THE LONGEST TIMESCALE X-RAY VARIABILITY REVEALS EVIDENCE FOR ACTIVE GALACTIC NUCLEI IN THE HIGH ACCRETION STATE

YOU-HONG ZHANG
Department of Physics and Tsinghua Center for Astrophysics (THCA), Tsinghua University, Beijing 100084, China; youhong.zhang@mail.tsinghua.edu.cn

Received 2010 April 12; accepted 2010 October 17; published 2010 December 10

ABSTRACT
The All Sky Monitor (ASM) on board the Rossi X-ray Timing Explorer has continuously monitored a number of active galactic nuclei (AGNs) with similar sampling rates for 14 years, from 1996 January to 2009 December. Utilizing the archival ASM data of 27 AGNs, we calculate the normalized excess variances of the 300-day binned X-ray light curves on the longest timescale (between 300 days and 14 years) explored so far. The observed variance appears to be independent of AGN black-hole mass and bolometric luminosity. According to the scaling relation of black-hole mass (and bolometric luminosity) from galactic black hole X-ray binaries (GBHs) to AGNs, the break timescales that correspond to the break frequencies detected in the power spectral density (PSD) of our AGNs are larger than the binsize (300 days) of the ASM light curves. As a result, the singly broken power-law (soft-state) PSD predicts the variance to be independent of mass and luminosity. Nevertheless, the doubly broken power-law (hard-state) PSD predicts, with the widely accepted ratio of the two break frequencies, that the variance increases with increasing mass and decreases with increasing luminosity. Therefore, the independence of the observed variance on mass and luminosity suggests that AGNs should have soft-state PSDs. Taking into account the scaling of the break timescale with mass and luminosity synchronously, the observed variances are also more consistent with the soft-state than the hard-state PSD predictions. With the averaged variance of AGNs and the soft-state PSD assumption, we obtain a universal PSD amplitude of $0.030 \pm 0.022$. By analogy with the GBH PSDs in the high/soft state, the longest timescale variability supports the standpoint that AGNs are scaled-up GBHs in the high accretion state, as already implied by the direct PSD analysis.

Key words: galaxies: active – galaxies: Seyfert – X-rays: galaxies

Online-only material: color figures

1. INTRODUCTION

Active galactic nuclei (AGNs) might be scaled-up galactic black hole X-ray binaries (GBHs; e.g., McHardy et al. 2006) because both are powered by a similar physical process, i.e., accretion onto (super-massive and stellar-mass, respectively) black holes. Therefore, it is important and fundamental to explore the observational similarities between the two classes of black-hole-accreting systems that have very different scales. Because it originates in the region closest to the black hole, X-ray emissions carry the most pivotal messages for the black-hole accretion process. Both AGNs and GBHs exhibit strong X-ray variability, which is usually quantified by the power spectral density (PSD; $P_\nu \propto \nu^\alpha$) of their X-ray light curves.

The GBH PSDs between 0.001 and 100 Hz are closely related to their X-ray spectral states (e.g., Done & Gierliński 2005; Klein-Wolt & van der Klis 2008). The template source most quoted is the persistent source Cyg X-1. In its low/hard state, in which the energy spectrum is dominated by a strongly variable power-law component, the hard-state PSD of Cyg X-1 is approximately described by a doubly broken power law (e.g., Pottschmidt et al. 2003), flattening from $\alpha \sim 2$ to $\alpha \sim 1$ at the (high)-frequency break ($\nu_b \sim 1$ Hz) and further flattening to $\alpha \sim 0$ at the low-frequency break ($\nu_{1LB} \sim 1$ tenths’ Hz) from high to low frequencies. The ratio of the two break frequencies is $\sim 10-100$. In its high/soft state, although the energy spectrum is dominated by a roughly constant thermal disk component, the highly variable power-law component is strong enough to construct the soft-state PSD of Cyg X-1, which is significantly distinguished from the hard-state PSD by showing only one (high-frequency) break ($\nu_b \sim 15$ Hz). The soft-state PSD slopes above and below $\nu_b$ are $\alpha \sim -2$ and $\alpha \sim -1$, respectively, and the $-1$ slope can be extended down to many decades of frequencies without further flattening (e.g., Axelsson et al. 2006). However, as already shown by Pottschmidt et al. (2003), even in Cyg X-1, the GBH PSD shape is not as simple as usually assumed.

