between $\sim 10^8-10^9 M_\odot$ (Côté et al. 2006; Sánchez-Janssen et al. 2019; Hoyer et al. 2021). NSCs themselves typically have masses in the range of $\sim 10^3-10^7 M_\odot$ with effective radii of a few parsecs, making them the densest known stellar environments (Böker et al. 2002, 2004; Ferrarese et al. 2006a; Turner et al. 2012; Leigh et al. 2012; Georgiev & Böker 2014; Pouliaiou et al. 2019).

There are two main proposed channels for the formation of NSCs: globular cluster infall due to dynamical friction (Tremaine et al. 1975; Lotz et al. 2001; Capuzzo-Dolcetta & Miocchi 2008; Agarwal & Milosavljević 2011; Gnedin et al. 2014) and in situ star formation (Seth et al. 2006; Walcher et al. 2006). In practice, there are likely contributions from both channels, as NSCs have been found to contain multiple stellar populations (Carson et al. 2015; Neumayer et al. 2020; Fahri et al. 2021; Hannah et al. 2021). The relative contribution of each channel likely depends on galaxy mass and environment (Hoyer et al. 2021).

It was once proposed that NSCs may take the place of massive BHs as the central compact massive object in low-mass galaxies and follow similar scaling relations with their host galaxies (Ferrarese et al. 2006a). However, NSCs and massive BHs have been found to coexist in some systems (Seth et al. 2008; Antonini 2013; Nguyen et al. 2018, 2021), including our own Milky Way (Schödel et al. 2009).

7 The absence of NSCs from the most massive galaxies is likely due to the richer merger history of the largest systems, which suffer from “core scouring” following major and some minor mergers (Ebisuzaki et al. 1991; Quinlan 1996).
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Antonini et al. 2012). The precise relationship between NSCs and massive BHs remains unclear. NSCs could form around a pre-existing BH (Antonini 2013), and/or could provide an environment in which massive BHs can more easily form.

Several dynamical processes have been proposed for the formation of an intermediate-mass BH within an NSC (Gürkan et al. 2004; Miller & Davies 2012; Stone et al. 2017; Antonini et al. 2019; Fragione & Silk 2020; Fragione et al. 2021; Natarajan 2021; Di Carlo et al. 2021). Miller & Davies (2012) suggest that massive BHs will form at any epoch in an NSC with a velocity dispersion greater than a critical value of \( \sigma \approx 40 \text{ km s}^{-1} \). This is because above 40 km s\(^{-1}\), heating from primordial binaries is unable to prevent the system from undergoing core collapse. Core collapse will produce a BH subcluster; interactions within the subcluster will then either leave one or no stellar-mass BHs. If there is no BH, one will form from runaway stellar mergers (Portegies Zwart & McMillan 2002). In both cases, the remaining stellar-mass BH proceeds to grow quickly through tidal capture and/or disruption events into a massive BH.

Stone et al. (2017) expand on the above works by calculating the circumstances necessary for an NSC to grow a central stellar-mass BH into a massive one. They specifically consider a runaway tidal capture process. Tidal capture has the largest cross section for any dynamical interaction process in a dense star cluster (Fabian et al. 1975; Lee & Ostriker 1986). Once there is a stellar-mass BH left at the center of the NSC, it can grow into an intermediate-mass BH through runaway tidal capture, provided that the NSC has sufficiently high central density and velocity dispersion. The runaway tidal capture will slow once the BH reaches \( \sim 10^{-3} M_\odot \). At this point, BH growth will continue through tidal captures and disruptions (and possibly also standard accretion processes) until the BH reaches massive size. Stone et al. (2017) compute a timescale for this process called the tidal capture rate (TC rate, or \( N_{TC} \)). They find that many existing NSCs have rates indicating they are unstable to this runaway growth. Stated another way, given a sufficiently dense NSC, tidal capture and tidal disruption will inevitably grow a stellar-mass BH into a massive BH in less than a Hubble time.

