DETECTION OF NUCLEAR X-RAY SOURCES IN NEARBY GALAXIES WITH CHANDRA

LUIS C. HO1, ERIC D. FEIGELSON2, LEISA K. TOWNSLEY2, RITA M. SAMBRUNA2,3, GORDON P. GARMIRE2, W. N. BRANDT2, ALEXEI V. FILIPPENKO4, RICHARD E. GRIFFITHS5, ANDREW F. PTAK3, AND WALLACE L. W. SARGENT6

To appear in The Astrophysical Journal (Letters).

ABSTRACT

We report preliminary results from an arcsecond-resolution X-ray survey of nearby galaxies using the Advanced CCD Imaging Spectrometer (ACIS) on board the Chandra X-ray Observatory. The total sample consists of 41 low-luminosity AGNs, including Seyferts, LINERs, and LINER/H II transition objects. In the initial subsample of 24 objects observed thus far, we detect in ~62% of the objects a compact, point-like source astrometrically coincident with either the optical or radio position of the nucleus. The high detection rate strongly suggests that the majority of the objects do contain weakly active, AGN-like cores, presumably powered by central massive black holes. The 2–10 keV luminosities of the nuclear sources range from $<10^{38}$ to $10^{41}$ erg s$^{-1}$, with a median value of $2 \times 10^{39}$ erg s$^{-1}$. Our detection limit corresponds to $L_X(2–10$ keV$) \approx 8 \times 10^{37}$ erg s$^{-1}$ for the typical sample distance of 12 Mpc; this limit is two orders of magnitude fainter than the weakest sources of this kind previously studied using ASCA or BeppoSAX. The new data extend toward lower luminosities the known linear correlation between hard X-ray and Hα luminosity for broad-line AGNs. Many narrow-line objects do contain X-ray cores, consistent with either weak AGNs or X-ray binary systems, but they have X-ray luminosities a factor of 10 below the $L_X – L_{H\alpha}$ relation of the broad-line sources. Their distributions of photon energies show no indication of exceptionally high absorption. The optical line emission in these nuclei is likely powered, at least in part, by stellar processes.

Subject headings: galaxies: active — galaxies: nuclei — galaxies: Seyfert — X-rays: galaxies

1. INTRODUCTION

Knowledge of the local space density of active galactic nuclei (AGNs) impacts many astrophysical issues. Surveys for nearby AGNs furnish critical data for quantifying the faint end of the AGN luminosity function, for characterizing the demography of massive black holes, and for investigating accretion physics. Optical spectroscopic surveys indicate that many nearby galaxies possess mildly active nuclei (Ho, Filippenko, & Sargent 1997b). Although a significant fraction of these objects do contain accretion-powered sources qualitatively similar to more powerful AGNs such as classical Seyfert nuclei and quasars (Ho 1999), the physical nature of many still remains ambiguous. Observations at ultraviolet and optical wavelengths sometimes point to stellar processes as the underlying agent responsible for the activity (e.g., Maoz et al. 1998; Barth & Shields 2000), but these data generally cannot rule out the presence of a highly obscured AGN component.

Unless Compton-thick conditions prevail, hard X-ray data provide a much more definitive probe. In recent years, observations using ASCA and BeppoSAX have shed considerable light on the nature of low-luminosity AGNs (see Terashima 1999 and Ptak 2001 for reviews). The fairly coarse angular resolution of these satellites, however, has biased detections to more luminous sources which are less contaminated by extended emission from the host galaxy. Moreover, the relatively long integration times required for the observations necessarily restricted the published studies to small, usually X-ray selected, and possibly unrepresentative samples.

The exquisite imaging capability of the Chandra X-ray Observatory offers significant advantages for the study of low-luminosity AGNs. The good instrumental response for photon energies up to 8 keV permits detection of faint AGN emission even if subject to absorption as high as $N_H \approx 10^{24}$ cm$^{-2}$. Thus, obscured AGNs can be found. Faint nuclei embedded deeply in the central regions of bright bulges can be detected reliably only under high angular resolution. As we demonstrate in this Letter, Chandra can probe the nuclear regions of nearby galaxies effectively and efficiently, allowing us to survey, for the first time, a sizable sample of optically selected galaxies covering a wide range of nuclear activity. With brief, “snapshot” exposures, we are able to detect or set stringent limits to compact nuclear X-ray sources with unprecedented sensitivity. We revisit some longstanding, unresolved issues concerning the physical nature of low-luminosity AGNs in light of the new measurements. The sharp X-ray images additionally reveal a plethora of previously unknown structural details in the circumnuclear...
environment of nearby galaxies.

