The Interplay among Black Holes, Stars and ISM in Galactic Nuclei
Proceedings IAU Symposium No. 222, 2004
T. Storchi-Bergmann, L. C. Ho & H. R. Schmitt, eds.

DOI: 10.1017/S1743921304001462

Chandra detection of ultra-low-luminosity AGNs in nearby galaxies

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Abstract. We present *Chandra* observations of the nuclear region of nearby inactive galaxies. The sample is selected based on the absence or weakness of optical emission lines in the nucleus. X-ray nuclei are detected in four out of six galaxies. This result, along with previous observations, suggests that more than half of galaxies, for which no evidence for nuclear activity is known, possess an ultra-low-luminosity "active" nucleus. X-ray emission from hot gas is detected in at least four galaxies. We estimate the Bondi accretion rate from the gas density, temperature, and central black hole mass and suggest that the accretion luminosity is not simply determined by the Bondi rate.

1. Introduction

It is believed that almost all galaxies with a bulge harbor a supermassive black hole (SMBH) in the nucleus. Only a small fraction of SMBHs are observed as a luminous active galactic nucleus (AGN), and the majority show weak (low-luminosity AGNs; LLAGNs) or no nuclear activity. A study of the nuclear activity and environment of such nearly inactive galaxies can be used to strongly constrain very low-luminosity accretion flows.

Our Galactic Center is the most remarkable example of an ultra-low-luminosity AGN (ultra-LLAGN), with an X-ray luminosity of 2×10^{33} erg s^{-1} and an Eddington ratio of 3.6×10^{-12}. The nucleus shows large amplitude flares in the X-rays and near-infrared (Baganoff et al. 2001; Genzel et al. 2003), which have never been observed from more luminous AGNs. Such completely new phenomena are of significant importance to understand the physics of accretion under an extremely low mass accretion rate (Yuan, Quataert, & Narayan 2003, 2004). On the other hand, X-rays are not detected from nuclei of some giant elliptical galaxies (NGC 1399, 4472, and 4636; Loewenstein et al. 2001) and their luminosities imply extremely low $L_{\rm X}/L_{\rm Edd}$ of $< 3 \times 10^{-8}$. All of these galaxies host a SMBH embedded in diffuse, X-ray-emitting hot gas, which could be a reservoir of accreting matter. It is still unknown what controls the accretion luminosity. In this paper, we present the results of a *Chandra* mini survey of nearby inactive galaxies to search for an AGN and to measure the environment in the vicinity of the black holes. More detailed results can be found in Ho, Terashima, & Ulvestad (2003) and Terashima, Ho, & Ulvestad (in preparation).

2. The Sample and Observations

Our sample is selected from the Palomar optical spectroscopic survey (Ho, Filippenko, & Sargent 1997). In order to constrain accretion flows with very low luminosities, galaxies with no or very weak optical emission lines shown in Table 1 in Ho et al. (1997) are the best candidates. We defined a distance-limited (<10 Mpc) sample from the table and found five galaxies in the *Chandra* archives (excluding M31, in which the presence of a ultra-LLAGN has been known). NGC 3379, which is not included in the table, is also added because its line emission is very weak and the presence of a large central black hole is known. There are six galaxies in the final sample presented here: M32, NGC 628, 3115, 3379, 4414, and 4494. All the objects were observed with the ACIS-S3 back-illuminated CCD. The exposure times range from 2 to 90 ksec. We also analyzed archival (M32) and proprietary (NGC 628 and NGC 3379) data taken with the Very Large Array (VLA) in its B configuration to search for radio cores, to measure a better nuclear position, and to study the radio properties of the nuclei.

