Carnegie Observatories Astrophysics Series, Vol. 1:
Coevolution of Black Holes and Galaxies, 2004
ed. L. C. Ho (Pasadena: Carnegie Observatories,
http://www.ociw.edu/ociw/symposia/series/symposium1/proceedings.html)

X-ray Variability of AGNs and its Use as a Black Hole Scale Measure

K. HAYASHIDA
Osaka University, Osaka, Japan

Abstract

X-ray variability of AGNs has been employed to constrain the size of an emission region as well as the mechanism of the emission. We propose an empirical method to estimate black hole (BH) masses in AGNs from their X-ray variabilities. We apply the method to various classes of AGNs, broad line Seyfert 1 galaxies (BLS1s), narrow line Seyfert 1 galaxies (NLS1s), and low-luminosity AGNs (LLAGN). The BH masses estimated for NLS1s are systematically smaller than those for BLS1s, which we consider the most important factor that discriminates these tow classes. We obtain the BH masses or their lower limits for LLAGNs, implying their Eddington ratio is much lower than typical Seyferts. Nevertheless, since our method is based on simple scaling assumptions, we need to calibrate the method. In this paper, we compare our mass estimation with other methods, particularly reverberation mapping of broad line regions. We find that our method is valid within about one order of magnitude, though further calibration points are needed particularly for NLS1s. We also add some future prospects with high sensitivity X-ray all sky monitoring missions.

1.1 Introduction

Variability of radiation from AGNs has been used to estimate the size of their emission region. The size estimated in such a way, together with a huge amount of the radiation, is considered to be one of the observational proof of the existence of super-massive black holes (SMBHs) in AGNs. X-ray variability is especially important and efficient to estimate the size of the BHs, because it usually has a shorter time scale than that in the longer wave-length. In fact, Barr & Mushotzky (1986) indicated that the time scale of the X-ray variability of AGNs, for which they employed the shortest doubling time, has a positive correlation with their X-ray luminosities. The upper limits of BH masses were provided by Wandel & Mushotzky (1986) from the same data.

We have proposed a new and empirical method to estimate the black hole masses in AGNs from their X-ray variability (Hayashida et al. 1998). Key assumptions of the method are 1) X-ray variability of BHs, from stellar BHs to AGN, are similar each other, 2) the variability time scales are linearly proportional to the central BH masses, and 3) Cyg X-1 BH mass is 10 $M_\odot$. We employ the normalized power spectrum density (NPSD) of X-ray light curve to define a variability time scale, where the NPSD is the power spectrum density normalized by the average intensity squared. If the X-ray variability is similar for different size of BHs, their NPSDs should align along the 1/frequency line, as we shown in Hayashida et al. (1998)

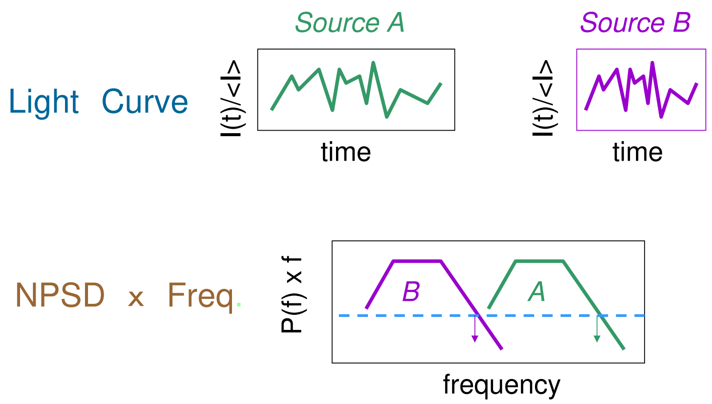

Fig. 1.1. Schematic Diagram of Scaling Relation of Variability. We consider there are two sources of which sizes are different by some factor. The assumption we made is that their X-ray light curves normalized by their average intensity is self similar expect for the scale of the time axis (top panels), and the time scale is linearly proportional to the BH size or mass. The corresponding NPSDs align in the NPSD×Frequency diagram side by side. The position of the two NPSD are differ by the ratio of their system size (BH mass). We measure the position from the crossing point of the NPSD and the horizontal bar (in our case we set fP(f)=1/1000). See Hayashida et al. (1998) on detailed description.

by a simple arithmetic. In other word, if we make NPSD × frequency of those sources, they should stand side by side in the diagram. Their positions in the NPSD × f diagram reflect the relative system size of those BHs. These procedures are illustrated in Fig. 1.1.

