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Estimation of Central Black Hole Masses in Low-Luminosity Active Galactic Nuclei

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Abstract

We analyzed six low-luminosity active galactic nuclei (hereafter LLAGNs), which consist of two bright LINERs (low-ionization nuclear emission line region) with broad Hα, and of four bright low-luminosity Seyferts observed by the X-ray satellite ASCA. We examined the time variabilities of these targets, and found that most targets show no significant time variabilities, although these galaxies belong to LLAGNs. By applying Fourier analysis to their light curves in the 2–10 keV band, we obtained the lower limits of their time variability scales, which correspond to their central black hole masses greater than several times $10^6\,M_\odot$. Our result suggests that these LLAGNs are harbors of super-massive black holes, but the emitting powers are only $< 1\%$ of the Eddington luminosities of the central engines in the LLAGNs due to their small accretion rates. Since a black hole would grow by mass accretion, it is hard to create such a super-massive black hole under a small accretion rate. Therefore, the mass-accretion rates in the past must have been larger than those at present, and the galaxies have probably been as luminous as QSOs. This will be a hint to find out the cause of the lack of QSOs in the local universe.

Key words: active — galaxies: evolution — galaxies: nuclei — X-rays: galaxies

1. Introduction

Although galaxies are supposed to be assemblies of stars, a small fraction show violent activities in their nuclear regions, which are called active galactic nuclei (AGNs). AGNs are thought to be powered by matter accreting onto massive black holes in the central regions. Their luminosities are widely distributed from 10^{40} to $10^{46}\,\mathrm{erg\,s^{-1}}$. Because the strong emissions photoionize the surrounding matter, highly ionized regions are formed. On the other hand, there are galaxies with weaker activities than AGNs, and their central regions are called low-ionization nuclear emission line regions (LINERs). About half of the galaxies are classified as LINERs, but their excitation mechanisms are still under debate. Based on recent studies of LINERs, the excitation mechanisms of most LINERs with a broad Hα were most likely photoionization by nuclear emissions. The luminosities of the LINERs are 1–3 orders of magnitude smaller than those of normal Seyfert galaxies (Ho 1999a; Terashima et al. 2000). Since LINERs with broad Hα, which exist in more than 10% of the bright galaxies, are now recognized as low-luminosity AGNs, there may be more AGNs, and thus more black holes, in the central regions of galaxies than we have believed (Ho et al. 1997).

In order to investigate what causes the difference in the central activity of galaxies by galaxies, we must know the characteristics of the central black holes and their environments. In the case of luminous AGNs, a time variability analysis is often used to estimate the central black hole masses in AGNs (e.g. Pounds, McHardy 1988). A positive correlation between the central black hole masses and the X-ray luminosities is reported (e.g. Barr, Mushotzky 1986). However, the time variabilities of low-luminosity objects are inconsistent with the analogy of the correlation found in luminous AGNs. Awaki et al. (1991) found that a bright LINER with a broad Hα, NGC 3998, showed no significant time variability from a Ginga observation. Furthermore, Ptak et al. (1998) also found little or no significant time variabilities for low-luminosity Seyferts and LINERs in analyzing the ASCA data. However, their samples included LINERs whose activities are induced by the central H II region. A small variability probably indicates the existence of a large black hole, such as a QSO. Hayashida et al. (1998) developed a new method to estimate black hole masses using the normalized power spectral density (hereafter NPSD). Using their method, we can determine the lower limit of the variability time scale for an X-ray source which does not show any significant variability. Assuming the same correlation between the time variability scales and the central black hole masses found in luminous AGNs, we can determine the black hole masses in low-luminosity objects.

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We select bright low-luminosity AGNs, and then estimate their central black hole masses by applying the NPSD method. We assume $H_0 = 75\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ in this paper.

