Finding Local Low-mass Supermassive Black Holes

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Abstract. The low-mass end of the supermassive black hole mass function is unknown and difficult to determine. Here we discuss our successful program to find active nuclei of late type “normal” galaxies using X-ray detections and multiwavelength identifications. We conclude that most of the Chandra detected nuclear X-ray sources are AGNs. We then outline methods of black hole mass determination when broad emission lines are unobservable.

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INTRODUCTION

The local low-mass (below $10^6 M_\odot$) supermassive black hole (SMBH) mass function is not well known. Current estimates of the SMBH mass function are based on host galaxy properties (luminosity of the bulge or bulge stellar velocity dispersion $\sigma$) and known scaling relationships between the mass $M_*$ of the SMBH and these properties (most prominently $M_*$ – $\sigma$ and $M_*$ – $M_{\text{bulge}}$). These estimates can be widely discrepant with each other at the low-mass end (see, for example, Fig. 8 in [1]). Much of the uncertainty arises because it is unknown how the scaling relationships extrapolate to very late-type and very low mass galaxies. Yet SMBHs do exist in very late-type spirals, e.g. NGC 4395, a spiral galaxy of type Sdm, with $M_* \sim 3 \times 10^5 M_\odot$ [2], and in very low mass galaxies, e.g. POX 52, a dwarf galaxy, with $M_* \sim 3 \times 10^5 M_\odot$ [3].

Most of the measured SMBH masses are $\sim 10^8 M_\odot$ or greater, however, as the sphere of influence of a less massive SMBH is extremely hard to resolve even at moderate distances, even with the Hubble Space Telescope (HST). For example, the sphere of influence of a $10^6 M_\odot$ SMBH at 15 Mpc is $\sim 30$ milliarcseconds. Since we cannot detect low-mass SMBHs by their dynamical signature, looking for them by signs of their accretion activity may be the only viable way of detecting them. An accreting low-mass SMBH should be a low-luminosity active galactic nucleus (LLAGN).

How can an LLAGN be identified? Broad emission lines in the optical spectrum allow an unambiguous confirmation of the presence of an AGN. The sample of low-mass SMBHs in Greene and Ho [4] was identified this way. However, as the luminosity of an AGN decreases, the optical spectrum of the galaxy nucleus becomes more and more dominated by host galaxy light, and the signature of the AGN becomes difficult to detect. For the lowest-luminosity AGNs, therefore, it is possible that a system based on optical
spectra would not classify the nuclei as AGNs at all. Even when the optical spectrum shows no clear evidence of an AGN, however, such evidence may still be present in other wavelengths, such as x-ray and radio [5], and infrared [6,7,8].

OUR CHANDRA PROGRAM

Why X-ray selection?

X-ray emission is an ubiquitous property of AGNs. If late type galaxies indeed host supermassive black holes in their nuclei, and yet they have not been discovered until now, they are most likely highly obscured. This is less of a problem in X-rays than in optical bands. X-ray observations with Chandra have uncovered AGNs in what were thought to be normal galaxies in clusters [9] and in fields [10]. X-ray surveys have also found new classes of AGNS, e.g. “X-ray bright optically normal galaxies” [XBONGS; 11]. Thus, it is highly likely that a strategy of uncovering hidden AGNs in optically normal galaxies using X-ray detections might work.

The sub-arcsecond angular resolution of Chandra is advantageous for this program for identifying the true nucleus from surrounding galactic sources. With these considerations we initiated a Chandra program to search for active nuclei in centers of nearby late type galaxies identified as X-ray sources. As we discuss below, this was relatively easy; we detected nuclear X-ray sources in a large number of galaxies. The second part, identifying the X-ray sources as accreting SMBHs was far more difficult. We used a variety of techniques and multiwavelength data for this purpose.

The sample

Our goal is to search for low-level nuclear activity in a representative sample of low-mass galaxies within 20 Mpc. We selected 38 galaxies from the NBG catalog [12] with following criteria: face-on spirals (S0–Sdm) or dE and NOT known to host AGNs. We excluded starburst galaxies from the sample to ease the identification of nuclear X-ray sources. LINER galaxies were included because the nature of their energy source is still a matter of debate. Based on their optical luminosities ($-21 < M_B \leq -15$) and morphology, most of these galaxies are expected to host SMBHs with $10^5 \lesssim M_\bullet \lesssim 10^7 M_\odot$, with a few objects hosting SMBHs as small as $10^4 M_\odot$.