This procedure was partly motivated by X-ray observations of stellar mass BHs. Belloni & Hasinger (1990) found that the NPSD of Cyg X-1 is stable at high frequency part, even when the X-ray intensity of the source varies significantly. Furthermore, Miyamoto et al. (1992) found that the NPSD (at high frequency part) is canonical for several stellar mass BH candidates among their hard (low) state. These facts, together with previous studies on X-ray variability of AGNs, implied us to use the NPSD as a BH scale measure.

Very recently Czerny et al (2001) presented a re-consideration of the BH mass estimation from X-ray variability. Their point was that their NPSD of Cyg X-1, which was cited from the paper on the XTE observation of the source, is different from the one we used by about factor of two, and should be used as a new template. However, as far as we looked at, the difference is mainly due to the different definition (normalization) of their NPSD and our NPSD. Czerny et al (2001) also claimed underestimation of the BH masses of AGNs in our paper by factor of 2.8. Their claim is not appropriate, since we used a consistent definition of the NPSD for AGNs and Cyg X-1 within our paper. As noted in Hayashida et al. (1998), we have to be careful about the exact definition for the normalization of NPSD when we compare the NPSD derived by different authors.

We first applied the method to several Seyferts observed with the Ginga satellite (Hayashida et al. 1998). We have expanded the work to various classes of AGNs observed with the ASCA satellite, and we compared the estimated BH masses with those by other methods.

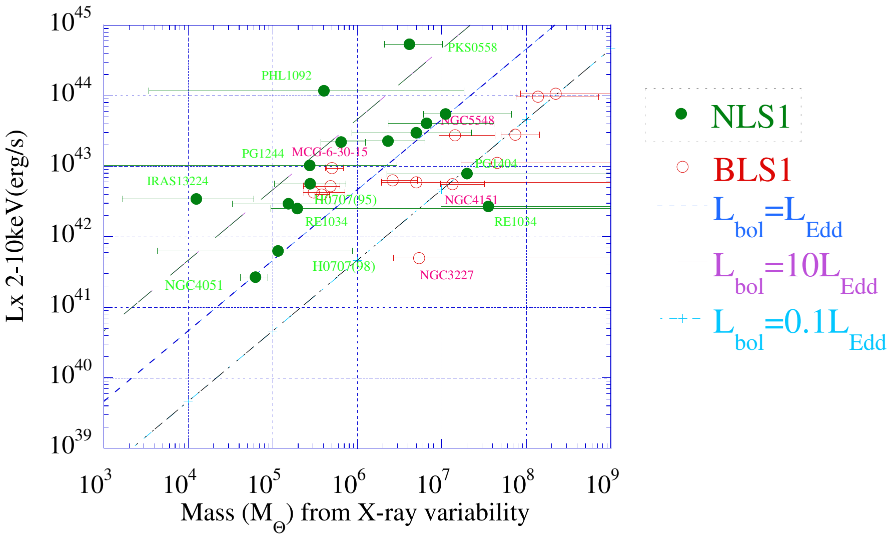

Fig. 1.2. BH masses Estimated from X-ray Variability. The figure is cited from Hayashida (2000). Closed circles indicate NLS1s, while open circles do BLS1s. Dotted, dashed, dotted-dashed lines indicate 1,10, 0.1 times of the Eddington luminosity, respectively, where bolometric correction of 27.2 is assumed.

We introduce those works in this paper. We note that some contents of this paper is appeared in Hayashida et al. (2003).

1.2 BH Mass and X-ray Variability for Various AGNs

1.2.1 Narrow Line Seyfert 1 and Broad Line Seyfert 1

Narrow Line Seyfert 1 (NLS1) galaxies are known to show a rapid and large amplitude X-ray variability. We quantified the X-ray variabilities of NLS1s by their NPSDs and estimated their BH masses. Fig. 1.2 cited from Hayashida (2000) illustrate systematic trends that the NLS1s have lower mass black hole than BLS1s; the BH masses in NLS1s range from 10^5-10^7 $M_\odot$, while those in BLS1s 10^7-10^8 $M_\odot$ according to our estimations. We think this is the most important factor which distinguish these two classes of Seyfert.