If the X-ray variability timescale linearly scales with black hole mass ($M_{\text{BH}}$) from GBHs to AGNs, the state-transition timescales of a few days observed in GBHs ($M_{\text{BH}} \sim 10 M_\odot$) suggest that AGNs of $M_{\text{BH}} \sim 10^7 M_\odot$ would show state transitions on timescales of a few thousand years. Thus, the state transitions of AGNs cannot be verified by direct X-ray observations if AGNs have state transitions that behave like GBHs and satisfy the generally accepted scaling law. Nevertheless, if we assume that AGNs have the same underlying variability mechanism as GBHs, the different subclasses of AGNs might be reasonably assumed to correspond to different spectral states of GBHs. In fact, this assumption can be tested by comparing the PSDs of different types of AGNs with those of GBHs in different spectral states. However, the scaling of timescales with mass reveals that it is very time-consuming to derive AGN PSDs. Compared to GBHs, the limited durations and low signal-to-noise ratios of AGN light curves usually produce incomplete and low-quality PSDs. As a result, it is not easy to constrain PSD shapes and important break frequencies for a large number of AGNs. Relatively high-quality AGN PSDs obtained so far, only available for a limited number (about a dozen) of Seyfert galaxies, are almost analogous to GBH soft-state PSDs (e.g., Uttley & McHardy 2005). The PSDs of Seyfert galaxies show only one break ($\nu_b$), flattening from $\alpha \sim -2$ to $\alpha \sim -1$. With present data, the PSDs do not show further flattening down to the
lowest frequencies ($\sim 10^{-8}$ Hz), which are 3–4 decades lower than the break frequencies. Like GBHs in the high/soft state, the fact that Seyfert galaxies show soft-state PSDs is strongly supported by their low radio fluxes and high accretion rates, which are larger than 2% of the Eddington accretion rate at which Cyg X-1 transits between the hard and soft spectral states (e.g., Maccarone et al. 2003).

Up to now, Ark 564 and NGC 3783 are the only AGNs whose PSD shows the second, low-frequency break ($\nu_{LFB}$). Ark 564 has strong evidence for the second break in its PSD (Pounds et al. 2001; Papadakis et al. 2002; Markowitz et al. 2003; McHardy et al. 2007). Nevertheless, the very high (possibly super-Eddington) accretion rate ($\dot{m}_E \sim 1$; Romano et al. 2004) suggests that Ark 564 may resemble GBHs in the very high state rather than in the low/hard state (McHardy et al. 2007), because in the very high state GBH PSDs show two distinct breaks as well. The low-frequency break in the PSD of NGC 3783, first presented by Markowitz et al. (2003), was questioned by Summons et al. (2007) with the improved PSD. Moreover, the moderately high accretion rate ($\dot{m}_E \sim 0.07$; Uttley & McHardy 2005) and radio quietness (e.g., Reynolds 1997) suggest that NGC 3783 is analogous to GBHs in the high/soft state. Therefore, NGC 3783 also became one of the AGNs showing soft-state PSDs, which leaves Ark 564 as the only non-soft-state AGN.

The X-ray variability of AGNs can also be quantified with the normalized excess variance ($\sigma_{NXS}$) of their X-ray light curves, which is approximately equal to the integral of the normalized PSDs of the same light curves (e.g., Vaughan et al. 2003; Zhang et al. 2005). Because it is much easier to calculate the variances than to calculate the PSDs, the variances have been used to explore the scaling relation of the X-ray variability to black-hole mass, i.e., the so-called variance–mass ($\sigma_{NXS} - M_{BH}$) relationship, and X-ray luminosity of AGNs. On the timescale of about half a day, the variance anti-correlates with mass (i.e., $\sigma_{NXS} \propto M_{BH}^{-1}$; e.g., Lu & Yu 2001; Bian & Zhao 2003; Liu & Zhang 2008; Zhou et al. 2010) and X-ray luminosity (e.g., Nandra et al. 1997). By scaling with Cyg X-1, the variance has been used as a method to estimate the $M_{BH}$ of AGNs (Nikolajuk et al. 2004, 2006, 2009; Gierliński et al. 2008; Zhang et al. 2005). Although the variance of an individual source does nothing for constraining AGN PSDs, the variance–mass relationship, which only requires calculating variances of a large sample of AGNs with known masses, achieves this function. If AGNs have the same underlying X-ray variability mechanism that scales with mass, the variance–mass relationship can be reproduced from a universal AGN PSD model. The comparison between the observed and predicted variance–mass relationship can determine AGN PSD shape and the scaling factors of its parameters with mass. For 10 Seyfert galaxies, which have been regularly observed in X-rays, the 2–10 keV variances calculated with 300-day-long Rossi X-ray Timing Explorer (RXTE) Proportional Counter Array (PCA) light curves anti-correlate with masses, that can be fitted by the hard-state PSD model (Papadakis 2004). With ASCA light curves of about half a day for a larger sample of AGNs, O’Neill et al. (2005) obtained a similar anti-correlation between variances and masses, which is also in agreement with the prediction of the hard-state PSD model. Using XMM-Newton data on timescales of about half a day, Papadakis et al. (2008b) and Miniutti et al. (2009) enlarged the AGN sample, especially objects with smaller masses, for the variance–mass relationship (Papadakis et al. 2008a) also extended the study of the variance–mass relationship to higher redshift AGNs.