The theoretical works described above reach a general consensus that NSCs should be able to form massive BHs through dynamical processes if they have velocity dispersions greater than \( \sim 40 \text{ km s}^{-1} \). Indeed, there is already tentative observational evidence for this point: dynamically confirmed massive BHs are very common in galaxies with \( \sigma \gtrsim 40 \text{ km s}^{-1} \), and uncommon below this threshold (see, e.g., Stone et al. 2017 Figure 1, or Greene et al. 2020 Figure 3). However, we emphasize here the circumstantial nature of existing evidence: dynamical mass measurements are challenging in the smallest galaxies, and the upper limits on BH mass produced by nondetections do not generally fall well below extrapolations of galaxy scaling relations (Greene et al. 2020, although there are notable exceptions to this, such as M33; Gebhardt et al. 2001). Here, we adopt a completely different approach to exploring the massive BH population among NSCs above and below the proposed 40 km s\(^{-1}\) threshold. Specifically, we use Chandra X-ray Observatory (CXO) imaging to search for X-ray emission in NSCs, as sufficiently bright X-ray emission is evidence for the presence of a massive BH. We then compare the velocity dispersions and TC rates of NSCs with/without X-ray emission. This approach provides a novel consistency check for the predictions of the TC runaway theory.

In Section 2, we describe the sample of NSCs. In Section 3, we describe the X-ray analysis and our assessment of X-ray binary contamination. Section 4 presents our results, and we discuss their implications in Section 5.

2. Sample Properties

Our parent sample contains 207 nearby (\( D < 50 \text{ Mpc} \)) galaxies hosting NSCs. All 207 have Hubble Space Telescope observations, which are necessary in order to resolve the scales necessary to study NSCs. These are selected from the samples of Böker et al. (2004); Côté et al. (2006) and Georgiev & Böker (2014) and were compiled by Stone et al. (2017) in order to compute tidal capture runaway timescales for actual NSCs. The parent sample consists of NSCs in both late and early-type galaxies.

All NSCs in the sample were modeled by a King profile (a tidally truncated isothermal sphere; King 1966), and have measured total masses, effective (half-light) radii, and concentration parameters. Note that for modeling, the concentration parameter (defined as \( C = r_{\text{tidal}}/r_{\text{core}} \)) was restricted to the set of \([5, 15, 30, 100]\) due to computational limitations. The galaxy stellar masses and NSC stellar masses for the parent sample were computed by Georgiev et al. (2016).

CXO observations were available in the archive or newly acquired for 108 out of 207 galaxies (see Section 3). These 108 galaxies are the focus of our analysis. The 108 galaxies in our sample range in distance from 2 to 50 Mpc. Galaxy masses range from \( 10^{9} - 10^{11} M_\odot \). The NSC masses range from \( 1 \times 10^3 - 2 \times 10^9 M_\odot \), and effective radii range from 0.3–42 pc. The sample of 108 objects is presented in Table 1.

3. X-Ray Analysis

We use CXO observations to study X-ray emission from our sample of NSCs. The angular resolution of CXO is necessary for determining whether any X-ray emission is coincident with the NSC. We searched the CXO archive for ACIS observations of the NSC sample. These were combined with our own program targeting the most dense, highest velocity dispersion NSCs. Fourteen objects were targeted with our program (GO-20700424; PI Baldassare), and 94 objects were in the CXO archive.

All observations were reprocessed and analyzed with the Chandra Interactive Analysis of Observations software (CIAO; version 5.13). We generate an initial source list using CIAO WAVDETECT. We then correct the astrometry by cross-matching the X-ray source list with sources in the USNO B-1 catalog. Matches were required to be within \( 2'' \) of one another, and we required three or more matches to apply the astrometry correction. We next filtered out any background flares in the observations. We then applied an energy filter in the 0.5–7 keV range and reran WAVDETECT with a threshold significance of \( 10^{-6} \), which corresponds to one false detection over a single ACIS chip.

Using SRCFLUX, we computed count rates, fluxes, and uncertainties in the soft (0.5–1.2 keV), broad (0.5–7 keV), and hard (2–10 keV) bands. We take the coordinates given by Georgiev & Böker (2014) to be the NSC position. If there was a WAVDETECT source coincident with the galaxy center, we extracted the counts in a circular region with a radius of \( 2'' \) at
the WAVDETECT source position. If there was not a source detected at the nucleus, we extracted counts in the same size circular region centered on the Georgiev & Böker (2014) coordinates. For the background region, we use a source-free annulus with inner and outer radii of ~20″ and ~35″, respectively. We compute the unabsorbed model flux for a power-law spectrum with $\Gamma$ = 1.8 and the Galactic $n_H$ value returned by the CIAO colden tool.

In all, 46/109 objects are X-ray detected. However, 5 of the 46 have diffuse X-ray emission rather than point sources. We do not consider these five as possible BHs and do not analyze them with the other 41 sources. An example of a galaxy with a nuclear X-ray point source is shown in Figure 1 and an example of a diffuse source is shown in Figure 2.