It should be noted that this result is based on the simplified assumption that the scaling relation between the light curves and BH masses of NLS1s is similar to that of BLS1s (and stellar mass BHs). If the X-ray variability of NLS1s is enhanced, we might underestimated the BH masses for NLS1s. This point is difficult to be examined until we have NLS1s of which mass is determined accurately with independent methods.

Another remarkable point of the NLS1s is their enhanced soft X-ray component, usually approximated with a blackbody of temperature of 0.1-0.2keV. If we regards the component as a thermal emission from an accretion disk, it constrains the BH mass and accretion rate

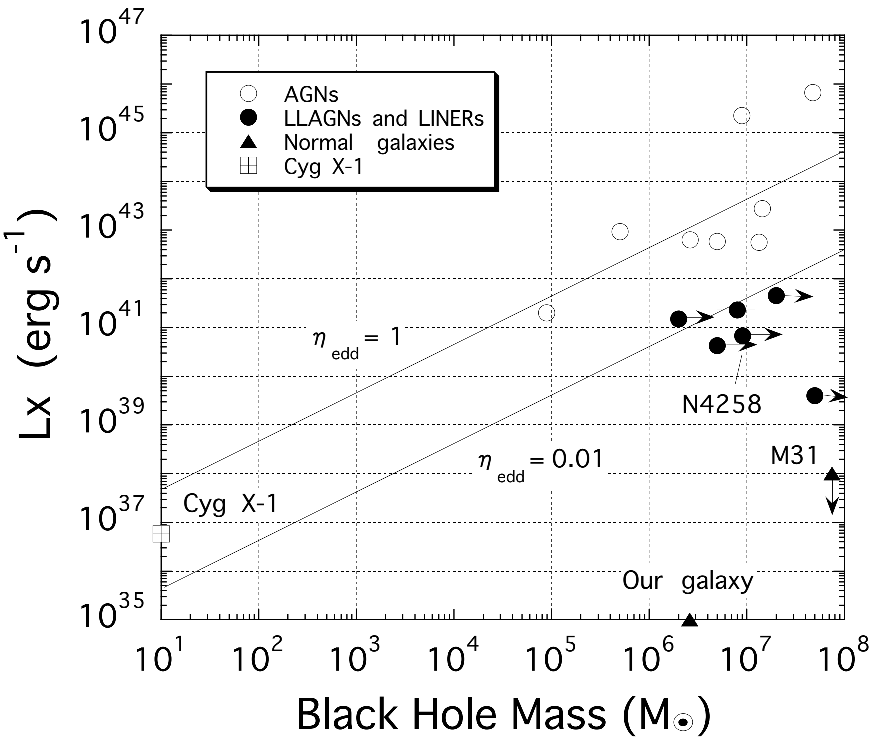

Fig. 1.3. The Lower limit of the BH Masses in LLAGNs Estimated from X-ray Variability. The lower limit of the BH masses are larger than 10^6 $M_\odot$, indicating those LLAGNs have super massive black hole as large as Seyferts and quasars but emit much lower power than those typical AGNs. The figure is cited from Awaki et al. (2001).

of the source. Such discussions are found in, e.g., Hayashida (2000) and Mineshige et al (1999).

1.2.2 Low-Luminosity AGNs

It is known that there is a class of AGNs of which luminosities are significantly lower than typical Seyferts or quasars. We investigated the X-ray variabilities of such low-luminosity AGNs (LLAGN), including LINERs, observed with ASCA (Awaki et al., 2001). Although they usually show a small amplitude X-ray variability, we obtained at least the lower limit of the BH mass from them. The results indicate those LLAGNs contain BHs 10^6 or larger, and they emit at extremely low efficiency, less than 1% of the Eddington luminosity (see Fig. 1.3, which is cited from Awaki et al. (2001)). Long term X-ray variability of the LLAGN, M81, were investigated by Ishisaki et al. (1996) and Iyomoto et al. (2001) . Iyomoto et al. (2001) employed a structure function in order to quantify the X-ray variability from highly gaped data.