2. OBSERVATIONS AND DATA ANALYSIS

Our targets were selected from the Palomar survey of nearby galaxies, a sensitive spectroscopic survey of a nearly complete sample of 486 bright $B_T \leq 12.5$ mag, northern ($\delta > 0^\circ$) galaxies (Ho, Filippenko, & Sargent 1997a,b). As part of the Guaranteed Observer program for the Advanced CCD Imaging Spectrometer (ACIS; Garmire et al. 2001) team, we chose a sample of 41 emission-line nuclei considered to be AGN candidates, including Seyfert nuclei, low-ionization nuclear emission-line regions (LINERs; Heckman 1980), and LINER/H II “transition” nuclei (Ho et al. 1997b). Thirty-five objects belong to a complete, volume-limited sample within 13 Mpc; the remaining were included as prototypes of different classes. To date, observations have been acquired for 24 galaxies. While this subsample is at the moment somewhat heterogeneous, it does form a representative subset of nearby objects with weak nuclear activity, and it covers a mixture of Hubble types. The sample, summarized in the table below, is equally divided among Seyfert, LINERs, and transition objects; of these, 1/3 are “type 1” and 2/3 are “type 2” sources, nuclei with and without evidence for broad emission lines, respectively. The median distance is 12 Mpc.

Each galaxy was observed with ACIS on board Chandra (Weisskopf, O’Dell, & van Speybroeck 1996). We used the on-axis backside-illuminated CCD chip in the spectroscopic array because it is more sensitive to soft (0.2 keV) X-rays than the frontside-illuminated chips in the imaging array. Most observations used the standard mode of reading out the full chip every 3.2 s, but in six cases where a bright nuclear source was known from ROSAT or ASCA studies, only a portion of the chip was read out more frequently in order to reduce photon pile-up. Exposures of 2 ks were requested, but the actual integrations ranged from 1.1 to 6.5 ks due to constraints on satellite scheduling.

Our treatment of the data starts with the Level 1 event file produced by the Chandra X-ray Center. We first apply a correction for charge-transfer inefficiency which reduces biases in event energies and grades (Townley et al. 2000). Next, the data are cleaned of events with bad status flags, hot columns, and bad flight grades from cosmic-ray impacts. We then select unresolved on-axis sources can be

| TABLE 1: Chandra Observations of Low-Luminosity AGNs |
| --- |
| TARGET GALAXIES | X-RAY PROPERTIES |
| NOC | $D$ (Mpc) | Hubble Type | Spectral Class | log $L_X$ (erg s$^{-1}$) | Exp. (ks) | ACIS Flags | Nuclear Position | Counts | log $L_X$ (erg s$^{-1}$) | X-ray Notes | Notes |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| 1005 | 12.6 | SBhb | T2: | 37.69 | 1.1 | a | O | $< 3$ | $< 18.19$ | IV | --- |
| 1008 | 9.1 | Sc | S2 | 38.36 | 2.4 | a | O | $< 3$ | $< 17.30$ | IV | --- |
| 2776 | 7.5 | S4+ | L1.9 | 38.71 | 1.2 | a, b | O | $< 3$ | $< 38.2$ | III | --- |
| 2841 | 12.0 | Sh | L2 | 38.89 | 1.7 | a | R | 6 | 38.26 | II | a |
| 3001 (M81) | 9.6 | Scb | S1.5 | 38.84 | 2.4 | --- | R | 20,000 | 40.90 | I, b, c |
| 3086 | 7.4 | SAhb | S2 | 37.85 | 1.5 | a, b | O | $< 3$ | $< 17.35$ | IV | --- |
| 3409 | 12.1 | SAhb+ | T2 | 38.48 | 1.8 | b | O | 11 | 38.23 | II | d |
| 3207 | 13.2 | SBab | T2 | 39.35 | 1.8 | --- | R | $< 3$ | $< 17.65$ | IV | e |
| 3368 | 13.2 | Sc prev | T2 | 37.83 | 1.8 | --- | R | $< 3$ | $< 17.65$ | IV | --- |
| 3575 | 12.8 | Shb | L2 | 38.22 | 1.8 | b | O | $< 3$ | $< 17.59$ | IV | --- |
| 4236 | 13.5 | SAhb+ | L1.9 | 38.68 | 1.8 | --- | R | 400 | 40.00 | I, g, c |
| G279S (M86) | 16.1 | E = | L1.9 | 39.00 | 1.4 | c | R | 300 | 40.00 | I |
| 4321 (M100) | 16.1 | SAHbb | T2 | 39.35 | 6.5 | b | R | $< 3$ | $< 18.20$ | II or IV | h |
| 4374 (M84) | 18.4 | E = | L2 | 39.35 | 3.1 | c | R | 37 | 39.12 | III | i, c |
| 4405 | 2.6 | Sm | S1.8 | 38.53 | 1.2 | --- | R | 110 | 39.50 | I, c |
| 4404 | 17.1 | Ei + | L1.9 | $< 37.79$ | 1.8 | a, b | O | 22 | 38.86 | I |
| 4409 (M60) | 16.8 | SAHbb | T2 | 40.28 | 1.7 | --- | R | 43 | 39.41 | II | j, c |
| 4575 (M86) | 16.8 | SAHbb | S1.9 | 39.72 | 4.1 | d | R | 3000 | 40.55 | I, k, c |
| 4594 (M104) | 9.8 | Sa | L2 | 39.48 | 1.8 | a, d | R | 300 | 40.14 | I, l, c |
| 4620 (M82) | 22.9 | SAHbb | S1.0 | 39.00 | 1.4 | c | R | 200 | 40.45 | II, c, m |
| 4725 | 13.0 | SAHbb prev | S2.7 | 39.25 | 1.7 | --- | R | 43 | 39.16 | II | a |
| 4856 (M74) | 7.5 | Shb | T2 | 39.13 | 1.8 | --- | R | $< 12$ | $< 17.94$ | II or IV | o, m |
| 5033 | 18.7 | Sc | S1.5 | 40.42 | 2.9 | c | R | 2000 | 40.71 | I | c |
| 5105 | 7.7 | B0 prec | L2 | 36.09 | 1.1 | a | O | $< 3$ | $< 17.30$ | IV | --- |
the four X-ray classes: I = dominant nucleus; II = nucleus comparable to nearby galaxies hosting low-luminosity AGNs, chosen to exemplify subluminescent galaxies; and IV = nucleus absent. Each panel subtends 90″ × 90″, and the 4″-diameter circle is centered on the radio or optical position of the nucleus.

