COMPACT X-RAY SOURCES IN NEARBY GALAXY NUCLEI

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ABSTRACT

We have found compact, near-nuclear X-ray sources in 21 (54\%) of a complete sample of 39 nearby face-on spiral and elliptical galaxies with available ROSAT HRI data. ROSAT X-ray luminosities (0.2 − 2.4 keV) of these compact X-ray sources are $\sim 10^{37}−10^{40}$ erg s\textsuperscript{−1}. The mean displacement between the location of the compact X-ray source and the optical photometric center of the galaxy is $\sim 390$ pc. ASCA spectra of six of the 21 galaxies show the presence of a hard component with relatively steep ($\Gamma \approx 2.5$) spectral slope. A multicolor disk blackbody plus power-law model fits the data from the spiral galaxies well, suggesting that the X-ray objects in these galaxies may be similar to a black hole candidate (BHC) in its soft (high) state. ASCA data from the elliptical galaxies indicate that hot ($kT \approx 0.7$ keV) gas dominates the emission. The fact that the spectral slope of the spiral galaxy sources is steeper than in normal type 1 active galactic nuclei (AGNs) and that relatively low absorbing columns ($N_H \approx 10^{21}$ cm\textsuperscript{−2}) were found to the power-law component indicates that these objects are somehow geometrically and/or physically different from AGNs in normal active galaxies. The X-ray sources in the spiral galaxies may be BHCs, low-luminosity AGNs, or possibly X-ray luminous supernovae. We estimate the black hole masses of the X-ray sources in the spiral galaxies (if they are BHCs or AGNs) to be $\sim 10^2−10^3$ M\textsubscript{$\odot$}. The X-ray sources in the elliptical galaxies may be BHCs, AGNs or young X-ray supernova also.

INTRODUCTION

An important unanswered question in extragalactic astronomy is whether supermassive black holes (BHs) exist in the nuclei of most galaxies. Since most galaxies are classified as “normal,” this question translates into: Are supermassive BHs present in the nuclei of most normal galaxies? Dynamical searches for BHs in normal galaxies reveal central dark objects with masses $\sim 10^6−10^{9.5}$ M\textsubscript{$\odot$} in many nearby galaxies (cf. Kormendy & Richstone 1995; Faber, these proceedings), so it is feasible that many normal galaxies do contain nuclear supermassive BHs. However, normal galaxy nuclei do not show optical evidence for broad-line regions and narrow-line regions and their optical/ultraviolet continua do not typically show the signature of the “big blue bump,” which is thought to be emission from the accretion disk in AGNs. One possible model of galaxies purports that supermassive BHs are present in all galaxies, but are “active” in some and “inactive” in the others (e.g. Cavaliere & Padovani 1988). In this scenario, normal galaxies could be galaxies in which the BH/accretion disk is relatively “inactive.”

As an example, consider the X-ray source in the nuclear region of the nearby normal galaxy NGC 1313.
A bright X-ray source in the nuclear region of this galaxy is located \( \sim1 \) kpc from the optical nucleus, has \( L_X(0.2-2.4 \text{ keV}) \sim 10^{40} \text{ erg s}^{-1} \), implying a BH mass of \( \sim10^3-10^4 \, M_\odot \) for an Eddington ratio of \( 10^{-2}-10^{-1} \) (Colbert et al. 1995). There is no evidence for an AGN at wavelengths other than X-ray, yet the implied mass is much larger than those of typical BH X-ray binaries (XRBs) \( (\sim5-10 \, M_\odot, \text{ Tanaka 1989}) \). We seek to understand the nature of these near-nuclear compact X-ray sources. Do they represent a class of low-luminosity AGN perhaps similar to Seyfert nuclei? Or are they BH XRBs with BH masses of \( \sim10^{-4} \, M_\odot \)? Or are they a new class of object with properties yet to be discovered?

**SAMPLE SELECTION, OBSERVATIONS AND DATA REDUCTION**

All galaxies with recessional velocities smaller than 1000 km s\(^{-1}\) were selected from an electronic version (vers. 3.9) of the Third Reference Catalog of Bright Galaxies (de Vaucouleurs et al. 1991;RC3). We omitted galaxies in which the disks were edge-on, since the additional large absorbing columns can significantly reduce the soft X-ray flux of the X-ray sources. We also omitted starburst galaxies, since they typically have multiple sources of X-ray emission and their X-ray morphologies are generally complex. See Colbert & Mushotzky (1998) for more details on the selection criteria. Our selection criteria produced a list of 39 nearby galaxies. All available data for the selected 39 galaxies were retrieved from the US ROSAT archives at NASA/GSFC. For the galaxies M33, M81, NGC 4374, NGC 4406 and NGC 4552, diffuse X-ray emission was noticed to be present in the nuclear region. For these galaxies, we modelled the radial profile of the X-ray emission to estimate the luminosity of the point-like component.