On the other hands, we found a contrasting case in NGC4395, which is known as the least luminous Seyfert. Regardless of its low luminosity (Lx$\sim 10^{39}$ erg/s) the optical-UV spectrum of NGC4395 is similar to that in a Seyfert type. We found rapid X-ray variability in the source, leading to the mass estimation of the BH of $10^4 - 10^5$ $M_\odot$ (Iwasawa et al., 2000).

1.2.3 Blazars

X-ray variabilities of blazars were systematically studied by Kataoka et al. (2001). It is found that the shape of the power spectrum densities of blazars is systematically different from that of Seyferts. Power law index of the PSD for blazars ranges from 2 to 3, while that for Seyferts 1 to 2. It may reflect their difference in the emission mechanism from radio quiet AGNs. Application of the scaling relation between stellar black hole candidates and Seyferts, which we assumed, may not be appropriate for the blazars. Instead, physical interpretation of the knee frequency of the power spectrum and size estimation from it are presented in Kataoka et al. (2001).

1.3 Calibration of BH Mass Estimation from X-ray Variability

1.3.1 Stability of the normalized power spectrum density

Stability of the NPSD (at high frequency part) of stellar mass BHs was one of the motivation of our using it as a BH scale measure. We now have some data to check the stability of the NPSD of AGNs. We confirm that the NPSD was stable within factor of two for MCG-6-30-15 observed several times with Ginga and ASCA. In the case of 1H0707-495, the NPSD was unchanged regardless of a flux drop of factor of 6 from 1995 to 1998 (see Fig. 1.4). On the contrary, we found inconsistency of nearly one order of magnitude in the NPSD of NGC5548, which might be due to a short data length compared with the variability time scale.

Related topics on the NPSD scaling relation among neutron star binaries and stellar black hole binaries was studied by Sunyaev & Revnivtsev (2000). In general, the NPSDs of neutron star binaries are placed at the higher frequency side than those of black hole binaries. However, the scaling is not exactly proportional to the central object mass. They discussed possible mechanism to reconcile the break in the simple scaling relation owing to the presence of neutron star.

1.3.2 Comparison with BLR reverberation mapping

BH mass estimation from X-ray variability is empirical and based on the assumptions which have not yet been proved. In order to examine the validity of our method, we need to refer the BH masses determined by other methods. For that purpose, we employ the dynamical masses of BHs determined from the broad line width in the AGNs. The distance of the broad line region (BLR) is estimated either by applying the photo-ionization model or by performing the reverberation mapping, though the latter is considered to be more reliable.

In Fig. 1.5, we compare the BH masses from the BLR reverberation mapping summarized in Wandel, Peterson, and Malkan (1999) with those from the X-ray variability for the AGNs both estimates are presented. It is found that the both methods agree within about one order of magnitude. Since Wandel et al. (1999) estimated the systematic error of their BH mass estimation is a factor of a few, the systematic error of our method is at most one order of magnitude.

It should be noted that there are small number of NLS1s to which reverberation mapping

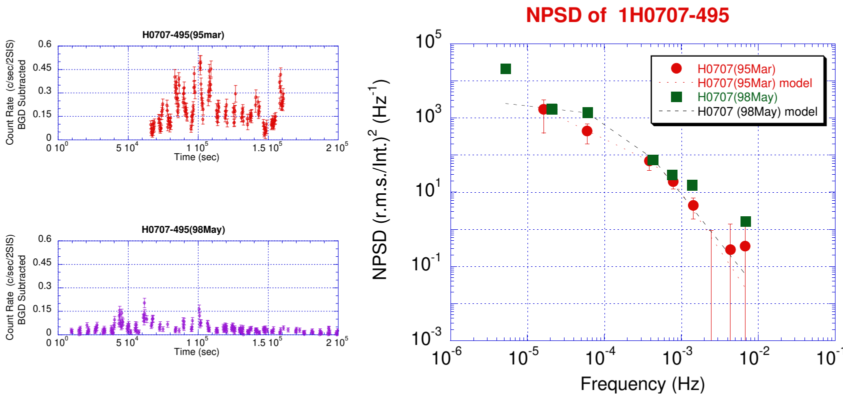

Fig. 1.4. X-ray Light Curves and NPSDs of 1H0707-495 Observed with ASCA both in 1995 and 1998. The X-ray flux decreased by factor of 6, while the NPSD was almost unchanged.