The studies of the variance–mass relationship suggest that AGNs have hard-state PSDs, which apparently is in contradiction to the conclusion from the direct PSD analysis that AGNs have soft-state PSDs. Importantly, the AGN sample of Papadakis (2004) and O’Neill et al. (2005) include most of the AGNs whose soft-state PSDs have been well determined. The reason for this inconsistency could be mainly attributable to the short duration of the light curves used to calculate the variances. In fact, even though AGNs do have hard-state PSDs, the short-timescale variances do not cover the frequencies where the low-frequency breaks are located for most of the AGNs. On short timescales, the hard-state PSD predicts the same variance–mass relationship as the soft-state PSD. The short-timescale variance–mass relationship is thus not able to differentiate the two PSD models. Consequently, in order to demonstrate whether AGN PSDs have second breaks, it is necessary to obtain the variance–mass relationship using very-long-timescale light curves, especially for AGNs with large masses. The values of $\nu_{LFB}$ for the GBH hard-state PSDs are about a few tenths of 1 Hz. If AGNs show the hard-state PSDs, from the scaling law of $\nu_{LFB}$ with mass, $\nu_{LFB}$ would be $\sim 10^{-7}$ Hz (on the order of one year) for AGNs with $M_{BH} \sim 10^7 M_\odot$. Therefore, in order to effectively distinguish the two AGN PSD models with the variance–mass relationship, a large number of AGNs should be continuously monitored for decades.

The longest data stream with a roughly continuous and regular sampling mode is from the All Sky Monitor (ASM) onboard the RXTE. The ASM has been monitoring a large number of AGNs since 1996 January. In this paper, we will use the ASM data to obtain the variances of 27 AGNs on the longest timescale so far, with which we will attempt to differentiate the two AGN PSD models.

## 2. THE ASM DATA AND AGN SAMPLE

The ASM operates in the 1.5–12 keV energy band and scans most of the sky every 1.5 hr. We start our analysis with the data of the one-day averages from the ASM quick-look pages. Each one-day-averaged data point is the average of the fitted source fluxes from a number (typically 5–10) of individual 90 s dwells over that day, and is quoted as the nominal 2–10 keV ASM count rate (counts per second). We make use of the full ASM data stream from 1996 January 1 to 2009 December 31 (Modified Julian Day [MJD] 50083–55196), which provides 14-year-long X-ray light curves for a large number of AGNs. In the ASM quick-look pages, we select AGNs that have a measurement of bolometric luminosity for 20 AGNs and PSD break timescales ($1/\nu_B$) for 12 AGNs in the literature.

Due to low sensitivity, the ASM signal-to-noise ratios are quite low for AGNs. As two examples, the left plots of Figures 1 and 2 show the background-subtracted one-day-averaged ASM light curves for the lowest and highest count-rate objects, Mrk 335 and IC 4329a, among our AGN sample, respectively. It can be seen that the one-day-averaged light curves contain many negative count rates. The light curves also do not show a legible variability trend, mainly caused by strong Poisson noise. In order to acquire meaningful variability information about AGNs from the ASM data, it is necessary to rebin the one-day-averaged light curves over a very long timescale (e.g., 300 days, 1

---

1 http://xte.mit.edu/ASM_lc.html
as used in Section 4). The right plots of Figures 1 and 2 present
the 300-day-averaged light curves of Mrk 335 and IC 4329a,
showing that the two objects are indeed variable on such a long
timescale, though the errors are still large. For comparison, the
300-day-averaged light curves of Mrk 335 and IC 4329a,
are also plotted on the top of the
light curves in the left plots of Figures 1 and 2.