Of the 41 NSCs with X-ray point sources, 35 are detected in both the 0.5–7 and 2–10 keV bands, and 6 are only significantly detected in the 0.5–7 keV band. Luminosities in the 0.5–7 keV band range from $2.0 \times 10^{37}$–$2.0 \times 10^{42}$ erg s$^{-1}$, with a median luminosity of $1.2 \times 10^{40}$ erg s$^{-1}$. The X-ray luminosities and upper limits are given in Table 2.

### 3.1. X-Ray Binary Contamination

Given the X-ray luminosities found for the NSCs in our sample, we must consider the possibility of contamination from X-ray binaries. While it is difficult to state definitively whether any particular source is a massive BH or an X-ray binary, we can estimate the likely X-ray luminosity from low-mass X-ray binaries (LMXBs) and high-mass X-ray binaries (HMXBs) for each NSC. The contribution from LMXBs traces the cumulative star formation history of the galaxy, and is thus proportional to the total stellar mass (Gilfanov 2004). The contribution from HMXBs traces recent star formation in the galaxy, and is proportional to the galaxy’s star formation rate (SFR; Grimm et al. 2003; Mineo et al. 2012).

Lehmer et al. (2019) use a sample of 38 nearby galaxies to constrain the scaling relations for X-ray binaries. Their sample spans a wide range of galaxy morphology, stellar mass, SFR, and metallicity. It includes both nucleated and non-nucleated galaxies; several of the galaxies in their sample overlap with our sample of 108 galaxies. The expected X-ray luminosity from LMXBs and HMXBs is given by

$$L_X = \alpha M_\star + \beta \text{SFR}. \quad (1)$$

![Figure 1](image.png)
Note. Columns 4–6 give the log of the 0.5–7 keV luminosity (in erg s$^{-1}$), lower limit, and upper limit, respectively. Columns 7–9 give the log of the 2–10 keV luminosity (in erg s$^{-1}$), lower limit, and upper limit, respectively. Column 10 states whether the detected X-ray emission was diffuse. The complete table is available in the online version of this paper.

(This table is available in its entirety in machine-readable form.)

Table 2

| Object | ObsID | Exp (Time) (ks) | $L_{0.5-7}$ | $L_{0.5-7,lower}$ | $L_{0.5-7,upper}$ | $L_{2-10}$ | $L_{2-10,lower}$ | $L_{2-10,upper}$ | Diffuse |
|--------|-------|----------------|-------------|-------------------|-------------------|-------------|-------------------|-------------------|---------|
| ESO138-G010 | 14800 | 9.84 | 38.04 | 37.58 | 38.37 | ... | ... | ... | 38.71 | N |
| ESO 241-G006 | 17004 | 4.7 | ... | ... | 38.32 | ... | ... | ... | 38.34 | N |
| ESO 359-G029 | 21468 | 3.07 | ... | ... | 38.06 | ... | ... | ... | 38.47 | N |
| IC 0239 | 7131 | 4.53 | ... | ... | 38.01 | ... | ... | ... | 38.52 | N |
| IC 0396 | 7134 | 4.87 | 39.08 | 38.94 | 39.22 | 38.69 | 38.24 | 39.02 | N |
| IC 4710 | 9877 | 15.25 | ... | ... | 37.28 | ... | ... | ... | 37.52 | N |
| IC 5256 | 17001 | 1.65 | ... | ... | 39.58 | ... | ... | ... | 39.99 | N |
| IC 5332 | 2067 | 55.24 | ... | ... | 36.47 | ... | ... | ... | 37.02 | N |
| M074 | 4753 | 5.28 | 38.05 | 37.71 | 38.32 | 38.04 | 37.28 | 38.49 | N |
| M108 | 2025 | 59.36 | 37.61 | 37.42 | 37.78 | 37.41 | 36.44 | 37.80 | Y |
| MCG-01-03-085 | 12981 | 9.82 | ... | ... | 37.48 | ... | ... | ... | 38.11 | N |
| NGC 0247 | 17547 | 5.01 | 39.19 | 39.16 | 39.22 | 39.17 | 39.12 | 39.22 | N |
| NGC 0428 | 16978 | 3.99 | ... | ... | 38.17 | ... | ... | ... | 38.55 | N |
| NGC 0672 | 7090 | 2.15 | ... | ... | 40.90 | ... | ... | ... | 41.46 | N |
| NGC 0959 | 7111 | 2.18 | ... | ... | 38.17 | ... | ... | ... | 38.65 | N |
| NGC 1003 | 7116 | 2.67 | ... | ... | 38.03 | ... | ... | ... | 38.50 | N |
| NGC 1042 | 12988 | 29.01 | 38.09 | 37.98 | 38.18 | 38.16 | 37.99 | 38.31 | N |
| NGC 1058 | 387 | 2.41 | 38.00 | 37.45 | 38.37 | 38.34 | 37.57 | 38.80 | N |
| NGC 1073 | 4686 | 5.74 | 38.90 | 38.75 | 39.03 | 39.03 | 38.80 | 39.22 | N |
| NGC 1325A | 7841 | 5.09 | ... | ... | 38.28 | ... | ... | ... | 38.76 | N |
| NGC 1385 | 21473 | 5.04 | 42.22 | 42.09 | 42.32 | 42.28 | 42.11 | 42.40 | N |
| NGC 1483 | 16981 | 2.51 | ... | ... | 39.01 | ... | ... | ... | 39.37 | N |
| NGC 1487 | 21469 | 2.05 | ... | ... | 38.12 | ... | ... | ... | 38.40 | N |
| NGC 1493 | 7145 | 10.03 | 38.76 | 38.64 | 38.85 | 38.47 | 38.18 | 38.70 | N |