was applied. It might be due to the small amplitude of the optical variability for NLS1s, which contrasts to their large amplitude variability in X-ray band. Whatever the reason of the small amplitude optical variability for the NLS1s is, two BH mass estimation methods, one from the X-ray variability and the other from the BLR reverberation mapping, are efficient for different types of AGNs; the X-ray variability method is efficient for NLS1s, while the BLR reverberation mapping methods is for BLS1s. Further calibration points of NLS1s are needed.

1.3.3 Various methods to estimate BH Masses

Dynamical masses of BHs in galactic, not only active but also normal, nuclei are estimated by observing the stellar kinematics or gas motion. One of the most accurate estimation was given for NGC4258 as 3.6×10^7 $M_\odot$ through maser line mapping (Miyoshi et al., 1995), which is now considered to be the most striking evidence for the existence of a SMBH. Observations of stellar kinematics through optical imaging spectroscopy also provide the BH masses in nearby galaxies. The number of such observations have rapidly increased these years, revealing most of them have SMBH at their nuclei. Large number of BH masses also lead to the finding of a interesting correlation between the BH mass and the velocity dispersion of galactic bulge (e.g., Gebhardt et al., 2000, Ferrarese et al., 2000). The correlation is so tight that it will be used to estimate the BH masses from the velocity dispersion of bulge.

There are many ways to estimate the masses of SMBHs in galactic nuclei. Each method

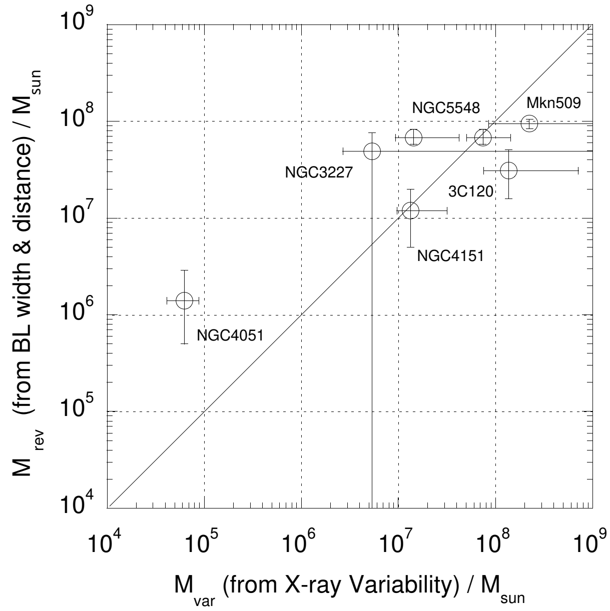

Fig. 1.5. BH Masses from Reverberation Mapping vs those from X-ray Variability. The masses are in the solar mass unit. The data of reverberation mapping are from Wandel et al. (1999). Agreement within about one order of magnitude indicates the systematic error of BH mass estimation from X-ray variability.

has merits and demerits, and its application range is different. It is now important to compare the results each other in order to check their validity. In the future, when the number of SMBHs of which dynamical mass are accurately measured is large enough, empirical methods (BH mass estimation from the X-ray variability or that from bulge velocity dispersion) will be less important. Nevertheless, the study on the X-ray variability or those on BH mass bulge velocity dispersion will still be important to examine the BH accretion physics or the formation of SMBHs in galaxies in turn. We suppose that the scaling relation of the X-ray variability over BH masses of 5 or 7 order of magnitude, even if it has an order of magnitude error, must be related the the BH accretion physics.

1.4 Future Prospects with Long-term X-ray Monitoring Missions

We add some comments on future prospect regarding long term X-ray monitoring observations of AGNs. We currently have a very limited time window for X-ray observations of AGNs so far. Typical X-ray observations with current X-ray missions are limited for one day to one week. Continuous observations of an AGN longer than one week is very exceptional case. All sky monitoring experiments could provide X-ray light curves over years, but for very limited number of sources. Higher sensitivity all sky monitoring missions, MAXI (Matsuoka et al., 1997) and Lobster (Fraser et al., 2002), either is planned on the

International Space Station. We would get daily X-ray fluxes of more than tens of AGNs over years with these missions.