Table 1

| Source Name | ASM Rate | σνXS (×10−4) | MBH (10^6 M☉) | Ref. Meth. | T0 (day) | Ref. | Lbol (erg s⁻¹) | Ref. |
|-------------|----------|--------------|----------------|------------|----------|-----|----------------|-----|
| Broad line objects |
| 3C 120  | 0.22 | 3.01 ± 0.69 | 5.55 | 1, r | ... | ... | 45.34 | 9 |
| 3C 390.3 | 0.16 | 1.57 ± 0.48 | 28.7 | 1, r | ... | ... | 44.88 | 9 |
| Ark 120  | 0.17 | 2.44 ± 0.82 | 15.0 | 1, r | ... | ... | 44.91 | 9 |
| Fairall 9 | 0.13 | 3.20 ± 1.53 | 25.5 | 1, r | 28.9 | 14 | 45.23 | 9 |
| IC 4329a | 0.51 | 0.95 ± 0.19 | 21.7 | 2, d | 4.6 | 2 | 44.78 | 9 |
| MR 2251-178 | 0.19 | 3.51 ± 0.92 | 0.83 | 3, o | ... | ... | ... |
| Mrk 79   | 0.14 | 6.89 ± 1.47 | 5.24 | 1, r | ... | ... | 44.57 | 9 |
| Mrk 279  | 0.12 | 14.3 ± 1.39 | 3.49 | 1, r | ... | ... | ... |
| Mrk 290  | 0.09 | 10.4 ± 2.59 | 1.12 | 4, o | ... | ... | 45.03 | 9 |
| Mrk 509  | 0.19 | 4.49 ± 1.13 | 14.3 | 1, r | ... | ... | ... |
| NGC 526a | 0.13 | 8.16 ± 1.81 | 12.9 | 3, o | ... | ... | ... |
| NGC 985  | 0.10 | 8.62 ± 2.78 | 11.2 | 4, o | ... | ... | ... |
| NGC 3227 | 0.18 | 8.63 ± 1.45 | 4.22 | 1, r | 0.59 | 14 | 43.86 | 9 |
| NGC 3516 | 0.13 | 11.3 ± 1.65 | 4.27 | 1, r | 5.8 | 14 | 44.29 | 9 |
| NGC 3783 | 0.27 | 2.08 ± 0.51 | 2.98 | 1, r | 2.9 | 14 | 44.41 | 9 |
| NGC 4151 | 0.42 | 20.2 ± 0.86 | 4.57 | 5, r | 9.2 | 14 | 43.73 | 9 |
| NGC 4258 | 0.09 | 3.81 ± 2.25 | 3.90 | 6, m | 513 | 14 | 43.45 | 9 |
| NGC 4593 | 0.16 | 5.58 ± 1.35 | 0.98 | 7, r | ... | ... | 44.09 | 9 |
| NGC 5548 | 0.19 | 7.51 ± 1.31 | 6.54 | 8, r | 18.3 | 14 | 44.83 | 9 |
| NGC 7469 | 0.14 | 10.4 ± 2.11 | 1.22 | 1, r | ... | ... | 45.28 | 9 |
| Narrow line objects |
| IC 5063  | 0.08 | 9.44 ± 4.02 | 5.50 | 9, d | ... | ... | 44.53 | 9 |
| MCG-6-30-15 | 0.27 | 1.81 ± 0.52 | 0.45 | 10, o | 0.15 | 14 | 43.56 | 14 |
| Mrk 335  | 0.07 | 13.1 ± 4.88 | 1.42 | 1, r | 0.068 | 15 | 44.69 | 9 |
| Mkr 478  | 0.09 | 6.05 ± 2.41 | 4.02 | 11, o | ... | ... | ... |
| NGC 4051 | 0.12 | 4.34 ± 1.58 | 0.16 | 12, r | 0.019 | 14 | 43.56 | 9 |
| NGC 5506 | 0.29 | 1.04 ± 0.39 | 8.80 | 11, d | 0.89 | 14 | 44.47 | 14 |
| PKS 0558-504 | 0.11 | 1.07 ± 0.88 | 4.50 | 13, o | ... | ... | ... |

Notes.

References for MBH: (1) Peterson et al. 2004; (2) Markowitz 2009; (3) Morales & Fabian 2002; (4) Bian & Zhao 2003; (5) Bentz et al. 2006; (6) Herrnstein et al. 1998; (7) Denney et al. 2006; (8) Bentz et al. 2007; (9) Woo & Urry 2002; (10) McHardy et al. 2005; (11) Papadakis 2004; (12) Denney et al. 2009; (13) Wang et al. 2001; (14) Uttley & McHardy 2005; (15) Arévalo et al. 2008. The letter in this column indicates the method used to estimate MBH: r—reverberation mapping; d—stellar velocity dispersion; m—maser; o—other methods.

References for T0: (14) Uttley & McHardy 2005; (15) Arévalo et al. 2008.

References for Lbol: (9) Woo & Urry 2002; (14) Uttley & McHardy 2005.

On board the RXTE, the PCA is much more sensitive than
the ASM. To judge the quality of the ASM light curves, we
compare the light curves obtained from the PCA and ASM
in the same time intervals. We choose two objects, namely
IC 4329a and NGC 3227, to perform this comparison. The
PCA monitored IC 4329a once every 4.26 days for 4.3 years,
from 2003 April 8 to 2007 August 7 (MJD 52737–54319;
observation identifiers 80152-03, 80152-04, 90154-01, 91138-
01, and 92108-01; see Markowitz 2009). NGC 3227 was
monitored by the PCA with different observing schemes (see
Uttley & McHardy 2005 for details) for 7.4 years, from 1999
March 23 to 2006 August 13 (MJD 51260–53960; observation
identifiers 40151-01, 40151-08, 40151-09, 50153-07, 50153-08,
60133-05, 70142-01, 80154-01, and 90160-04). We obtained
the long-term PCA light curves of the two objects from the
HEASARC archive data search form2 in which we selected
“XTE Target Index Catalog” and downloaded the merged light
curves. We then reselected the one-day-averaged ASM light
curves of the two objects in the same time intervals, as spanned
by their long-term PCA light curves. Both the PCA and ASM
light curves are averaged over 300 days and are shown in
Figure 3. In order to compare the PCA and ASM light curves
easily, they are normalized to their respective mean count
rates. Although the discrepancies of the normalized count rates
between the ASM and PCA light curves are present in some
points of the light curves and the PCA errors are much smaller
than the ASM ones, the ASM light curves could still be thought
to roughly track the PCA light curves on a binned size of 300 days.
Therefore, the 300-day-averaged ASM light curves can be used
to study long-term variability of AGNs.

