DO NORMAL GALAXIES HOST A BLACK HOLE? THE HIGH ENERGY PERSPECTIVE [1]

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ABSTRACT

We review ASCA results on a search for low luminosity active nuclei at the center of nearby normal galaxies. More than a dozen low-luminosity AGN have been discovered with 2–10 keV luminosity in the range 10^{40-41} ergs s^{-1}. Their X-ray properties are in some respects similar to those of luminous Seyfert galaxies, but differ in other respects. We also present estimated black hole masses in low luminosity AGNs and a drastic activity decline in the nucleus of the radio galaxy Fornax A. These results altogether suggest that relics of the past luminous AGNs lurk in nearby normal galaxies.

KEYWORDS: Galaxies; Low luminosity AGNs; LINERs; Black holes

1. Introduction

The number density of quasars is peaked at a redshift of $z \sim 2$ and rapidly decreases toward smaller redshifts. In the local universe, there is no AGN emitting at huge luminosity like quasars. These facts infer that quasars evolve to supermassive black holes in nearby apparently normal galaxies (e.g. Rees 1990).

The growing evidence for supermassive black holes in nearby galaxies are obtained from recent optical and radio observations of gas/stellar kinematics around the center of galaxies (e.g. Ho 1998a; Magorrian et al. 1998; Kormendy & Richstone 1995). If fueling to the supermassive black hole takes place with a small mass accretion rate, they are expected to be observed as very low luminosity AGNs compared to quasars.

Recent optical spectroscopic surveys have shown that low level activity is fairly common in nearby galaxies. In particular, a number of LINERs (low ionization nuclear emission line regions; Heckman 1980), which are characterized by strong low ionization optical emission lines such as [NII]λ6583, [SII]$\lambda\lambda$6716, 6731, and [OI]λ6300, are detected in nearby bright galaxies ($\sim$40% of northern galaxies with $B_T \leq 12.5$; Ho et al. 1997a, b, c). Low luminosity Seyfert galaxies are also detected in 10% of the same galaxy sample. These galaxies with low level activity are good candidates of relics of quasars ("dead" or "dormant" quasars) with a supermassive black hole at the center.

A remarkable example is NGC 4258. Makishima et al. (1994) discovered a low luminosity AGN with a X-ray luminosity 4×10^{40} ergs s^{-1} in this galaxy. The mass

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Table 1. Observed galaxies

classification	name
LINER 1	NGC 315, NGC 1052, NGC 1097, NGC 3998, NGC 4203, NGC 4438
	NGC 4450, NGC 4579, NGC 4594, NGC 5005, IC 1459
LINER 2	NGC 404, NGC 4111, NGC 4569, NGC 4736, NGC 5195, NGC 7217
Seyfert 1	NGC 2639, NGC 3031, NGC 4258, NGC 4565, NGC 4639, NGC 5033
Seyfert 2	NGC 2273, NGC 3079, NGC 3147, NGC 4941

of the central black hole is measured as $3.6 \times 10^7 M_\odot$ by H_2O mega maser observations (Miyoshi et al. 1995). These observations proved that the luminosity is indeed quite low: $\sim 10^{-5}$ of the Eddington luminosity.

We present results of X-ray observations of nearby galaxies and discuss the origin of low level activity and show low luminosity AGNs (hereafter LLAGNs) are numerous in the local universe. We also summarize X-ray properties of LLAGNs and attempt to set a limit on the central black hole mass. An example of a drastic decline of activity in the radio galaxy Fornax A is also presented.

2. A search for AGN in nearby galaxies

2.1 Low level activities in nearby galaxies

Optical spectroscopic surveys revealed that LINERs are very numerous. The origin of LINERs are still under debate and several mechanisms are proposed to explain LINER optical emission lines, such as photoionization by LLAGNs, photoionization by very hot stars, shocks, and so on (see Filippenko 1996 for a review). Recent observational progress in various wavelengths provide pieces of evidence for LLAGNs in at least some fraction of LINERs (Ho 1998b and references therein). X-ray observations are one of the most important tools to search for LLAGNs and we summarize the results of *ASCA* observations in the following subsections.