We expect extension of the frequency range of the X-ray power spectra of AGNs toward the lower frequency side by two or three order of magnitudes. The extension is particularly important for the AGNs showing slow variability, which may be higher mass BHs with our assumptions. The X-ray variability of AGNs over months time scale has been examined with RXTE data for four AGNs by Uttley et al. (2002). Both a broken power law model and a knee model provides a good fit to each of the four power spectra. Such kinds of test will accurately be made with the future long term X-ray monitoring experiments.

For a 10^6 $M_\odot$ BH, the light crossing time for 10 Schwarzshild radius (Rs) is 100s, while that for 10^9 $M_\odot$ BH is 10^5 s, longer than 1 day. We expect significant high frequency cut in their power spectra at frequencies corresponding to such a time scale. Search for periodic variability, such as reported in IRAS18325-5926 (Iwasawa et al., 1998) and Mrk766 (Boller et al., 2001), and search for bursting events will surly be the target of the future long term monitoring missions.

1.5 Summary

We have presented our studies on X-ray variability of AGNs focusing on its scaling relation and its use as a BH scale measure. After a short introduction of our method, we applied it to various kinds of AGNs. Calibration of the method was also presented by comparing the BH mass estimated with other methods, estimating the uncertainty is about less than one order of magnitudes. Although mass estimations from X-ray variability, including ours, inevitably be an empirical one and may be less reliable than dynamical ones, the scaling relation of the X-ray variability itself must be related to some fundamental physics of BH accretion, considering that the relation roughly holds over several decades of the BH mass.

References

Awaki, H., Sakano, M., Terashima, Y., & Hayashida, K. 2001, PASJ, 53, 647
Barr, P., & Mushotzky, R. F. 1986, Nature, 320, 421
Belloni, T., & Hasinger, G. 1990, A&A, 227, L33
Boller, Th., Keil, R., Trumper, J., O'Brien, P. T., Reeves, J., & Page, M. 2001, A&A, 365, L146
Czerny, B., Nikolajuk, M., Piasecki, M., & Kuraszkiewicz, J. 2001, MNRAS, 325, 865
Ferrarese, L., & Merritt, D. 2000, ApJ, 539, L9
Fraser, G. W., et al. 2002, Proc. SPIE, 4497, 115
Gebhardt, K., et al. ApJ, 2000, 539, L13
Hayashida, K. 2000, New Astron. Reviews, 44, 419
Hayashida, K., Horikawa, T., Fujita, R., & Awaki, H. 2003, in Proceedings of MAXI-Workshop on AGN Variability, in press
Hayashida, K., Miyamoto, S., Kitamoto, S., Negoro, H., & Inoue, H. 1998, ApJ, 500, 642
Ishisaki, Y., et al. 1996, MNRAS, 48, 237
Iwasawa, K., Fabian, A. C., Almaini, O., Lira, P., Lawrence, A., Hayashida, K., & Inoue, H. 2000, MNRAS, 318, 879
Iwasawa, K., Fabian, A. C., Brandt, W. N., Kunieda, H., Misaki, K., Terashima, Y., & Reynolds, C. S. 1998, MNRAS, 295, L20
Iyomoto, N., & Makishima, K. 2001, MNRAS, 321, 767
Kataoka, J., et al. 2001, ApJ, 560, 659
Matsuoka, M., et al. 1997, Proc. SPIE, 3114, 414
Mineshige, S., Kawaguchi, T., Takeuchi, M., & Hayashida, K. 2000, PASJ, 52, 499
Miyamoto, S., Kitamoto, S., Iga, S., Negoro, H., & Terada, K. 1992, ApJ, 391, L21

Miyoshi, M., Moran, J., Herrnstein, J., Greenhill, L., Nakai, N., Diamond, P., & Inoue, M. 1995, Nature, 373, 127
Sunyaev, R., & Revnivtsev, M. 2000, A&A, 358, 617
Wandel, A., & Mushotzky, R. F. 1986, ApJ, 306, L61
Wandel, A., Peterson, B., & Malkan, M. A. 1999, ApJ, 526, 57