3. Results

3.1. *X-ray Nucleus*

X-ray nuclei are detected in four out of six galaxies in our sample. An example of a *Chandra* image is shown in Fig. 1. The luminosities in the 2–10 keV band ($L_{\rm X}$) are very low ($6.4 \times 10^{35} - 1.4 \times 10^{38}$ erg s^{-1}), which correspond to Eddington ratios of $L_{\rm X}/L_{\rm Edd}$ $= 2.6 \times 10^{-10} - 6.0 \times 10^{-7}$. In particular, the Eddington ratio of NGC 3115 is the second lowest known so far next to the Galactic Center. Three objects (M32, NGC 628, and NGC 3379) have sufficient counts to measure their rough spectral shape. A power-law model fit yielded a photon index of $\Gamma = 2.23^{+0.46}_{-0.48}$, 1.5 ± 0.3, and 2.9 ± 1.2, respectively. To measure the luminosities of the other objects, we assumed a power-law model with $\Gamma = 2.0$ modified by Galactic absorption.

Off-nuclear sources are also detected, and the probability of chance coincidence of an unrelated X-ray binary with the nucleus is not negligible for some cases. We examined this issue by two means. First, we estimated the probability by assuming the radial distribution of X-ray sources is the same as that of the optical/near-infrared stellar light. Note that the number of off-nuclear sources is relatively large in early-type galaxies and that the population is primarily low-mass X-ray binaries. The probability is largest for NGC 3115 ($\sim$ 43%), but much smaller for the other galaxies. Since the detection rate (4/6) is much larger than the chance coincidence probability, a significant fraction of the nuclear X-ray source, if not all, are associated with an extremely low-luminosity AGN.

Another test is to search for a radio core. Since X-ray binaries are weak radio sources, it is impossible to detected an extragalactic X-ray binary in the radio unless it is significantly beamed toward us. Radio data are available for three objects (M32, NGC 628, and NGC 3379). A compact radio core has been known in NGC 3379 (Fabbiano *et al.* 1989). We measured its radio spectrum and found a flat spectral index, as is often observed in LLAGNs (e.g., Anderson, Ulvestad, & Ho 2004). The detection of a flat-spectrum radio core in NGC 3379 strongly supports the AGN interpretation of its X-ray nucleus. No radio core is detected in M32 and NGC 628, with upper limits of 30 μJy and 58 μJy, respectively, at 8.4 GHz. These limits are consistent with the range of radio loudness for LLAGNs (Terashima & Wilson 2003).

3.2. *Environment*

In order to examine the environment around the black holes, we searched for X-ray-emitting hot gas and measured its physical parameters. If a nuclear region contains sufficient X-ray counts, the parameters (or their upper limits) of the gas are derived from spectral fits. For the other cases, the hot gas component was measured in an off-nuclear region. Diffuse emission from hot gas is detected in M32, NGC 628, NGC 3115, and

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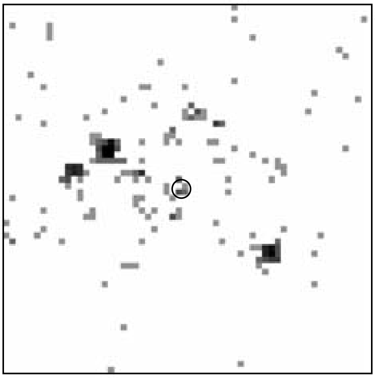

Figure 1. Chandra image of the central region of NGC 3379 in the 2–8 keV band. Image size is 1.2 kpc × 1.2 kpc.

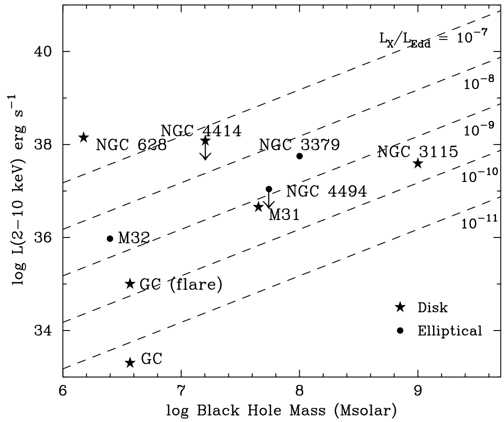

Figure 2. X-ray luminosities and black hole masses. Dashed lines represent L_X/L_{Edd} = constant lines.