With this study we hope to set firm lower limits to the number of galaxies which host low mass BH, and to address the following questions:
– What fraction of galaxies host active SMBHs and what governs the activity of these SMBHs?
– How does the fraction of active galaxies depend on the galaxy morphology & environment?
– What is the primary component of a galaxy that relates to its BH mass: the bulge or the dark matter halo? Finding active nuclei in bulge-less spirals would imply the latter.
– What is the relation between nuclear star formation activity and accretion onto a BH?
– Is there a lower bound to the local BH mass function?
– How do we understand BH growth and its relation to hierarchical galaxy formation? [e.g. 13]

Of the 38 Chandra targets, 28 have been observed to date. We also found 16 galaxies in the Chandra archive meeting our selection criteria. Additionally, there were 6 galaxies in the archive which met similar criteria applied to the RC3 catalog. We discuss the latter sample first.

RESULTS

The archival sample I

The six galaxies in this sample have morphological types Sa, Sb, Sc, Scd (2) and Sd. All six have nuclear X-ray sources. For two galaxies, NGC 4713 (Sd) and NGC 4647 (Sc), the data are inconclusive, but we cannot rule out that they are AGNs. Interestingly, for two weak-bulge galaxies NGC 5457 (Scd) and NGC 3184 (Scd) we can make a strong case that they host AGNs; these galaxies are discussed in detail in Ghosh et al. (these proceedings). The remaining two galaxies, NGC 3169 (Sa) and NGC 4102 (Sb) are almost certainly AGNs; we discuss these here.

NGC 3169: This is an Sa galaxy at 20 Mpc, classified optically as a low ionization nuclear emission line region (LINER). Chandra detected a nuclear hard X-ray source (Fig. 1), indicative of an AGN. The X-ray spectrum is an absorbed power-law with slope $\Gamma \sim 2$ and column density $N_H \sim 10^{23}$ cm$^{-2}$. The AGN identification is clinched by the fact that the X-ray source coincides with a 7mJy mas-scale VLA radio source [14]. Thus the source is almost certainly an AGN.

NGC 4102: This is a Sb galaxy at 17 Mpc, classified optically as a HII nucleus. Chandra detected a hard point source in its nucleus with extended soft emission (Fig. 1). The spectrum of the nuclear point source is a power-law with $\Gamma \sim 2$ and no intrinsic absorption. However, a strong Fe K-\alpha line is detected with EW=2.5 keV. Even though the error on the EW is large, owing to the low S/N of the spectrum, the EW is inconsistent with the ($\sim 300$ eV) value observed in unabsorbed AGNs. Thus the spectrum is that of a reflection-dominated source. The Chandra image and the spectrum are similar to those of Seyfert 2 galaxies [15]. The nucleus is also a FIRST radio source. Moreover, it is also an IR point source (2MASS) with luminosity $10^{43}$ erg/s. This puts the source squarely in the AGN regime.

These observations show the power of X-ray detection and multiwavelength identification of AGNs in what were thought to be “normal” galaxies. (See [16] for complete analysis of the sample.)

The whole sample

The six galaxies in the archival sample discussed above were scrutinized one by for the possible signature of an AGN. This has been a hard job owing to the low luminosity of the sources (except for the two best cases discussed above). Dilution of the AGN
signature due to contamination from the host galaxy light then becomes a major problem. Obscuration also affects the observed properties. As a result, traditional diagnostics of finding AGNs, such as UV excess, X-ray to optical flux ratio, X-ray to IR flux ratio, existence of broad emission lines, line ratios of narrow emission lines, all break down. Indeed, if it were not a difficult task, we would have already known that these galaxies host AGNs!

The identification problem becomes somewhat easier with a larger sample. In addition to the six galaxies discussed above, we found 16 more from Tully [12] in the Chandra archive following our selection criteria. Nuclear X-ray sources were detected in 12. Thus, 18 of the 22 archival galaxies host a nuclear X-ray source. Moreover, in most cases, the nucleus was the brightest X-ray source, in one the second brightest X-ray source and in one the only X-ray source. It is highly unlikely that the brightest X-ray binary, a star, or any other normal galactic X-ray source resides in the nucleus most of the time. Thus we conclude that most of the Chandra detected nuclear X-ray sources are AGNs.