reliably located as faint as z ≃ 4 counts. Nuclear counts were typically extracted from a 2″-diameter circle without background subtraction, but certain cases required special treatment (see notes to Table 1). ACIS count rates are converted to X-ray luminosities assuming an intrinsic power-law spectrum with photon index Γ = 1.8 and absorption from our Galactic interstellar medium with column density \( N_H = 2 \times 10^{20} \text{ cm}^{-2} \). These assumptions give \( L_X(2-10 \text{ keV}) = 3.6 \times 10^{37} \text{ erg s}^{-1} \) (ACIS cts/ks) \( (D/10 \text{ Mpc})^2 \). We quote X-ray luminosities in the 2–10 keV range for ease of comparison with literature data.

Examination of the images quickly revealed that, in many cases, the nucleus is only one, and not necessarily the brightest, of many X-ray sources or structures in the core regions of the target galaxies. Astrometric alignment of the X-ray image to the galaxy is thus critical. The satellite aspect system based on star-tracker cameras gives absolute astrometric alignments in the \textit{Hipparcos} frame with accuracies usually within ±2″. But in a few cases, X-ray sources unrelated to the galaxy are found to be associated with foreground stars (\( R \simeq 10 - 15 \text{ mag} \)) with positions from the USNO A-2 catalog accurate to ±0′′.3. For most of the target galaxies, the location of the nucleus is known to high accuracy (±0′′.3 and often <0′′.1) from radio observations. But for some, no radio source is found, and positions are based on relatively inaccurate measurements from sky survey Schmidt plates (around ±2″). Thus, our ability to align the ACIS image to the galaxy ranges from a few tenths to several arcseconds.

A more detailed discussion of the X-ray analysis will be presented for the full volume-limited sample in a forthcoming paper.

\footnote{The hard X-ray spectra of most low-luminosity AGNs are well fit by \( \Gamma \approx 1.8 \), and in many cases no significant absorption in excess of the Galactic foreground is indicated (e.g., Terashima 1999). None of our objects suffer heavy Galactic extinction; the median \( N_H \approx 2 \times 10^{20} \text{ cm}^{-2} \). The luminosities would increase by a factor of 1.8 and 6.7 for intrinsic columns of \( 2 \times 10^{21} \) and \( 2 \times 10^{22} \text{ cm}^{-2} \), respectively.}

3. RESULTS AND DISCUSSION

The morphologies of the X-ray images can be loosely grouped into four classes (Fig. 1): (I) dominant nuclear source; (II) nuclear source comparable in brightness to off-nuclear sources in the galaxy; (III) nuclear source embedded in diffuse emission; and (IV) no nuclear source. A compact X-ray source can be associated with the optical or radio nucleus in 62% (15/24) of the galaxies. It is of interest to compare the detection frequency as a function of AGN spectral type. All eight of the broad-line nuclei (3 LINER 1s, 5 Seyfert 1s) were detected, by contrast to only 44% (7/16) of the narrow-line sources (1/3 Seyfert 2s, 4/5 LINER 2s, 2/8 transition objects). For LINERs as a class, the detection rate ranges from ~60% to ~90%, depending on whether we include or exclude transition objects as LINERs.