In the case of the heavily binned ASM light curves, the
sampled PSD at vmax (vmax = 1/(2Δt), where Δt is the binned size
of the light curves) might be massively affected by aliasing effects,
especially because of vB ≫ vmin (vmin = 1/T, where T is the
duration of the light curves), for most of the objects. Therefore,

http://heasarc.gsfc.nasa.gov/
the observed $\sigma_{\text{NXS}}^2$ (see Equation (1) for definition) is not equal to the integral of the intrinsic PSD between $v_{\text{min}}$ and $v_{\text{max}}$. This should not be a serious problem, as it should affect all sources in a similar way. Nonetheless, it is worth investigating this aliasing effect by simulating a red-noise light curve. We follow the procedure described by Timmer & König (1995) to fake a light curve (see Zhang 2002 and Zhang et al. 2004 for details) by assuming a single power-law PSD ($P_\nu = a \times \nu^\alpha$, where $a$ is the PSD normalization factor). The experiment is performed twice, once with the slope of $\alpha = -1$ and once with $\alpha = -2$. In order to closely imitate the ASM light curves, we produce a light curve with 5100 points (one per day). For simplicity, we do not consider the effect of Poisson noise. The light curve is normalized to have a mean count rate of 0.2 and a variance of $7.56 \times 10^{-2}$. The normalized variance is the integral of the intrinsic PSD between $1/T$ and $1/(2\Delta t)$, where $T = 5100$ days and $\Delta t = 1$ day correspond to the length and binsize of the simulated light curve. Under these assumptions, one can derive the value of $a$, which is $9.64 \times 10^{-3}$ and $1.72 \times 10^{-10}$ for $\alpha = -1$ and $\alpha = -2$, respectively. With the known $a$, we can calculate the value of the integral of the intrinsic PSD in any frequency range. For the case of $T = 5100$ days and $\Delta t = 300$ days, the integral is $\sigma_{\text{NXS,300d}}^2 = 2.06 \times 10^{-2}$ and $\sigma_{\text{NXS,300d}}^2 = 6.67 \times 10^{-2}$ for $\alpha = -1$ and $\alpha = -2$, respectively. The simulated light curve is then rebinned with $\Delta t = 300$ days (i.e., the binsize of our ASM light curves), resulting in 17 bins (one per 300 days), and its normalized variance, $\sigma_{\text{NXS,300d}}^2$, is estimated. The aliasing effect can be examined by comparing the value of $\sigma_{\text{NXS,300d}}^2$ with that of $\sigma_{\text{NXS,300d}}^2$. The procedure is repeated 1000 times, from which we obtain the median and error (90% confidence level) of $\sigma_{\text{NXS,300d}}^2$ which are $(2.12^{+1.25}_{-0.99}) \times 10^{-2}$ and $(6.57^{+0.57}_{-1.24}) \times 10^{-2}$ for the PSD slope of $\alpha = -1$ and $\alpha = -2$, respectively. The $\sigma_{\text{NXS,300d}}^2$ values are thus approximately equal to the median values of $\sigma_{\text{NXS,300d}}^2$ for both PSD cases. Figure 4 presents the probability distribution of $\sigma_{\text{NXS,300d}}^2$ where the $\sigma_{\text{NXS,300d}}^2$ median are also plotted, showing that the $\sigma_{\text{NXS,300d}}^2$ value is very close to the peak (or the median) of the $\sigma_{\text{NXS,300d}}^2$ sample for both cases.

![Figure 1](image1.png)

**Figure 1.** ASM light curve for the lowest count rate object, Mrk 335. The left plot shows the one-day-averaged light curve (black solid circles whose errors are not shown for clarity), with the 300-day-averaged light curve (red solid squares whose errors are smaller than the symbol size) plotted on top. The right plot again presents the 300-day-averaged light curve to clearly show the source variations on the timescale of 300 days. (A color version of this figure is available in the online journal.)