2. The Data

Terashima (1998) carried out a detailed analysis of X-ray data for low-luminosity Seyferts and LINERs. Their X-ray luminosities range from 10^{38}–10^{42} erg s^{-1} in the 2–10 keV band. He examined the nuclear activity in these objects using ratios between the X-ray luminosities in the 2–10 keV band and the Hα luminosities, and found that the ratios of most LINERs with a broad Hα and those of low-luminosity Seyferts are similar to those of luminous AGNs. He concluded that their optical emission lines are photoionized by high-energy photons from AGNs. Their point-like X-ray images in the 2–10 keV band also supported his conclusion.

Terashima (1998) found that eight LINERs and seven low-luminosity Seyferts satisfied his criteria of low-luminosity AGNs. They have 2–10 keV luminosities with 10^{39}–10^{42} erg s^{-1}, and belong to the lowest end of the AGN activities. We call them low-luminosity AGNs (hereafter LLAGNs) in this paper. We selected the brightest objects (two LINERs and four low-luminosity Seyferts) with AGN activity among his samples. These galaxies have larger X-ray luminosities than the superposition of stars and supernova remnants in the galaxies (Awaki 1999), and have larger source count rates than twice the background count rates. All of the targets were observed by both SIS and GIS (Tanaka et al. 1994). During observations, SIS and GIS were operated in Faint and PH modes, respectively. The screened data of our samples were obtained from the ASCA Guest Observer Facility at NASA/GSFC. The screening criteria are provided at a web site, ⟨http://adfwww.gsfc.nasa.gov/asca/processing_doc/proc/processing.html⟩. The observation time for most targets was about one day. The observational log of our targets is listed in table 1.

Low-luminosity extragalactic objects often have soft X-ray components described by thin thermal emissions with $kT \sim 1$ keV together with hard X-ray emissions from nuclei (e.g. Terashima 1998; Okada 1999). In order to extract hard X-ray components efficiently, we chose data in the 2–10 keV band. We used only GIS data, because GIS has a higher sensitivity than SIS above 3 keV. The X-rays from each target were obtained in the region with a radius $< 6'$ from the source. The data with GIS 2 and GIS 3 were combined in order to obtain better signal-to-noise ratios. We estimated its background from a nearby blank-sky region in the same GIS field. In the case of M 81, there are two X-ray sources, SN 1993J and X-6, near to the center of M 81 (Ishisaki et al. 1996). The count rate of the sum of SN 1993J and X-6 was about half of the nuclear emission from M 81 in the 2–10 keV band. We selected a source region with elliptical shape, and a background region across SN 1993J and X-6 from the M 81 central region in order to remove any contamination of the source region by SN 1993J and X-6 (see figure 1).

Table 1. Target list.

Target	Distance* (Mpc)	Date of observations (dd/mm/yy)	Count rate† ($\mathrm{c\,s^{-1}}$)
NGC 1097 (LINER)	14.5	12/01/94	0.036
M 81 (S1.5)	1.4	16/04/93	0.114
NGC 3998 (LINER)	21.6	10/05/95	0.097
NGC 4579 (S1.9)	16.8	25/06/95	0.062
NGC 5033 (S1.5)	18.7	14/12/95	0.067
NGC 4258 (S1.9)	6.8	25/06/95	0.077

* Taken from Tully bright galaxy catalog.

† The GIS count rate in the 2–10 keV band. The background emission was not subtracted.

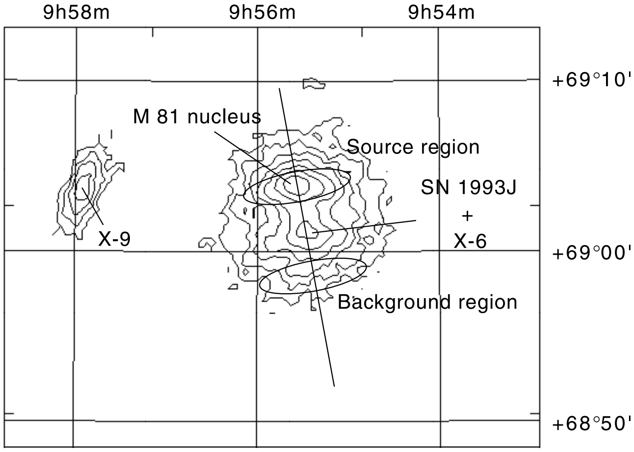

Fig. 1. Source and background regions for a timing analysis of M 81. The contour map shows the GIS image in the 2–10 keV band.