The gross properties of the optical emission-line spectra of AGNs can be explained by photoionization from the central AGN continuum. In support of this picture, the strength of the hydrogen recombination lines generally scales with the X-ray luminosity in powerful Seyfert 1 nuclei and quasars (e.g., Kriss, Canizares, & Ricker 1980; Ward et al. 1988). The \( L_X - L_{H\alpha} \) correlation has been shown to extend down to the regime of low-luminosity AGNs, both in the soft X-ray band (Koratkar et al. 1995; Roberts & Warwick 2000; Halderson et al. 2001) and in the hard X-ray band (Terashima, Ho, &
Ptak 2000a)\(^8\). This is consistent with the idea that low-luminosity AGNs share the same basic physical processes as in high-luminosity AGNs. Terashima et al. (2000a,b) find, however, that type 2 sources generally show systematically lower values of \(L_X/L_{\text{H}\alpha}\) compared to type 1 objects.

Our sample reinforces these conclusions, as shown in Figure 2. Low-luminosity Seyfert 1s and LINER 1s trace the \(L_X/L_{\text{H}\alpha}\) relation to \(\log L_X \approx 38.5\), with a median \(L_X/L_{\text{H}\alpha}\) of 15; the slope is close to, but slightly steeper than, unity. The best-fit unweighted linear regression line, calculated using the ordinary least-squares solution bisector with jackknife resampling (Feigelson & Babu 1992), for type 1 objects (including low-z quasars) is \(\log L_X = (1.11 \pm 0.054) \log L_{\text{H}\alpha} - (3.50 \pm 2.27)\). The detected type 2 objects loosely follow the same correlation, but with somewhat greater scatter and offset toward lower \(L_X/L_{\text{H}\alpha}\) (median \(\sim 2\)). The ACIS observations contribute nine stringent upper limits in the regime \(\log L_X \gtrsim 38.0\), all of which deviate significantly from the correlation established by the type 1 sources (most have \(L_X/L_{\text{H}\alpha} < 1\)). The majority of the upper limits are transition objects.

Note that the intrinsic scatter in the \(L_X/L_{\text{H}\alpha}\) relation should be significantly less than indicated in Figure 2. The photometric errors associated with the luminosities for any individual object may be substantial (see footnote 7 for \(L_X\) and Ho et al. 1997a for \(L_{\text{H}\alpha}\)). The non-simultaneity of the X-ray and optical observations likely introduces additional scatter. Although the variability characteristics of low-luminosity AGNs are poorly constrained, some of them do vary, at least in the X-rays (e.g., Ptak et al. 1998). The \(\text{H}\alpha\) measurements of Ho et al. (1997a) were extracted from a 2′×4′ aperture, somewhat larger than that used for the X-rays, but the effect of aperture mismatch should be minimal because the optical line emission tends to be highly centrally concentrated (Pogge et al. 2000).

The present sample is still small and incomplete, and we caution against premature generalizations based on the above statistics. Nonetheless, these early results are in broad agreement with the following:

1. Most, perhaps all, low-luminosity type 1 objects, both Seyferts and LINERs, are genuine AGNs similar to classical Seyfert 1 nuclei and quasars.

2. A significant fraction of low-luminosity type 2 sources do contain a central X-ray core, consistent with the presence of an AGN, but they are underluminous in X-rays compared to type 1 nuclei of the same \(\text{H}\alpha\) luminosity. This suggests that the optical line emission may not be powered exclusively by a central AGN. Although detailed spectral fitting was not performed, examination of the photon energies indicates that few, if any, of the nuclear sources are absorbed by columns in the range \(N_H \approx 10^{22} - 10^{24}\) cm\(^{-2}\). Our data thus tentatively suggest that the standard unified model for Seyferts (Antonucci 1993) may not hold at very low luminosities. But we cannot exclude the presence of spectral components with \(N_H \gtrsim 10^{25}\) cm\(^{-2}\), nor the possibility that the X-ray emission in these systems arises entirely from X-ray binaries without any AGN component.

3. Most transition objects are unrelated to AGNs.

4. At least 60% of LINERs contain AGNs, consistent with the estimates of Ho (1996, 1999).

This work was sponsored by NASA contract NAS 8-38252 (Garmire, PI). The research of L. C. H. and A. V. F. is partly funded by NASA LTSA grant NAG 5-3556, and by NASA grants GO-06837.01-95A, AR-07527.02-96A, and AR-08361.02-97A from the Space Telescope Science Institute (operated by AURA, Inc., under NASA contract NAS5-26555). W. N. B. acknowledges support from NASA LTSA grant NAG 5-8107.

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\(^8\)As these papers show, the \(L_X/L_{\text{H}\alpha}\) correlation is not an artifact of distance effects.