Data for eight observations (of six galaxies) in our sample were retrieved from the ASCA archives. The six galaxies selected were three spiral galaxies (M33 [two observations], NGC 1313 [two observations], and NGC 5408) and three elliptical galaxies (NGC 4374, NGC 4406 and NGC 4552). These galaxies were selected because (1) they have compact X-ray sources in the HRI images, (2) no adjacent X-ray sources were present in the ASCA fields (so that the ASCA spectra include emission only from the compact X-ray source under study), and (3) public archival ASCA data were available.

**RESULTS FROM ROSAT HRI SURVEY**

Of the 39 galaxies for which HRI imaging data were available, we found (detection > 3\( \sigma \)) compact X-ray sources within \( \sim1' \) of the nucleus of 21 galaxies. Lira et al. (these proceedings) find a similar result. Here we have used the optical position listed in RC3 (the photometric center) as the location of the nucleus. X-ray fluxes and luminosities in the 0.2–2.4 keV band were calculated from the count rates, assuming a power-law (\( \text{photon index } \Gamma = 1.7 \)) spectrum and absorption from the Galactic hydrogen column (Dickey & Lockman 1990).

A histogram of the 0.2–2.4 keV luminosities is shown in Figure 1. Luminosities of the compact sources ranged from \( 8 \times 10^{36} \text{ erg s}^{-1} \) to \( \sim10^{40} \text{ erg s}^{-1} \), with a mean of \( 3 \times 10^{39} \text{ erg s}^{-1} \). For reference, Seyfert galaxies typically have \( L_X \sim 10^{42}-10^{44} \text{ erg s}^{-1} \) and the Eddington luminosity of a 1.4 \( M_\odot \) accreting neutron star is \( 10^{38.3} \text{ erg s}^{-1} \). So, on average, the X-ray sources are at least one order of magnitude more luminous than the most luminous (i.e., Eddington ratio of unity) neutron star X-ray binaries, but are several orders of magnitude less luminous than typical AGN in Seyfert nuclei. Also shown in Figure 1 are the galaxy types of the host galaxies. Note that the most luminous X-ray sources (\( L_X \sim 10^{40} \text{ erg s}^{-1} \)) tend to be found in elliptical hosts.

The offsets of the X-ray sources from the galaxy nucleus (photometric center) is significant in many of the sources. An interesting result of our study is that \( \sim40\% \) (9 of 21) of the compact sources were located \( \gtrsim 10'' \) (\( \gtrsim 0.3 \text{ kpc at the mean distance of our sample} \)) from the photometric optical center (as listed in RC3). For comparison, most observed objects have ROSAT X-ray positional errors of \( \lesssim 10'' \) (Briel et al. 1996). In Figure 2, we show a plot of \( L_X \) vs. the angular separation between the X-ray source and the photometric center. It is noteworthy that the mean luminosity of sources with small (\( \lesssim 200-400 \text{ pc} \)) separation is similar to the mean luminosity of sources with large (\( \gtrsim 200-400 \text{ pc} \)) separation.

**RESULTS FROM ASCA SPECTRAL FITTING**

We first tried fitting the spectra with two single component models: (1) a Raymond-Smith (RS) thermal plasma and a power-law (PL) model. The power-law was, in general, a better fit for the spiral galaxy spectra, while the RS model was a better fit to the elliptical galaxy spectra. The spiral galaxies were fit
Figures: Figure 1 (left) shows a histogram of the 0.2–2.4 keV luminosities and the galaxy “T” type as listed in RC3. Figure 2 (right) shows the 0.2–2.4 keV luminosity vs. the separation (Δ) between the position of the X-ray source and the photometric center of the galaxy (from RC3). Unclassified galaxies are shown as open rectangles and active galaxies are shown as filled rectangles.

with a relatively steep power law slope (Γ = 2.3 – 2.8), except for one of the observations of NGC 1313, for which Γ = 1.7. We also tried modelling the data with multiple component fits, for example a RS+PL model, and a disk blackbody (DBB, Mitsuda et al. 1984) plus power-law model (DBB+PL). In nearly all cases, the two-component fits are preferred. It is worthwhile to note that the elliptical galaxies are much better fit by a RS+PL model compared to a DBB+PL model, indicative of a hot gas component which is known to be common in these galaxies.