2.2 ASCA observations of LINERs and low luminosity Seyfert galaxies

We analyzed X-ray data of 17 LINERs obtained with *ASCA* and also 10 low luminosity Seyfert galaxies (hereafter LLSeyferts) with Hα luminosities less than $\sim 10^{40}$ ergs s^{-1}. Optical classifications are adopted from Ho et al. (1997a) except for NGC 1097 (Storchi-Bergman et al. 1993) and IC 1459 (Philipps et al. 1986). The observed galaxies and optical classifications are summarized in Table 1.

Since the X-ray continuum shape of LLAGNs are quite similar to luminous AGNs as discussed in the next section, we searched for a point-like X-ray source with an AGN-like continuum at the center of LINER-type galaxies. We detected X-ray sources from all LINERs but for NGC 404. X-ray spectra are well represented by a two component model: a power-law with a photon index of $\Gamma \sim 1.7-2$ suffered from

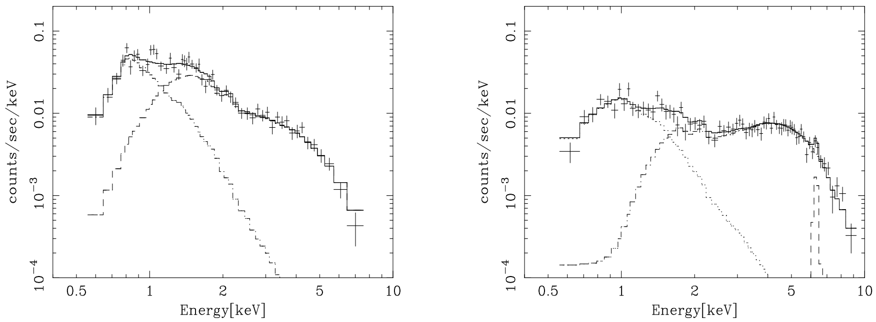

FIGURE 1. Examples of ASCA SIS spectra (*left*) LINER 1.9 NGC 4594, and (*right*) LINER 1.9 with polarized broad Hα NGC 1052.

photo electric absorption ($N_{\rm H}\sim 10^{20}-10^{23}$ cm^{-2}) plus a soft thermal component with a temperature of $kT\sim 0.5-1$ keV. The hard component of most of the galaxies can be also represented by a thermal bremsstrahlung model with a temperature of several keV. X-ray luminosities of the hard component range from 4×10^{39} ergs s^{-1} to 6×10^{41} ergs s^{-1}. Examples of *ASCA* spectra of LINERs are shown in Figure 1.

2.3 Ionizing source of LINERs

Hard X-ray emission from galaxies can be produced by various origins such as AGN, X-ray binaries, and starburst activity. If LLAGNs are the dominant energy source of X-ray emission and optical LINER emission lines, optical emission line luminosities are expected to be proportional to X-ray luminosities as is observed in luminous Seyfert 1 galaxies and quasars (e.g. Ward et al. 1988). Figure 2 shows the correlation between X-ray luminosities ($L_{\rm X}$) and Hα luminosities ($L_{{\rm H}\alpha}$: total of broad and narrow Hα) for LINERs with broad Hα (hereafter LINER 1s) and Seyfert 1s. Data for luminous Seyfert 1s and quasars are taken from Ward et al. (1988). The correlation extends to lower luminosities and strongly supports the hypothesis that the primary ionizing source of LINER 1s is LLAGNs. Note that the $L_{\rm X}/L_{{\rm H}\alpha}$ for starburst galaxies are about 2 orders of magnitudes smaller than Seyfert galaxies (Pérez-Olea & Colina 1996).

Thus the hard X-ray emission from LINER 1s is most likely to be dominated by LLAGN. Then we compare luminosity ratios $L_{\rm X}/L_{{\rm H}\alpha}$ of LINERs without broad Hα (hereafter LINER 2s) with those of LINER 1s and LLSeyferts. Histograms of $L_{\rm X}/L_{{\rm H}\alpha}$ values for LINER 1s + LLSeyferts and LINER 2s are shown in Figure 2. The $L_{\rm X}/L_{{\rm H}\alpha}$ values for LINER 2s are systematically lower than LINER 1s and LLSeyferts except for NGC 4736, which has a $L_{\rm X}/L_{{\rm H}\alpha}$ ratio similar to LINER 1s + LLSeyferts.