Our new Chandra survey was much shallower than the archival observations. Preliminary analysis indicates that 6 out of 28 galaxies host a nuclear X-ray source.

**DISCUSSION**

**How to measure BH masses**

Reverberation mapping of broad emission lines provides a standard method for measuring BH masses in AGNs. Alternatively, scaling relations using the width of broad
emission lines and AGN luminosity are used. How should we measure BH masses in our newly discovered AGNs which do not show broad emission lines? This can be done in a variety of ways:

1. As noted above, host galaxy contamination is a major contributor toward hiding the AGN signature of our low-luminosity sources. Broad emission lines of these AGNs might have been swamped by the host galaxy light in ground-based spectra. Therefore it is imperative to obtain spectra of these sources with the highest possible spatial resolution from space, e.g. with STIS on HST. This might uncover broad emission lines.

2. Construction of power-density spectra (PDS) using X-ray variability analysis provides a powerful tool for BH mass determination [17]. The break frequency in PDS is found to correlate strongly with the BH mass; since our sources are X-ray detected, this is potentially a highly feasible method.

3. The X-ray power-law slope correlates strongly with the Eddington luminosity ratio [18]. Measuring the X-ray slope and luminosity would then estimate the BH mass.

4. SMBH mass is known to correlate with the bulge velocity dispersion [19, 20] and the bulge luminosity [21, 22, 23]. These relations can be used for BH mass determination, once we ascertain the existence of a SMBH. This method, however, will not work for bulge-less galaxies. Moreover, if we do not have independent measurements of BH masses, we cannot extend these known correlations to low BH masses.

5. SMBH mass is also known to correlate with the circular velocity of the host galaxy [24, 25]. This method will have the same caveat mentioned above, though it works for bulge-less galaxies as well.

Thus there are several ways to estimate masses of SMBHs which we uncover using X-ray detections. This is obviously a hard job; at this point, however, we are at the step of finding these low-mass SMBHs in the first place.

What’s Next?

In order to make progress in finding and identifying low-mass SMBHs and measuring their masses several steps need to be taken.

1. Through our Chandra survey and the accompanying archival programs we have realized that traditional diagnostics for identifying AGNs fail for low-luminosity AGNs embedded in luminous galaxies. We need to develop new diagnostic tools using multi-wavelength data for this purpose.

2. Deep X-ray spectra of likely AGNs. This will help secure AGN identification. We have obtained XMM-Newton data on one of our candidate.

3. HST STIS spectroscopy. As noted above, this will uncover broad emission lines if any and possibly change the narrow emission line flux ratios.

4. HST ACS imaging. This will help obtain true colors of the AGN, after removing a substantial contribution of the host galaxy. We can then identify an AGN with traditional “UV excess” and/or with broad-band spectral energy distribution.

5. IR diagnostics: Spitzer IRAC colors. While AGNs are blue in the optical, they are red in mid-IR. AGNs occupy a distinct location in the IRAC color-color plot, allowing identification of X-ray sources [26].
6. IR diagnostics: near IR spectra. High ionization IR emission lines with IRS on *Spitzer* have been used to uncover AGNs by Satyapal et al. [8]. With the end of *Spitzer* cryogenic mission, IRS is no longer available. Finding near-IR “coronal” lines might prove useful for the same purpose.

7. Radio observations. Finding a radio point source coincident with the X-ray point source will help secure the identification. VLA observations of our candidate AGNs is an obvious next step.

8. Bigger *Chandra*/*Spitzer* survey will provide better statistics on fraction of galaxies hosting AGNs. A deeper survey will allow us to determine AGN duty cycle to lower luminosities.

9. Hard X-ray observations. A survey of nearby galaxies in hard X-rays will detect and identify nuclear SMBHs (as well as off-nuclear accreting BHs). The Indian X-ray mission ASTROSAT, which has hard X-ray capabilities is due to launch in 2009. ASTROSAT observations will be invaluable in our BH quest.

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