3. Analysis and Results

First, we examined the short-time variability within a few thousand seconds. However, we could not detect any significant variability. We next examined the long-term variability. The data points were binned in 5760 s, which is the orbital period of the ASCA satellite. Figure 2 shows the light curves of our samples. The background levels are shown by the solid lines in figure 2. It is found that most targets show a small significant variability from a χ^2-test (χ^2 in table 2). This result is consistent with that by Ptak et al. (1998) for M 81, NGC 3998, NGC 4579, and NGC 4258.

We know that the power spectral densities (PSDs) of the time variabilities of luminous AGNs are described as $f^{-\alpha}$ with α of 1–2, where f is frequency (Pounds, McHardy 1988). Since the shape of the PSDs has no structure, it is hard to define a characteristic frequency from the shape. Hayashida et al. (1998) introduced a NPSD and determined the characteristic frequency, f_0, by $f_0 \times \mathrm{NPSD}(f_0) = 10^{-3}$, where the NPSD is defined as a PSD divided by the square of the averaged intensity [see equation (1) in Hayashida et al.'s paper]. From the scaling relation of a NPSD, they derived the formula $M_{\mathrm{BH}} = 10 \times [45.5/f_0(\mathrm{Hz})]\,M_\odot$ to estimate the central black hole mass (M_{BH}) as a function of f_0 from a well-known galactic