If we assume a spectral energy distribution from UV to X-ray in the form of a power-law with an index of -1 ($f_\nu \propto \nu^{-1}$), Case B recombination (Osterbrock 1989) and a covering fraction of 1, the objects with low $L_{\rm X}/L_{{\rm H}\alpha}$ are likely to be too X-ray weak to ionize optical emission lines. If an AGN is present in these objects, such

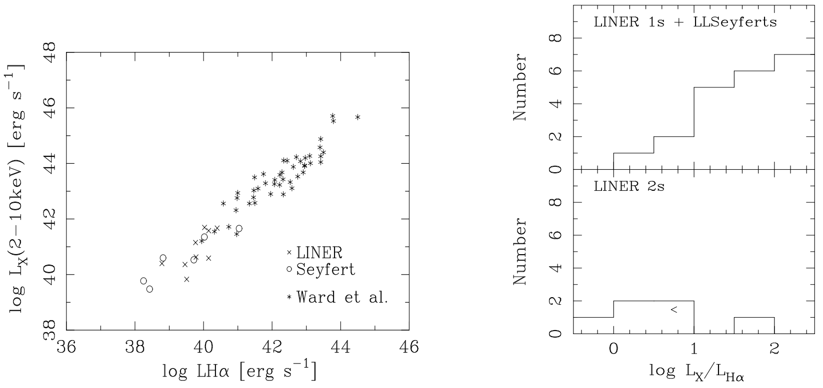

FIGURE 2. (*left*) Correlation between X-ray and Hα luminosity for LINER 1s and Seyfert 1s. (*right*) X-ray to Hα luminosity ratio for LINER 1s + LLSeyfert (*upper*) and LINER 2s (*lower*).

AGN should be obscured even at energies above 2 keV. Alternatively there might be other ionization sources. Actually UV spectra of NGC 4569 and NGC 404 obtained with *HST* Faint Object Spectrograph (FOS) show the presence of hot stars (Maoz et al. 1998).

According to the optical spectroscopic survey by Ho et al. (1997a), Seyferts, LINER 1s and LINER 2s are detected in 11%, 5%, 28% of northern bright galaxies. If we assume the most extreme case that all Seyferts and LINER 1s are AGNs and all LINER 2s are not AGNs, we estimate the fraction of AGNs in bright galaxies is ~16 %. Since a certain fraction of LINER 2s is probably genuine AGNs, this percentage should, however, be regarded as a lower limit. Therefore the number density of AGNs in the local universe is considered to be larger than previously thought.

3. X-ray properties of low luminosity AGNs and black hole mass

3.1 X-ray spectra

We summarize X-ray properties of LLAGNs using galaxies from which X-ray emission is dominated by AGNs. X-ray images of these galaxies are consistent with point like in the hard X-ray band and $L_{\rm X}/L_{\rm H\alpha}$ ratios are also similar to luminous Seyferts. We use data of (1) NGC 315, 1097, 3031, 3079, 3147, 3998, 4203, 4450, 4579, 4594, 4639, 4736, 5033, IC 1459 and (2)NGC 1052, 2273, 2639, 4258, 4941. The absorption column densities for galaxies in the group (1) and group (2) are $N_{\rm H} < 10^{23}$ cm^{-2} and $N_{\rm H} > 10^{23}$ cm^{-2}, respectively. We classify these subclasses as Type 1 and Type 2 LLAGNs, respectively.