NGC 4414. Their temperatures are in the range $kT = 0.3 - 0.9$ keV; upper limits were determined for the other objects. We calculated the Bondi accretion radius (R_A) and Bondi accretion rate ($\dot{M}_{Bondi}$) from the parameters obtained above (Fig. 3). The region sampled by the observations corresponds to 1–1000 R_A, depending on the black hole mass and method used.

4. Discussion

X-ray nuclei are detected in four out of six galaxies in our distant-limited sample of inactive galaxies. This fact lends additional support to the notion that almost all galaxies host a SMBH. Fig. 3 summarizes the observed X-ray luminosities and Bondi accretion rates derived in the previous section. We also include some ultra-LLAGNs and galaxies without X-ray nuclei taken from the literature (Di Matteo et al. 2001a, b; Loewenstein et al. 2001). This figure demonstrates that the observed luminosities are not simply scaled by the Bondi accretion rate. In other words, the radiative efficiency η ($L_X = \eta \dot{M}_{Bondi} c^2$) is scattered over a wide range ($4 \times 10^{-9} - 6 \times 10^{-5}$, excluding upper or lower limits).

One possible origin of the scatter might be that a significant fraction of the accreted matter is converted to jets/outflows rather than radiation. We examined this hypothesis by comparing the radio loudness parameter, defined using the X-ray luminosity [$R_X = \nu L_\nu(5 \text{ GHz})/L_X$; Terashima & Wilson 2003] and η. Since radio emission most likely comes from jets, R_X provides a rough estimate of the jet power relative to the accretion luminosity (L_X). If $\dot{M}_{Bondi}$ indeed goes to jets, we expect large R_X for low-η objects. The data (Fig. 4) show that this is not the case. Thus, we conclude that the branching ratio between jets and radiation is not the only cause for the variation in η. We speculate that other parameters influence the actual accretion rate, radiative efficiency, and jet power. A candidate may be the viscosity parameter, which determines the behavior of radiatively inefficient accretion flows such as ADIOS and CDAF (e.g., Igumenshchev & Abramowicz 2000).

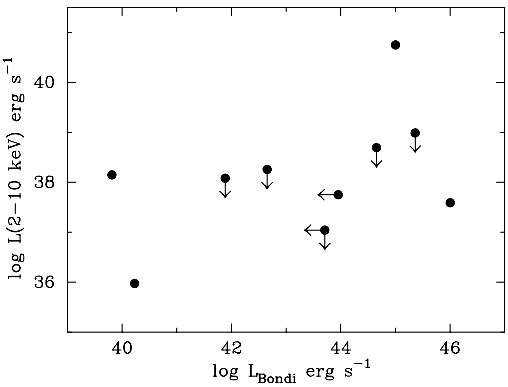

Figure 3. X-ray luminosities plotted against $L_{\rm Bondi} = \dot{M}_{\rm Bondi} c^2$.

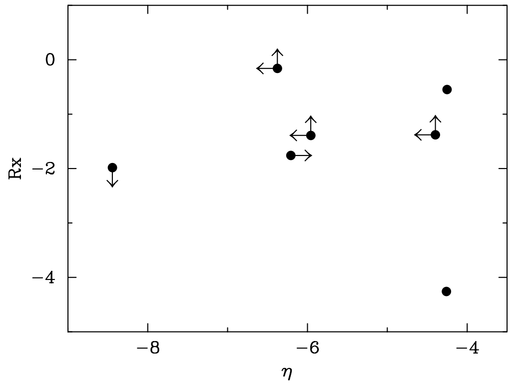

Figure 4. Radio loudness ($R_{\rm X}$) vs $\eta = L_{\rm X}/\dot{M}_{\rm Bondi} c^2$.

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https://doi.org/10.1017/S1743921304001462 Published online by Cambridge University Press