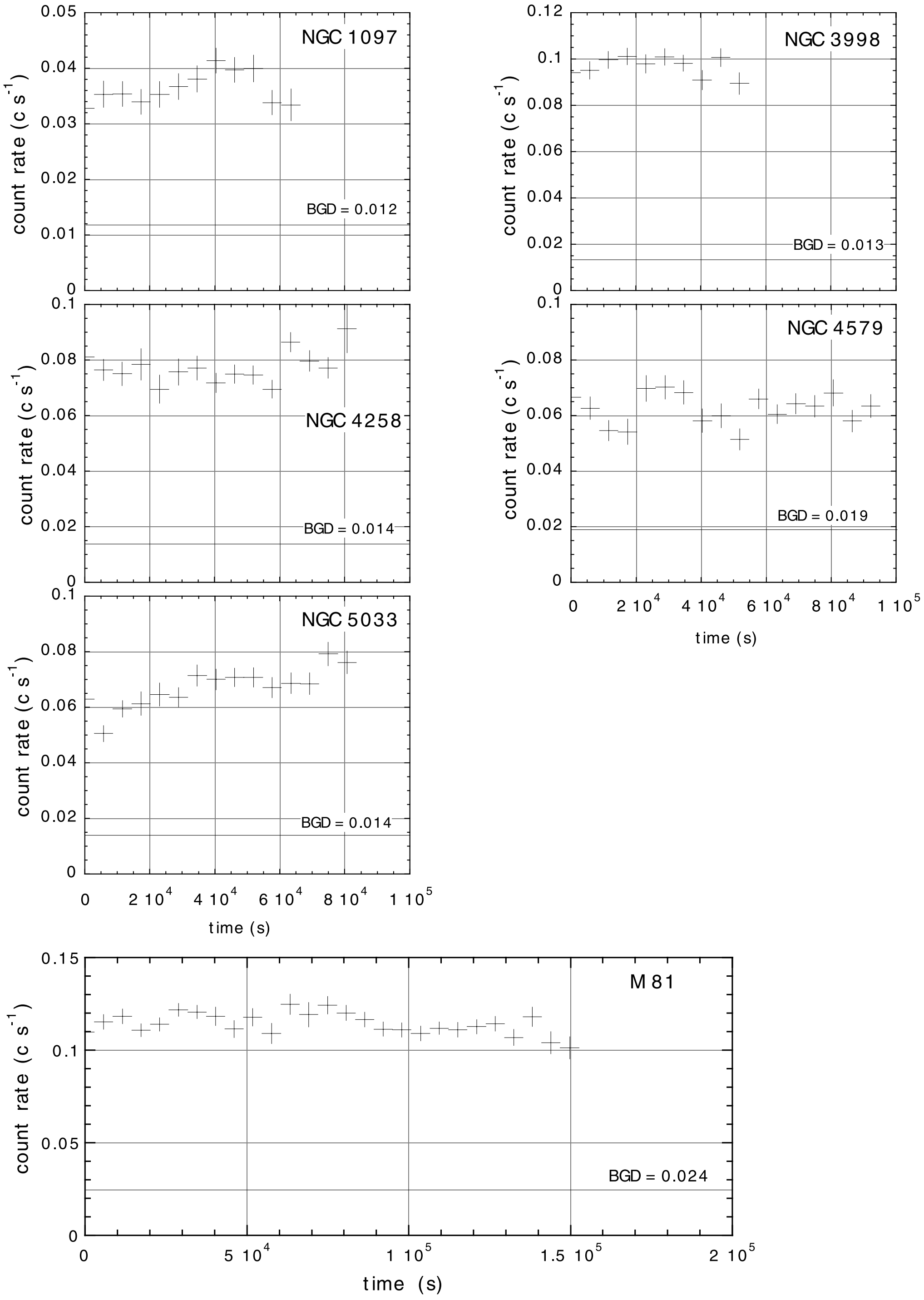

Fig. 2. X-ray light curves of our samples in the 2–10 keV band obtained with GIS 2 and GIS 3. The solid lines show the background count rate.

black hole candidate, Cyg X-1. The advantage of this method is that even if there is no significant variability, we can obtain PSDs by applying Fourier transforms to light curves, and thus obtain the upper limit of the characteristic frequency under the given power-law index.

We estimated the averaged backgrounds using the data within the background regions for target sources, then subtracted the averaged backgrounds from the continuous data for our samples in the source regions. We applied Fourier transforms to the continuous data after background subtraction. Most NPSDs have large errors due to small variability. Although we fitted NPSDs with a power-law function of frequency, i.e. NPSD = $Nf^{-\alpha}$, it is difficult to determine both the slope, α, and normalization, N, of the NPSD for our samples. It is known that the slope, α, ranges from 1 to 2. In order to obtain the lower limit of the characteristic frequencies, we fixed the slope to be two, because the normalization with $\alpha = 2$ is the largest in the range $1 \leq \alpha \leq 2$. We searched the normalizations

Table 2. Result of a timing analysis.

Target	χ^2/bin*	Frequency† (Hz)	Black hole mass† ($M_\odot$)	L_X‡ (erg s^{-1})	Reference§
NGC 1097 (LINER)	17.9/12	$< 1 \times 10^{-4}$	$> 5 \times 10^6$	4.3×10^{40}	1
M 81 (S1.5)	33.3/27	$< 1 \times 10^{-5}$	$> 5 \times 10^7$	4×10^{39}	1
NGC 3998 (LINER)	8.7/10	$< 2 \times 10^{-5}$	$> 2 \times 10^7$	4.5×10^{41}	1
NGC 4579 (S1.9)	26.6/17	$< 2 \times 10^{-4}$	$> 2 \times 10^6$	1.5×10^{41}	1
NGC 5033 (S1.5)	58.6/15	$7 \pm 3 \times 10^{-5}$	$(5–12) \times 10^6$	2.3×10^{41}	1
NGC 4258 (S1.9)	20.7/15	$< 5 \times 10^{-5}$	$> 9 \times 10^6$	6.8×10^{40}	1
Our Galaxy			2.6×10^6	1×10^{35}	2
M 31			7.5×10^7	$< 6 \times 10^{38}$	3

* χ^2-test to no time variability model.