We next discuss the results of the spiral galaxy spectra in terms of emission expected from a BH XRB. In the hard state, BH XRBs typically have hard spectra with power-law slopes Γ ≈ 1.3 – 1.9, whereas in the soft state, the power-law slope steepens to ≈ 2.4 (e.g., Ebisawa, Titarchuk, & Chakrabarti 1996) and a soft component appears in the X-ray spectrum (usually modelled as a multicolor disk blackbody component). One of the observations of NGC 1313 exhibits a slope more consistent with a BH XRB in its hard state, while in the other observation (2.4 years later) the slope steepens to >2.5, more consistent with a soft state. To further investigate the hypothesis that the emission is from XRB-like objects in their soft state, we fitted the spectra from these galaxies with the bulk-motion (BM) model promoted by Titarchuk and collaborators (e.g., see Shrader & Titarchuk 1998). In general, the fits were acceptable, although the reduced χ² values were typically higher than those for the RS+PL and DBB+PL fits. Again, the power-law slopes were quite steep (∼2.5, except for the later observation of NGC 1313). The normalization to the BM model fits allows us to directly estimate the masses of the central BH. We estimate M_{BH} values of 117, 590, and ∼8500 M☉ for M33, NGC 1313, and NGC 5408, respectively.

DISCUSSION

For both the fits to the elliptical galaxies and the spiral galaxies, the power-law slopes are considerably steeper than found for ASCA analysis of type 1 AGN, in which <Γ > = 1.91 ± 0.07 (Nandra et al. 1997). The mean value and standard deviation for our three elliptical galaxies is 2.55 ± 0.76. This may be indicative of a different kind of emission process, for example both Narrow-Line Seyfert 1 galaxies and BH XRBs in their soft state have comparably steep power-law slopes. The power-law slopes for the spiral galaxies are
also comparatively steep. The mean and standard deviation of the slope $\Gamma$ (excluding the single observation of NGC 1313 in which the slope was shallow) is $2.54 \pm 0.38$ (DBB+PL fit).

There does not seem to be a single explanation that works for all of the compact X-ray sources. For example, the X-ray luminosities of the sources in the galaxies with evidence for nuclear activity in the optical/UV are larger than those luminosities of the sources in the otherwise normal (or “unclassified”) galaxies (mean $0.2$–$2.4$ keV luminosity $4.4 \times 10^{39}$ erg s$^{-1}$ vs. $2.4 \times 10^{39}$ erg s$^{-1}$). The mean separation of the X-ray sources from the galaxy nucleus is also larger for the normal galaxies (see Figure 2). This suggests that there may be two different types of X-ray emitting objects in these two types of galaxies. Compact X-ray sources are found in nearly all cases in which previous possible evidence for a BH or an AGN had been found (e.g., large-scale radio sources, dynamical dark core masses $> 10^6$ M$\odot$, or optical spectral classification as Seyfert, LINER, or “transition” object). This indicates that some of the X-ray sources in our sample are probably AGN or at least accretion-driven objects with supermassive BHs.

The soft components in the ASCA spectra in the elliptical galaxies are better fit by a Raymond-Smith thermal plasma than a multicolor disk blackbody model. This suggests that some of the X-ray emission from the central X-ray sources in the elliptical galaxies may be emission from hot gas, a component which has been known to be present in many other elliptical galaxies (e.g., Matsushita et al. 1994). The elliptical galaxy spectra are adequately fit with a two-component Raymond-Smith thermal plasma model plus an absorbed power-law model. The spiral galaxy spectra are well-fit by a two-component model consisting of a multicolor disk blackbody model plus a power-law model. Assuming both components suffer the same intrinsic absorption, we find intrinsic absorption of a few $10^{21}$ cm$^{-2}$ and, again, steep power-law slopes of $\Gamma \approx 2.5$.

What does seem to be universal among the X-ray sources is that they have relatively steep spectral slopes compared with those of Seyfert 1 nuclei. This, and the fact that large absorbing columns are not found, suggests that the X-ray sources are probably different physically or geometrically from typical AGN in active X-ray bright galaxies.

CONCLUSIONS

The emerging picture of the compact X-ray sources in nearby galaxies is that they are probably high-mass ($M \gtrsim 100$ M$\odot$) accreting black holes (or X-ray luminous supernovae with no historical optical evidence). It is not clear how black holes with mass $\sim 10^2$–$10^4$ M$\odot$ might form. It is not clear whether they are binary systems or not, but the steep hard X-ray emission is consistent with that of a BHC in its soft (high) state. Such steep slopes are also consistent with what has been observed in Narrow-Line Seyfert 1 galaxies.

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