Figure 2. Chandra X-ray Observatory imaging (left) and Hubble Space Telescope imaging (right) for NGC 4449, a galaxy with diffuse X-ray emission in the center. The green circles have a radius of 2″ and are centered on the galaxy coordinates from Georgiev & Böker (2014). The HST image was taken with the ACS WFC in the F814W band. The NSC is visible in the HST image.

The best-fit values from Lehmer et al. (2019) are $\alpha = 1.8 \times 10^{39} \text{erg s}^{-1} \text{M}^{-1}_{\odot}$ and $\beta = 5.1 \times 10^{39} \text{erg s}^{-1} (\text{M}_{\odot} \text{yr}^{-1})^{-1}$. We compute the expected X-ray binary luminosity for each of our galaxies. Note that this uses the 0.5–8 keV luminosity; we compute the 0.5–8 keV luminosities for our X-ray sources in order to compare to the estimated luminosities from Lehmer et al. (2019).

Galaxy stellar masses are taken from Georgiev & Böker (2014). To compute the SFHs, we use the formalism from Kennicutt & Evans (2012), where

$$\log M_{\odot}(\text{yr}^{-1}) = \log L_{\text{FUV, corr}} - 43.35. \tag{2}$$

The FUV luminosity is corrected for dust extinction using the 25 μm luminosity, where $L_{\text{FUV, corr}} = L_{\text{FUV, obs}} + 3.89 \times L_{25,\text{mic}}$.

We use GALEX data (Martin et al. 2005) to measure the FUV luminosities for each galaxy in our sample. We measure the FUV flux within an aperture with a radius equal to the galaxy radius reported in Georgiev & Böker (2014) (their $R_{25,\text{e}}$ from HyperLeda; Paturel et al. 2003). We use W4 magnitudes from AllWISE (Wright et al. 2010) to compute the 25 μm flux density and correct the FUV luminosity.

We are interested in the expected X-ray binary luminosity within the CXO point-spread function (PSF). Following similar analyses presented in Foord et al. (2017) and Lee et al. (2019), we assume that the galaxy mass traces the light profile, and measure the fraction of galaxy light in the central 2″ for each system using available HST imaging. We note that galaxies were imaged with different cameras and filters. The median fraction of light in the central 2″ is 0.035. For a handful of cases, the galaxy is larger than the HST image field of view; for these galaxies, we take the fraction to be 0.05, slightly more conservative than the median value.