† 90% confidence region. The black hole masses for our Galaxy and M 31 are quoted from Genzel et al. (1997) and Ford et al. (1994), respectively.

‡ X-ray luminosities in the 2–10 keV band.

§ 1 Terashima et al. (2000); 2 Koyama et al. (1996); 3 Okada (1999).

of the NPSDs using χ^2 fitting, and obtained the 90% confidence regions. The normalizations were converted to the characteristic frequencies using the relation $f_0 = (10^{-3}/N)^{1/(1-\alpha)}$. Table 2 gives the estimated f_0 for our sample.

We note that Iyomoto and Makishima (2001) recently applied a structure function analysis to estimate f_0. This method is powerful to analyze the sparse data obtained in a long-term observation. However, our data were obtained in a one-day observation, and are a series of time. Therefore, we performed Fourier analysis to the data after background subtraction.

The lower limits of the central black hole masses of several $10^6\,M_\odot$ were derived from the upper limit of f_0 (see table 2.). Our time-variability analysis shows possibility of the presence of super massive black holes in the LLAGNs. The filled circles in figure 3 show the central black hole masses of our samples. Their X-ray luminosities are quoted from Terashima et al. (2000). Estimations of the central black hole masses were performed with several methods, for instance reverberation mappings, stellar kinematics, and water masers. For NGC 4258, the central black hole mass of $3.6 \times 10^7\,M_\odot$ was estimated from water masers (Miyoshi et al. 1995). Our lower limit of the $M_{\rm BH}$ is consistent with Miyoshi et al.'s result. For M 81, the central mass of $4 \times 10^6\,M_\odot$ is determined from stellar and gas kinematics (Bower et al. 1996), which is much smaller than our result. However, Ho (1998) pointed out that the mass is quite uncertain and has probably been underestimated. Our result for M 81 is consistent with the estimation from the relation between black hole masses and bulge luminosities (Ho 1998).

We note that we can not rule out the possibility of an alternative explanation for lack of rapid variability, such as existence of a disk truncated at much larger radius. However, the consistency between black hole masses estimated by gas/stellar dynamics and by the time-variability method suggests that a lack of rapid time variability is mainly due to the existence of large black holes.

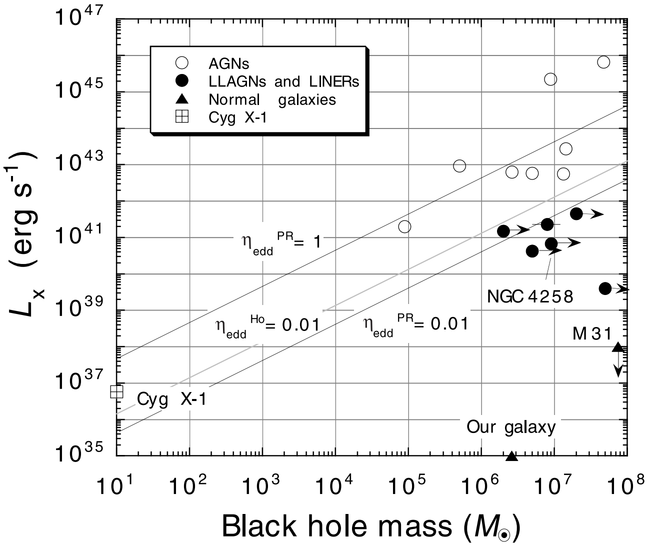

Fig. 3. Correlation plot between the central black hole masses and X-ray luminosities in the 2–10 keV band. The open circles show the data of Seyfert galaxies and QSOs, which are quoted from Hayashida et al. (1998). The closed circles and triangles show those of the galaxies in our sample, and those of normal galaxies, respectively. The two solid lines indicate Eddington ratios, $\eta_{\rm edd}^{\rm PR}$, of 1 and 0.01, calculated with the bolometric correction by Padovani and Rafanelli (1998); the dashed line indicates a $\eta_{\rm edd}^{\rm Ho}$ ratio of 0.01 with a correction of 10.