The luminosity dependence of photon indices for Type 1 AGNs is shown in

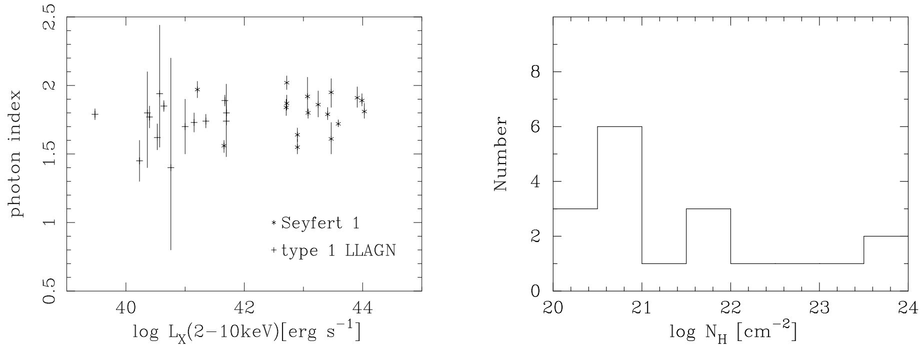

FIGURE 3. (*left*) Luminosity dependence of photon indices of type 1 AGNs. (*right*) Distribution of absorption column densities of LLAGNs

Fig 3. The data for luminous Seyfert 1 galaxies are taken from Nandra et al. (1997b). The histogram of absorption column densities is also shown in Fig 3. These figures indicate that X-ray spectra of Type 1 LLAGNs have quite similar photon indices to luminous AGNs. The photon indices of Type 2 LLAGNs also show no luminosity dependence, although errors for indices are large for both luminous and low luminosity Type 2 AGNs. The absorption column densities range from 10^{20} cm^{-2} to 10^{24} cm^{-2} and there exists LLAGNs both with heavy absorption and small absorption as in Seyfert galaxies. Note that the present sample is not complete and that the distribution of absorption column densities does not reflect the optical depths and geometry of the obscuring matter around LLAGNs.

Thus X-ray continuum shape of LLAGNs are quite similar to luminous AGNs. On the other hand, iron K emission line properties and variability in Type 1 LLAGNs are different from luminous AGNs. No significant iron K emission is detected from our Type 1 LLAGN sample except for NGC 3031, NGC 4579, and NGC 5033, in contrast to Seyfert 1s which generally show iron K emission at 6.4 keV. The center energy of the iron K lines in NGC 3031 and NGC 4579 are 6.7 keV (Ishisaki et al. 1996; Terashima et al. 1998a), which is significantly higher than Seyfert 1s, while that of NGC 5033 is 6.4 keV (Terashima et al. 1998b). These iron line properties are possibly due to difference of physical states of accretion disks between LLAGNs and luminous AGNs.

3.2 X-ray variability and black hole mass

Rapid time variability on time scales less than one day is generally observed in luminous Seyfert 1 galaxies. It is well known that lower luminosity Seyfert 1 galaxies tend to show larger amplitude and shorter time scale variability (Lawrence & Papadakis 1993; Nandra et al. 1997a).

We searched for short-term variability on time scales less than one day for the galaxies in the present sample. Only two low luminosity Seyfert 1 galaxies (NGC

3031 and NGC 5033) indicate variability on time scale of $\sim 10^4$ sec (Ishisaki et al. 1996; Terashima et al. 1998b). Thus small amplitude or no detectable variability is quite common in LLAGNs, and luminosity dependence of variability properties observed in luminous Seyfert 1s are no longer seen in LLAGN with luminosities below $\sim 5 \times 10^{41}$ ergs s^{-1}.

One possibility of such difference between luminous and less luminous AGNs is that the structure of an accretion disk is different between these two classes (Ptak et al. 1998). Alternatively, if the variability time scale reflects the size of the X-ray emitting region, the variability on longer time scales would infer larger system size and larger black hole mass.

We attempt to measure black hole masses in LLAGNs from X-ray variability using the method by Hayashida et al. (1998). Hayashida et al. (1998) defined a new variability time scale: the frequency at which (normalized power spectral density) × (frequency) crosses a certain level, where a normalized power spectral density is defined as the power spectral density divided by the averaged source intensity squared. If we assume that the black hole masses are linearly proportional to the variability time scale and that the mass of Cyg X-1 is $10M_\odot$, which is used as a reference point, we can estimate the black hole mass in AGNs.