Putting the above steps together, we find expected X-ray binary luminosities in the central 2″ ranging from $6 \times 10^{30}$–$3 \times 10^{30} \text{erg s}^{-1}$. The ratio of observed 0.5–8 keV luminosity to that expected from X-ray binaries ranges from 0.09 to 3980, with a median ratio of 6.27. Table 3 gives the expected X-ray binary luminosities and ratios of observed-to-expected luminosity.
A caveat to this analysis is that it does not take into account additional potential emission due to the NSC environment, i.e., preferential LMXB/HMXB formation in the central parsecs. Additionally, a possible formation channel for NSCs is through inspirals of globular clusters, where X-ray binary formation is efficient (Clark 1975; Sivakoff et al. 2007). As our formation channel is driven by runaway tidal capture LMXB formation in NSCs, this may seem contradictory. However, we consider as a comparison case the central parsec of the Milky Way galaxy, which indeed possesses an overabundance of LMXBs (Hailey et al. 2018), which may themselves be BH-LMXBs that have formed through tidal capture (Generozov et al. 2018). Except during brief periods of LMXB outburst (Muno et al. 2005), the combined X-ray luminosity of this LMXB subcluster is \( \lesssim 10^{34} \) erg s\(^{-1}\), likely due to the low mass transfer rates in most tidal capture LMXBs. Furthermore, the Milky Way NSC lacks clear evidence for an overabundance of NS-LMXBs, which form at elevated rates in globular clusters due to chaotic binary-single scatterings (Ivanova et al. 2008). This signifies (i) a low rate of NS-LMXB formation in NSCs relative to globular clusters, likely due to lower binary fractions resulting from the higher velocity dispersion environment of the galactic nucleus\(^8\), and (ii) that whatever NS-LMXBs were brought in through globular inspiral have since deactivated. As the typical NS-LMXB lifetime is \( \sim 1 \) Gyr (Ivanova et al. 2008), the latter conclusion would be unsurprising if most globular inspiral events happened in the distant past.

Given the generally low X-ray luminosity of LMXBs in the Milky Way NSC and lacking an NSC-specific X-ray background (XRB) luminosity estimator, we proceed with our estimates of probable X-ray emission based on SFR and stellar mass within the PSF. We note, however, that we may be underpredicting the true total XRB luminosity of some NSCs if their dynamics deviate strongly from that of the Milky Way NSC.

Going forward, we consider anything with an observed luminosity a factor of 2 higher than expected to be due to a massive BH (e.g., Birchall et al. 2020). Objects with observed luminosities less than twice the expected are treated as nondetections. This removes 10 detections from the \( \sigma > 40 \) km s\(^{-1}\) regime, and two from the \( \sigma < 40 \) km s\(^{-1}\) regime. These tend to be lower luminosity systems; the median 0.5–7 keV luminosity for the likely X-ray binary systems is \( \sim 10^{38} \) erg s\(^{-1}\), compared to \( 10^{39} \) erg s\(^{-1}\) for the more secure massive BHs. Our results do not change if we use a more conservative factor of 3 instead of 2.

In Figure 3, we show the X-ray luminosity versus galaxy mass, NSC mass, and SFR for likely massive BHs and likely XRBs. At a given X-ray luminosity, the likely XRBs tend to be in more massive galaxies and those with higher SFRs. This is expected as more massive galaxies will have more stellar mass within the central 2\(''\).

In addition to the 12 point-source objects we treat as likely X-ray binaries, all five of the galaxies with diffuse X-ray emission have X-ray luminosities less than the expected luminosity from X-ray binaries. Their luminosities range from \( \sim 0.1–0.5 \) times the expected X-ray binary luminosity.

### 3.2. Hardness Ratios

We compute hardness ratios for our sources using the aperture fluxes reported by SRCFUX. The hardness ratio is given by \( [F(H) - F(S)]/[F(H) + F(S)] \) where \( F(H) \) is the flux in a hard band and \( F(S) \) is the flux in a soft band. Here, we use the 0.5–2 keV band as the soft band and the 2–7 keV band as the hard band. In Figure 4, we show the hardness ratios for the likely active galactic nuclei (AGN) and likely XRBs. The

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**Note.** Column 4 gives the expected 0.5–8 keV luminosity from X-ray backgrounds (XRBs) following the scalings derived in Lehmer et al. (2019). Column 5 gives the 0.5–8 keV luminosity of the detected X-ray source. Column 6 gives the ratio of the source luminosity to the expected XRB luminosity. The complete table will be available in the online version of the paper.

8. However, the Milky Way NSC has a high-velocity dispersion and low binary fraction at least in part because of the presence of an SMBH; in an NSC lacking a central massive BH, the binary fraction might be high enough to favor dynamical NS-LMXB formation in three-body scatterings.
samples of likely AGN and XRBs both span a wide range in hardness ratios (from $-1$ to $1$), with similar distributions. Many are consistent with a typical AGN spectrum with $\Gamma = 1.8$.