![Figure 2](image2.png)

**Figure 2.** Same as Figure 1, but for the highest count rate object, IC 4329a. (A color version of this figure is available in the online journal.)
Figure 3. PCA (red solid squares whose errors are smaller than the symbol size) and ASM (black solid circles) 300-day-averaged light curves in the time interval over which the long-term PCA observations were performed. For direct comparison, both light curves are normalized to their respective mean count rates. The left plot is for IC 4329a and the right plot is for NGC 3227. Although the differences are present for some time points, the ASM light curves could be considered to roughly follow the PCA ones.

(A color version of this figure is available in the online journal.)

Figure 4. Probability distribution (the black solid line) of $\sigma^2_{\text{NXS}}$, estimated from the simulated 5100-day-long light curves with a 300-day binsize. The blue long-dashed line indicates the median of the distribution. The red short-dashed line presents the value of the integral of the intrinsic PSD from $\nu_{\text{min}} = 1/T$ to $\nu_{\text{max}} = 1/(2\Delta t)$, where $T = 5100$ days and $\Delta t = 300$ days.

(A color version of this figure is available in the online journal.)

Our simulations demonstrate that the estimated $\sigma^2_{\text{NXS}}$ values are not significantly affected by the heavy binning of light curves. Therefore, the $\sigma^2_{\text{NXS}}$ values of the 300-day-averaged ASM light curves (see Section 4) are a good estimator of the integral of the intrinsic PSD.

3. RELATIONSHIP BETWEEN $\sigma^2_{\text{NXS}}$ AND PSD

3.1. The Assumed PSD Shape

The normalized excess variance, $\sigma^2_{\text{NXS}}$, of a light curve is defined as (e.g., Zhang et al. 2002)

$$\sigma^2_{\text{NXS}} = \frac{1}{N\bar{x}^2} \sum_{i=1}^{N} \left[ (x_i - \bar{x})^2 - \sigma_i^2 \right],$$

where $N$ is the number of bins in the light curve, $x_i$ and $\sigma_i$ are the count rate and its error of the $i$th bin, and $\bar{x}$ is the unweighted arithmetic mean of all $x_i$. The error on $\sigma^2_{\text{NXS}}$ due to Poisson noise is estimated with Equation (11) of Vaughan et al. (2003).

A light curve is characterized by its duration, $T$, and binsize, $\Delta t$. The PSD of the light curve can be estimated at frequencies between the minimum frequency, $\nu_{\text{min}} = 1/T$, and the maximum frequency, $\nu_{\text{max}} = 1/(2\Delta t)$ (i.e., the Nyquist frequency).

The AGN hard-state PSD (e.g., O’Neill et al. 2005) is defined as the doubly broken power law, with slope $-1$ below the low-frequency break ($\nu_{\text{LFB}}$), slope $-1$ between $\nu_{\text{LFB}}$ and the high-frequency break ($\nu_{b}$), and slope $-2$ above $\nu_{b}$:

$$P(\nu) = A(\nu_{\text{LFB}}/\nu_{b})^{-1} \quad (\nu < \nu_{\text{LFB}}),$$

$$P(\nu) = A(\nu/\nu_{b})^{-1} \quad (\nu_{\text{LFB}} \leq \nu \leq \nu_{b}),$$

$$P(\nu) = A(\nu/\nu_{b})^{-2} \quad (\nu > \nu_{b}).$$

Here we define the AGN soft-state PSD as the singly broken power law, with the slopes of $-1$ and $-2$ below and above the
break frequency, \( \nu_b \):\(^{5}
\begin{align*}
P(v) &= A(v/\nu_b)^{-1} \quad (v \leq \nu_b), \\
P(v) &= A(v/\nu_b)^{-2} \quad (v > \nu_b).
\end{align*}
\end{equation}

Note that the break frequency in the soft-state PSD model is identical to the high-break frequency in the hard-state PSD model, and both are denominated as \( \nu_b \).

Regarding \( \nu_b \), there are two different assumptions. First, we assume that \( \nu_b \) inversely scales with \( M_{\text{BH}} \) in the form of
\begin{equation}
\nu_b = C_b/M_{\text{BH}}.
\end{equation}
By fitting the hard-state PSD predictions (see Section 3.2.2) to the short-timescale variance–mass relationship, O’Neill et al. (2005) obtained \( C_b = 43 \) (Hz M\(_{\odot}\)). Using the longer-timescale variance–mass relationship, Papadakis (2004) also found a similar value for \( C_b \). The second assumption for \( \nu_b \) is that \( \nu_b \) depends not only on \( M_{\text{BH}} \), but also on bolometric luminosity, \( \nu_{\text{bol}} \). Based on the results from the PSD analysis of the light curves of 10 AGNs and 2 GBHs, McHardy et al. (2006) obtained the following relation:
\begin{equation}
\log \nu_b = -2.1 \log M_{\text{BH}} + 0.98 \log \nu_{\text{bol}} + 2.32,
\end{equation}
which shows that \( \nu_b \) (in units of day\(^{-1}\)) roughly inversely scales with the square of \( M_{\text{BH}} \) (in units of 10\(^6\) M\(_{\odot}\)) and roughly linearly scales with \( \nu_{\text{bol}} \) (in units of 10\(^4\) erg s\(^{-1}\)) from GBHs to AGNs.