4. Discussion

4.1. Position of LLAGNs in $M_{\rm BH}$–$L_{\rm X}$ Diagram

Luminous AGNs often show short time variabilities. For high-luminosity AGNs, the correlation between the black hole masses and X-ray luminosities is reported from an analysis of the time variability (e.g. Barr, Mushotzky 1985). For a comparison, we show data plots of AGNs quoted from Hayashida et al. (1998) in figure 3. On the analogy of the correlation for these AGNs, we expected violent time variabilities and smaller black hole masses, $M_{\rm BH} = 10^4$–$10^6\,M_\odot$, for LLAGNs. However, our LLAGNs showed small, or no, time variability during the observations. The radiation from AGNs is generated by mass accretion onto the central black holes. In order to characterize the mass-accretion rates, we employed the Eddington ratio (η_{edd}) which is the ratio between the bolometric (L_{bol}) and Eddington luminosities [$L_{\mathrm{edd}} = 1.26 \times 10^{38} (M_{\mathrm{BH}}/M_{\odot})\,\mathrm{erg\,s^{-1}}$]. The bolometric luminosities were estimated from the X-ray luminosities using the bolometric correction ($L_{\mathrm{bol}}/L_{\mathrm{X}}$) of 27.2 given by Padovani and Rafanelli (1998). In figure 3, we show the solid lines of $\eta_{\mathrm{edd}} = 1$ and $\eta_{\mathrm{edd}} = 0.01$. The Eddington ratios of high-luminosity AGNs range from 0.1 to 1, while those of the LLAGNs are smaller than 10^{-2}. Since the Eddington ratio indicates the fraction to the maximum power, the central engines in the LLAGNs are working under $< 1\%$ of the Eddington luminosities. We note that Ho (1999b) found the bolometric correction ranged from 3 to 16 for LLAGNs. This value is smaller than those for luminous AGNs due to a lack of the big blue bump. Using his correction, L_{bol} and the Eddington ratios are smaller than our estimation. In figure 3, we add a dashed line representing the Eddington ratio of 0.01 with a bolometric correction of 10.

Recent observations have revealed that normal galaxies have a huge mass in their nuclear region (e.g. Magorrian et al. 1998; Ho 1998; Kormendy, Richstone 1995). For example, the mass in the nuclear region of our Galaxy and the Andromeda galaxy were estimated to be about $2.6 \times 10^{6}\,M_{\odot}$ (Genzel et al. 1997) and $7.5 \times 10^{7}\,M_{\odot}$ (Ford et al. 1994) using stellar dynamics, respectively. Normal galaxies would be distributed at the bottom of figure 3, since the activity in the nuclear region is so small. The activity classes are not caused by a difference in the black hole masses, but by a difference in the mass-accretion rates.