4. Results

As described in Section 3, 41 NSCs have X-ray point sources coincident with the NSC position. Twelve of these have X-ray luminosities close to the expected values for X-ray binary emission based on the scaling relations derived by Lehmer et al. (2019). In this section, we explore the properties, velocities dispersions, and tidal capture rates of NSCs with/without X-ray emission, treating the 12 likely X-ray binary contaminants as nondetections. Henceforth, “X-ray detected” refers to galaxies with X-ray detections likely to be from a massive BH.

4.1. Galaxy Properties

In Figure 5, we show the distributions of galaxy mass, NSC stellar mass, and galaxy SFR. At a given X-ray luminosity, the likely XRBs are in more massive galaxies/NSCs and have higher SFRs. We also emphasize the galaxies with diffuse X-ray emission. These are all likely XRB systems and have some of the lowest detected X-ray luminosities.

4.2. Detection Rate versus Velocity Dispersion

Our goal in this section is to compare the X-ray properties of NSCs with velocity dispersions above and below the 40 km s$^{-1}$ threshold. The cluster averaged velocity dispersion $\sigma$ is defined by $\sigma = \sqrt{G M_{\text{tot}}/3 r_{\text{eff}}}$ where $r_{\text{eff}}$ is the half-mass–radius from the best-fit King model. In Figure 6, we show the X-ray luminosity versus velocity dispersion for the entire sample.

However, we cannot take the detection fractions above and below this velocity dispersion threshold at face value. The X-ray sample is nonhomogeneous and observations have different limiting fluxes. To account for this, we compute the fraction for samples with artificially imposed X-ray detection limits. For each imposed detection limit $L_{\text{det}}$, we exclude any nondetections with upper limits greater than that value (since we cannot say whether they are detected down to a limit of $L_{\text{det}}$). We count the number of NSCs with measured X-ray luminosities greater than $L_{\text{det}}$, and treat anything with an X-ray luminosity lower than $L_{\text{det}}$ as a nondetection. Note that any galaxies with X-ray luminosities likely to be due to X-ray binaries are also treated as nondetections. We then compare the number of detected NSCs against those with upper limits lower than $L_{\text{det}}$. We repeat this for different values of $L_{\text{det}}$. Figure 7 demonstrates how the sample looks for different values of $L_{\text{det}}$. 
Figure 5. Properties of galaxies with and without X-ray detected NSCs. From left to right, we show galaxy stellar mass, NSC stellar mass, and NSC effective radius. The solid lines show the median values of each distribution.

Figure 6. X-ray luminosity (0.5–7 keV) vs. NSC 1-D velocity dispersion. Detections are shown as black circles, and upper limits are represented by gray triangles. The vertical dashed red line marks the 40 km s$^{-1}$ threshold.

Figure 8 shows the X-ray detection fraction versus $L_{\text{det}}$ for NSCs above and below the velocity dispersion threshold.

From Figures 7 and 8, we can see that for all values of $L_{\text{det}}$, the detection fraction is significantly higher for the $\sigma > 40$ km s$^{-1}$ sample. At $L_{\text{det}} = 10^{39}$ erg s$^{-1}$, the detection fraction for $\sigma < 40$ km s$^{-1}$ is $6.8\pm5\%$ and the detection fraction for $\sigma > 40$ km s$^{-1}$ is $28\% \pm 8\%$ (uncertainties are given for the 90\% confidence limit).

As expected, the detection fraction increases as we increase our sensitivity (i.e., lower the value of $L_{\text{det}}$), but does so similarly for the low- and high-velocity dispersion regimes.

4.3. Detection Rate versus Tidal Encounter Rate

We also look at the X-ray detection rate versus the tidal capture (TC) rates determined by Stone et al. (2017). The tidal capture rate $\dot{N}_{\text{TC}}$ is given by Equation (14) in Stone et al. (2017) and depends on the mass of the initial stellar-mass BH, the velocity dispersion, central cluster density, and the average mass and radius of the cluster stars. Some of the NSCs in our sample have only lower limits on the TC rate due to the discrete concentration values used in fitting the light profiles of the NSCs (objects with “Core Resolve” = 0 in Table 1). We exclude these from computations of the detection rate since we cannot say conclusively whether they are unstable to runaway TC over a Hubble time. We also note that the TC rates are uncertain by ~one order of magnitude for this reason. We refer the reader to Section 6.1 of Stone et al. (2017) for a detailed discussion of these uncertainties.

