X-ray Variability and Black Hole Mass of AGNs  
– Application to Various Classes of AGNs and Calibration of the Method –

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Abstract

X-ray variability of AGNs has been employed to constrain the size of the emission region as well as the mechanism of the emission. We propose an empirical method to estimate the black hole (BH) masses in AGNs from their X-ray variability. 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 two 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. We also mention possible targets for the future X-ray all sky missions, such as MAXI.

Key words: active—galaxies: nuclei—X-rays: galaxies: variability: black hole

1. Black Hole Mass Estimation from X-ray Variability

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 wavelength. In fact, Barr and 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 and 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⊙. 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) 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.

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. We introduce those works in this paper. In addition, we also propose possible targets of future all sky X-ray monitor experiments, such as MAXI.

2. Black Hole Mass and X-ray Variability for Various Classes of AGNs

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. 2 cited
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.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 hand, we found a contrasting case in NGC4395, which is known as the least luminous Seyfert. Regardless of its low luminosity ($L_x \sim 10^{39}$ 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).

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).

3. Calibration of BH mass estimation from X-ray Variability

3.1. Stability and canonicality 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.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.

Very recently Czerny et al (2001) presented a reconsideration 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 just a 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 (and the following results) is not appropriate, since we used a consistent definition of the NPSD 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.

3.2. Comparison of BH mass estimation from X-ray Variability with that from 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. 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.

They also mentioned that the value of NGC4051 was preliminary. It should be noted that there are small
number of NLS1s to which reverberation mapping 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.

3.3. Various ways 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 $3.6 \times 10^7 \, M_\odot$ 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 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.

4. Targets of MAXI mission

One of the distinctive features of the MAXI mission is its high sensitivity or low detection limit. It will enable us to obtain daily X-ray fluxes for tens of AGNs. If we adopt the scaling hypothesis on the X-ray variability of AGNs such as we made, the longer time scale variability will extend out work to larger mass AGNs, namely, quasars. X-ray variability data for quasars with time scales longer than days is also important in the sense that there is a possibility to observe a possible break in their power spectrum. For a $10^6 \, M_\odot$ BH, the light crossing time for 10 Schwarzschild radius (Rs) is 100s, while that for $10^9 \, M_\odot$ BH is $10^5$ s, longer than 1 day. The X-ray light curves of quasars obtained with the MAXI mission will first enable us to examine significant reduction of the power corresponding to such a scale.

We assumed the X-ray variability of AGNs is ape-
Fig. 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.

Periodic. In fact, there have been only a few reports on the possible detection of the periodicity in AGNs: IRAS18325-5926 (Iwasawa et al., 1998), and Mrk766 (Boller et al., 2001). Nevertheless, the observation span might have been too short for the periodicity to be detected. Whatever the origin of the periodicity is, the time scale must directly tell us the size of some physical processes in the AGNs. We will expect systematic search for the periodicity in X-rays from AGNs with the MAXI mission.

Finally, we would point out another point of long term unbiased X-ray monitoring of AGNs. Most of the AGNs currently observed with X-ray missions are selected from the sample observed in the previous missions or all sky surveys. As mentioned in Horikawa et al. in this volume, some of the AGNs, in particular NLS1s, show X-ray variability over one order of magnitude. The number of AGNs of which X-ray flux was observed to decrease by more than one order of magnitude is larger than that of the increasing case. We might have missed to catch AGNs of which X-ray flux increased suddenly, namely bursting phase of the AGN phenomena.

References
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Fig. 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.