4.2. *Implication for a Connection between LLAGNs and QSOs*

Hasinger (1998) obtained X-ray luminosity functions of AGNs sliced in redshift space using the ROSAT ultra-deep survey, and found that the comoving number density of the QSOs with $L_{\mathrm{X}} > 10^{43}\,\mathrm{erg\,s^{-1}}$ at $z \sim 2$ was $\sim 1 \times 10^{-3}\,\mathrm{Mpc^{-3}}$, which is about 100-times larger than that in the local universe. If the massive black holes in the AGNs do not disappear in cosmological time, there must be massive black holes in galaxies in the local universe. We consider that LLAGNs are candidates of QSO remnants, because LLAGNs have massive black holes, and the lifetime of QSOs are considered to be much shorter than the cosmological time (e.g. Shier et al. 1996; Haiman, Hui 2001). We compared the number density of LLAGNs with that of high-luminosity AGNs at $z = 2$. Using the fraction of LLAGNs ($\sim 10\%$; Ho et al. 1997) and the number density of galaxies of $\sim 6 \times 10^{-3}\,\mathrm{Mpc^{-3}}$ with $M_{\mathrm{B}} < -20\,\mathrm{mag}$ (e.g. Marzke 1998), the number density of LLAGNs are estimated to be $6 \times 10^{-4}\,\mathrm{Mpc^{-3}}$. This indicates that the number density of LLAGNs is almost comparable to that of QSOs at $z = 2$.

We examined the possibility of the activity of the LLAGNs in the past considering the formation of super-massive black holes. Since the central black holes would grow by mass accretion, the mass accretion rates must be greater than $7.5 \times 10^{-4} (M_{\mathrm{BH}}/10^{7}\,M_{\odot})(H_0/75)\,M_{\odot}\,\mathrm{yr^{-1}}$ in order to create such massive black holes in cosmological time. Taking a conversion efficiency (ε) of 0.1, such as for the case of luminous AGNs, the minimum accretion rate corresponds to an X-ray luminosity of $1.6 \times 10^{42} (M_{\mathrm{BH}}/10^{7}\,M_{\odot})\,\mathrm{erg\,s^{-1}}$, or Eddington ratios of about 0.03. The observed values are smaller than the minimum one. In the Ho's bolometric correction, the discrepancy is larger. Therefore, large mass accretion must have occurred in the past, which means that these galaxies were once luminous. We note that the constraint of the Eddington ratios to form massive black holes can be relaxed in the advection-dominated accretion flow (ADAF) model, which is often applied to objects with small accretion rates (e.g. Mahadevan 1997; Lasota et al. 1996 for LINERs and Narayan et al. 1998 for our galactic center). In the ADAF model, the conversion efficiency is correlated with the mass-accretion rate, because some fraction of the energy generated by mass accretion falls into the central black hole. The mass-accretion rates are estimated to be $\sim 1 \times 10^{-3} (M_{\mathrm{BH}}/10^{7}\,M_{\odot})(\eta_{\mathrm{edd}}/10^{-3})^{0.5}\,M_{\odot}\,\mathrm{yr^{-1}}$ in the viscosity parameter of 0.3; thus $\eta_{\mathrm{edd}} > 0.001$ is required. The lower limit of the central masses for several galaxies satisfied $\eta_{\mathrm{edd}} > 0.001$, but those for M 81 and NGC 4258 are still out of the range of η_{edd}.

Our result will give a hint to solve the problem of the small number density of QSOs in the local universe. Using the highest sensitivity of the Chandra, XMM-Newton, and future missions, such as Astro-EII, Constellation-X, and XEUS, we will be able to solve this problem.

5. Conclusion

We analyzed the ASCA data of six LLAGNs whose nuclear activities were established by Terashima (1998) and Ho et al. (1997). Applying the NPSD method to their light curves, we found that the central black hole masses are greater than several $10^{6}\,M_{\odot}$. This result indicates that LLAGNs are harbors of super-massive black holes, as are high-luminosity AGNs. However, their central engines are working under $< 1\%$ of the Eddington luminosities due to their small accretion rates. Their activities are not mainly affected by the central black hole masses, but by the mass-accretion rates.

We compared the number density of LLAGNs with that of high-luminosity AGNs at $z = 2$, then found that their number densities are comparable. LLAGNs are possible candidates of QSO remnants. Considering the formation of super-massive black holes, LLAGNs in the past had been probably more luminous than those at present.

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