In Figure 9, we plot the X-ray detection fraction versus $L_{\text{det}}$ for NSCs with TC rates above and below $\dot{N}_{\text{TC}} = 10^{-8}$ yr$^{-1}$. NSCs with TC rates $\dot{N}_{\text{TC}} > 10^{-8}$ yr$^{-1}$ should be unstable to runaway growth of a stellar-mass BH through TC. While the fractions are higher for the $\dot{N}_{\text{TC}} > 10^{-8}$ yr$^{-1}$ sample, the uncertainties are larger due to the smaller number of objects in the sample. The two groups are consistent with one another within the 90\% confidence intervals. In order to confirm whether the X-ray detection fractions are truly higher among NSCs with $\dot{N}_{\text{TC}} > 10^{-8}$ yr$^{-1}$, we will need to obtain better-constrained measurements of $\dot{N}_{\text{TC}}$ for a greater number of NSCs.

5. Discussion

5.1. BH Formation in NSCs

Our analysis finds that NSCs with velocity dispersions higher than 40 km s$^{-1}$ are X-ray detected at roughly twice the rate of NSCs below that threshold. This is consistent with theories (Miller & Davies 2012; Stone et al. 2017) that suggest NSCs with high-velocity dispersions can form and grow massive BHs.

This is not the only possible interpretation of our results. One alternative scenario is that the NSCs with higher velocity dispersions had pre-existing massive BHs and the NSC formed around the BH. One implication of this scenario is that these NSCs have higher velocity dispersions due to the presence of the BH. To further explore this scenario, we turn to results from Antonini (2013), which models the formation of NSCs through star cluster inspiral in galaxies with/without a pre-existing massive BH. They find that if a massive BH is already present, the resulting NSC has a lower density than would form in a galaxy without a massive BH. In the presence of a pre-existing BH, the radius of the NSC is set by the tidal field of the BH. This could explain why NSCs are not typically found in galaxies with stellar masses greater than $\sim 10^{10} M_{\odot}$; the tidal field of a sufficiently large BH will prevent an NSC from forming.$^9$

$^9$ Other factors, such as the increasingly long dynamical friction inspiral time (Antonini 2013) and core scouring in multiple mergers (Thomas et al. 2014), also likely play a role in suppressing high-mass NSC formation.
If the high-$\sigma$, X-ray detected NSCs formed around pre-existing BHs, they should have systematically lower densities. In Figure 10 we plot the distributions of mean density for NSCs with and without X-ray detections. For those with X-ray detections, we divide the sample into NSCs with $\sigma$ above and below the 40 km s$^{-1}$ threshold. We find that the X-ray detected, high-$\sigma$ NSCs tend toward higher densities, in contrast to expectations for collisionless NSC formation around a pre-existing BH. Interestingly, the X-ray detected NSCs with low $\sigma$ —those that do not meet the theoretical requirements for forming a massive BH—skew toward lower densities. Their lower densities are consistent with this population having formed around pre-existing BHs rather than forming a BH later on.

Another interpretation of our findings is that high density/high-velocity dispersion NSCs are more efficient at fueling massive BHs, leading to higher accretion rates and thus higher X-ray luminosities. Naiman et al. (2015) simulate massive BH growth in NSCs during galaxy mergers. They find that NSCs can enhance BH fueling in this scenario, provided that the NSC meets the condition of $\sigma_{\text{NSC}} > \sqrt{\nu^2 + c_s^2}$, where $\nu$ is the relative velocity of the NSC through the gas, and $c_s$ is the sound speed. However, this pertains only to systems undergoing mergers; simulations of the impact of NSCs on BH fueling in nonmerging systems are needed.

Results from dynamical studies of nearby nucleated galaxies lend support to the scenario in which massive BHs can form...
and grow in high-velocity dispersion systems. M33 is one of the most nearby, well-studied nuclei; HST kinematics show an NSC velocity dispersion of 24 km s$^{-1}$ and no detected BH (at least to an upper limit of 1500 $M_\odot$; Gebhardt et al. 2001; Merritt et al. 2001). Nguyen et al. (2018) carry out dynamical modeling of the nuclear star clusters in M32 (see also Seth 2010), NGC 205, NGC 5102, and NGC 5206. The three clusters that have velocity dispersions $>40$ km s$^{-1}$—M32, NGC 5102, and NGC 5206—are those that are found to have evidence for central black holes. Nearby galaxies with X-ray detections presented here would be good targets for follow-up with high-resolution dynamical modeling.