Note that these two assumptions (Equations (7) and (8)) are note consistent with each other, although \( \nu_b \) has a stronger dependence on \( M_{\text{BH}} \) than on \( \nu_{\text{bol}} \) in the second assumption.

In the hard-state PSD model, the ratio of \( \nu_b \) to \( \nu_{\text{bol}} \), marked as \( C_{\text{LFB}} \), is assumed to be the same for all AGNs. Because the short-timescale variance–mass relationship cannot constrain the value of \( C_{\text{LFB}} \), O’Neill et al. (2005) fixed \( C_{\text{LFB}} = 20 \) in their fits, assuming that AGNs have similar values of \( C_{\text{LFB}} \) to those of GBH hard-state PSDs. Papadakis (2004) also found a similar value.

The PSD normalization factor \( A \) is the power at \( \nu_b \). The “universal PSD amplitude,” defined as \( \text{PSD}_{\text{amp}} = A \nu_b \), is assumed to be the same for all AGNs. Based on the fit to the variance–mass relationship from the hard-state PSD prediction, O’Neill et al. (2005) obtained \( \text{PSD}_{\text{amp}} = 0.024 \), similar to the one found by Papadakis (2004). Nevertheless, constant \( \text{PSD}_{\text{amp}} \) (i.e., same for all objects) is only an assumption. If \( \text{PSD}_{\text{amp}} \) is not constant, then Equations (11) and (14) should not predict a constant \( \sigma_{\text{NXS}}^2 \), either.

By definition, \( C_b \) and \( \text{PSD}_{\text{amp}} \) have the same values in the two PSD models. Therefore, the values of \( \text{PSD}_{\text{amp}} \) and \( C_b \) derived from the fits of the hard-state PSD predictions to the observed variance–mass relationships (O’Neill et al. 2005; Papadakis 2004), also apply to the soft-state PSD model.

\section{3.2. Model Predictions of Excess Variance}

If the hypothesized PSDs are able to describe the X-ray variability of AGNs, the observed variance of a light curve is approximately equal to the predicted variance that is the integral of the PSD between \( \nu_{\text{min}} \) and \( \nu_{\text{max}} \):
\begin{equation}
\sigma_{\text{NXS}}^2 \approx \int_{\nu_{\text{min}}}^{\nu_{\text{max}}} P(v) dv.
\end{equation}
The predicted \( \sigma_{\text{NXS}}^2 \) can be analytically expressed in terms of the parameters of both the light curve and the PSD, depending on where the break frequencies are located with respect to \( \nu_{\text{min}} \) and \( \nu_{\text{max}} \).

\subsection{3.2.1. Soft-state PSD Predictions}

If \( \nu_{\text{min}} \geq \nu_b \), the predicted variance, integrating the PSD over the \( \alpha = -2 \) part only, linearly scales with \( \nu_b \):
\begin{equation}
\sigma_{\text{NXS}}^2 = \text{PSD}_{\text{amp}} (T - (2 \Delta t)) \nu_b. \quad (10)
\end{equation}
If \( \nu_{\text{max}} \leq \nu_b \), the predicted variance, integrating the PSD over the \( \alpha = -1 \) part only, is independent of \( \nu_b \):
\begin{equation}
\sigma_{\text{NXS}}^2 = \text{PSD}_{\text{amp}} (\ln T - \ln (2 \Delta t)). \quad (11)
\end{equation}
If \( \nu_{\text{min}} < \nu_b < \nu_{\text{max}} \), the predicted variance is
\begin{equation}
\sigma_{\text{NXS}}^2 = \text{PSD}_{\text{amp}} (\ln \nu_b + \ln T - (2 \Delta t) \nu_b + 1). \quad (12)
\end{equation}

\subsection{3.2.2. Hard-state PSD Predictions}

If \( \nu_{\text{min}} \geq \nu_b \), the predicted variance, integrating the PSD over the \( \alpha = -2 \) part only, linearly scales with \( \nu_b \):
\begin{equation}
\sigma_{\text{NXS}}^2 = \text{PSD}_{\text{amp}} (T - (2 \Delta t)) \nu_b. \quad (13)
\end{equation}
which is the same as Equation (10).