We estimate the black hole masses from *ASCA* light curves of bright LLAGNs (NGC 1097, 3031, 3998, 4579, 5033, 4258) under an additional assumption: the power spectral density for LLAGNs are same as luminous AGNs, i.e. the power-spectral slope is $\alpha \approx 2$. We obtained lower limit for the black hole masses similar to or larger than Seyfert 1 galaxies analyzed by the same method (MCG–6–30–15, NGC 4151, NGC 5548, etc. ; Hayashida et al. 1998) (Awaki et al. 1998). The lower limit of the black hole masses obtained here are consistent with those obtained by other method (NGC 3031, NGC 4258, NGC 4579). Since X-ray luminosities of LLAGNs are 1–3 orders of magnitude smaller than luminous Seyfert 1 galaxies, the Eddington ratios ($L_{\rm bolometric}/L_{\rm Eddington}$) of LLAGNs are estimated to be at least 1–3 orders of magnitude smaller than luminous AGNs. These results support the idea that LLAGNs have a black hole with a huge mass but radiating at a very low Eddington ratio.

4. Declined Activity in the Nucleus of Fornax A

The decline of the space density of quasars indicate that AGN activity lasts shorter than the cosmological time scale. A remarkable example of a decline of activity is the radio galaxy NGC 1316 (Fornax A) (Iyomoto et al. 1998).

NGC 1316 is a radio galaxy with prominent radio lobes (e.g. Ekers et al. 1983) which indicate Fornax A was active in the past. However the nucleus of NGC 1316 is very inactive in radio and X-ray at present, and this suggests that the nucleus is currently inactive and that the lobes are a relic of the past activity. We summarize observational facts and estimate various time scales of the lobes and decline of activity according to Iyomoto et al. (1998).

4.1 The Nucleus

The nucleus of NGC 1316 is quite faint in the radio band. The ratio of the core flux to the total (lobe + core) flux is about two orders of magnitude smaller than the typical value for radio galaxies. A *ROSAT* HRI failed to detected an X-ray nucleus (Kim, Fabbiano, & Mackie 1998). An *ASCA* spectrum is consistent with normal elliptical galaxies, i.e. a hot plasma of $kT \sim 1$ keV and hard component presumably due to discrete X-ray sources in the host galaxy, and its X-ray luminosity in the 2–10 keV is 1.3×10^{40} ergs s^{-1}. An upper limit of the AGN contribution to the hard X-ray emission is calculated to be 2×10^{40} ergs s^{-1} by assuming various absorbing column densities ($< 10^{24}$ cm^{-2}) for the AGN component. If AGN is completely obscured in the energy band below 10 keV, only the scattered component might be expected. In this case, the intrinsic luminosity is constrained to be less than 1.4×10^{41} ergs s^{-1}, if an upper limit of iron K emission and assumed scattering fraction $\sim 1\%$ are taken into account.

4.2 The Lobes

The inverse Compton X-rays, which are produced when the relativistic electrons scatter off the cosmic microwave background photons, are observed from radio lobes of NGC 1316. Comparing the radio and X-ray brightnesses, the magnetic field strength in the lobes has been determined to be 3 μG (Feigelson et al. 1995; Kaneda et al. 1995). The lobe radio spectrum extends at least to 5 GHz without a cutoff. Then the electron emitting 5 GHz photons lose half their energy on a characteristic time scale of $\tau \sim 0.08$ Gyr, which can be regarded as the synchrotron life time of the lobes. Thus the nucleus must have been active until at least τ years ago, or even until a more recent epoch.

The X-ray luminosity that the NGC 1316 nucleus used to have in the past can be estimated to be $\sim 4 \times 10^{41}$ ergs s^{-1} from the kinetic energy of the radio lobes, a correlation between kinetic luminosities and optical narrow line luminosities, and a correlation between [OIII] and X-ray luminosities. Then the present activity is at least an order of magnitude lower than the estimated past activity and the nucleus of NGC 1316 has become dormant during the last 0.1 Gyr. This suggests the possible abundance of "dormant" quasars in nearby galaxies.

5. Summary

We have detected many LLAGNs in nearby galaxies and show that a number of AGNs in the local universe is significantly larger than that previously thought. Our estimation of the black holes in LLAGNs indicates that these LLAGNs host a supermassive black hole and radiate at a very low Eddington ratio. A drastic decline of activity is observed in the nucleus of NGC 1316. These facts suggest that relics of the past luminous AGNs lurk in the nearby normal galaxies.

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