These results also have important implications for our understanding of massive BH formation. If NSCs do facilitate the formation of massive BHs at relatively low redshift, this complicates efforts to use the present-day occupation fraction to constrain models of BH formation (see Greene et al. 2020). If massive BH seeds form only at high redshift, the low-mass end of the occupation fraction is expected to be sensitive to high-redshift BH seed formation models. However, this effect could be washed out if NSCs (which reside in low-mass galaxies) form massive BHs at later epochs.

\subsection*{5.2. BH Growth in Low-mass Galaxies}

The most massive BHs are expected to be assembled by $z \sim 2$, with progressively lower mass BHs undergoing more of their growth at lower redshifts. This is known as “downsizing” in BH accretion (Marconi et al. 2004; Di Matteo et al. 2008). In this section, we carry out a simple analysis to explore possible growth histories for the accreting BHs in the sample of nucleated galaxies presented here.\footnote{We note that Georgiev & Böker (2014) do exclude bright AGN from their initial sample of late-type galaxies based on their AGN class indicator in HyperLeda (Paturel et al. 2003). This primarily would have removed bright AGN in massive galaxies unlikely to have NSCs. Indeed, NGC 4395—one of the brightest and most well-known low-mass AGN—is still part of the sample.}

In order to estimate the mass accreted over time, we assume the current 2–10 keV X-ray luminosity for each galaxy is representative and use it as an average X-ray luminosity for that BH over the last 10 Gyr. We assume a bolometric correction of 10 (Marconi et al. 2004) and a radiative efficiency of 10%. Using this analysis, we find accreted masses spanning a large range ($\sim 10^{8}$–$10^{10}$ $M_\odot$), with a mean accreted mass of $\sim 10^{3}$ $M_\odot$. The mean value is several orders of magnitude below the saturation mass, an order-of-magnitude estimate for BHs grown primarily through tidal capture and/or tidal disruption processes (Equation (37) in Stone et al. 2017). The red line reflects a saturation mass equal to the accreted mass.

This suggests that—if the current X-ray luminosities can generally be used to compute an average mass accretion rate—these BHs have not grown much through gas accretion. There are several ways to interpret this result. One possibility is that these BHs were more active in the past and underwent most of their growth at higher redshift. Given the general trend of downsizing in BH accretion, this seems unlikely. Another possibility is that the bolometric correction and/or radiative efficiency are higher for low-mass AGN. However, the accretion properties would have to be substantially different to make up for the several orders of magnitude difference between the estimated accreted mass and saturation mass. A third possibility is that BHs in low-mass galaxies grow primarily through intermittent phases of short, highly super-Eddington accretion due to tidal capture and/or tidal disruption events. While there remain open questions surrounding the fraction of mass accreted in both tidal captures (Generozov et al. 2018) and in tidal disruption events (Metzger & Stone 2016; Bonnerot & Lu 2020), we consider this the most likely scenario. This is consistent with recent work demonstrating that the duty cycles of TDE-powered AGN are consistent with the observed fractions of AGN in present-day dwarf galaxies (Zubovas 2019).

Figure 10. Mean density distributions for NSCs with/without X-ray detections. The mean density is defined as $\bar{\rho} = 5M_{\odot}/(4\pi r_0^3)$. The sample of nondetected NSCs is shown in light gray. X-ray detected NSCs with detections. The mean density is de...
6. Summary

We analyze Chandra X-ray Observatory imaging for 108 nearby galaxies with NSCs. Of these, 29 have X-ray emission that is likely to be due to an accreting massive BH. We then study the properties of NSCs with and without evidence for a massive BH. Our conclusions can be summarized as follows:

1. NSCs with mean velocity dispersions $\geq 40$ km s$^{-1}$ are X-ray detected at roughly twice the rate of those below this threshold.

2. Tentatively, NSCs with TC rates high enough to form an intermediate-mass BH in less than a Hubble time are X-ray detected at a higher rate than those below this limit.

3. These results are consistent with a scenario in which sufficiently dense, high-velocity dispersion NSCs can form an intermediate-mass BH through dynamical processes.

4. Better constraints on the active fraction as a function of velocity dispersion and TC rate could be obtained by improved morphological modeling of the NSCs (i.e., finer sampling of the concentration parameters) and additional X-ray observations.

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