If \( \nu_{\text{min}} < \nu_{\text{min}} < \nu_{\text{max}} \leq \nu_b \), the predicted variance, integrating the PSD over the \( \alpha = -1 \) part only, is independent of \( \nu_b \):
\begin{equation}
\sigma_{\text{NXS}}^2 = \text{PSD}_{\text{amp}} (\ln \nu_b + \ln T - (2 \Delta t) \nu_b + 1). \quad (14)
\end{equation}
which is the same as Equation (11).

If \( \nu_{\text{min}} < \nu_b < \nu_{\text{max}} \), the predicted variance is
\begin{equation}
\sigma_{\text{NXS}}^2 = \text{PSD}_{\text{amp}} (\ln \nu_b + \ln (2 \Delta t)), \quad (15)
\end{equation}
which is the same as Equation (12).

If \( \nu_{\text{min}} \leq \nu_{\text{min}} < \nu_{\text{max}} \leq \nu_b \), the predicted variance is
\begin{equation}
\sigma_{\text{NXS}}^2 = \text{PSD}_{\text{amp}} (1 + \ln C_{\text{LFB}} - \ln \nu_b - \ln (2 \Delta t) - C_{\text{LFB}} T^{-1} \nu_b^{-1}). \quad (16)
\end{equation}
If \( \nu_{\text{min}} < \nu_{\text{min}} < \nu_{\text{max}} \), the predicted variance is
\begin{equation}
\sigma_{\text{NXS}}^2 = \text{PSD}_{\text{amp}} (2 + \ln C_{\text{LFB}} - C_{\text{LFB}} T^{-1} \nu_b^{-1} - (2 \Delta t) \nu_b). \quad (17)
\end{equation}
Finally, if \( \nu_{\text{max}} \leq \nu_{\text{min}} \), the predicted variance is
\begin{equation}
\sigma_{\text{NXS}}^2 = \text{PSD}_{\text{amp}} C_{\text{LFB}} ((2 \Delta t)^{-1} - T^{-1}) \nu_b^{-1}. \quad (18)
\end{equation}
In this case, the variance linearly inversely scales with \( \nu_b \) when it is measured only over the \( \alpha = 0 \) part of the PSD. Obviously, this is the strongest signature for the presence of the second, low break (\( \nu_{\text{LFB}} \)) at which the PSD flattens from \( \alpha = -1 \) to \( \alpha = 0 \).

\subsection{3.3. Dependence of Excess Variance on \( M_{\text{BH}} \) and \( \nu_{\text{bol}} \)}

If \( \nu_b \) scales with \( M_{\text{BH}} \) only, the PSD predictions (Equations (10)–(18)) can be further expressed in terms of \( M_{\text{BH}} \) by substituting \( \nu_b \) with \( C_b/M_{\text{BH}} \). In such a way, if \( \nu_b < \nu_{\text{min}} \), the variance linearly inversely scales with \( M_{\text{BH}} \) in both PSD models. The hard-state PSD predicts that the variance linearly scales with \( M_{\text{BH}} \) if \( \nu_{\text{max}} \leq \nu_{\text{min}} \), which does not exist for the soft-state PSD.

On short timescales, even if \( \nu_{\text{min}} < \nu_b \) (but \( \nu_{\text{min}} > \nu_{\text{LFB}} \)), the two PSD models predict the same variance–mass relationship (see Equations (10)–(15)). Accordingly, the observed short-term variance–mass relationships cannot be used to differentiate the soft-state and hard-state PSD models. In order to effectively distinguish the two PSD models, the variance should be measured
with a long-term light curve whose length is long enough to have $v_{\text{min}} < \nu_{t\text{FB}}$, because on this sufficiently long timescale the soft-state PSD prediction is different from the hard-state PSD prediction. If the light curves are sampled at a binsize whose corresponding $v_{\text{max}}$ is smaller than $\nu_{t\text{FB}}$, the hard-state PSD predicts that the variance linearly increases with $M_{\text{BH}}$ (Equation (18)), whereas the soft-state PSD still predicts that the variance is independent of $M_{\text{BH}}$ (Equation (11)).

If taking into account the scaling of $v_b$ with both $M_{\text{BH}}$ and $L_{\text{bol}}$, the predicted variance can be further expressed in terms of $M_{\text{BH}}$ and $L_{\text{bol}}$ by substituting $v_b$ with Equation (8). In this case, it is impossible to describe the variance as the function of mass (or luminosity) separately. For the correct PSD model, however, the predicted variances would be equal to the observed variances. Of course, a number of AGNs should be monitored for a sufficient length of time (requiring $v_{\text{min}} < \nu_{t\text{FB}}$) and with a regular sampling rate in order to determine whether or not AGN PSDs have the second, low-frequency break.

4. RESULTS

Reliable estimation of observed $\sigma_{\text{NXS}}^2$ requires the light curve to have a high signal-to-noise ratio and sufficient number of data points. However, the ASM sensitivity is not sufficient to directly calculate the variances from the one-day-averaged curves (see the discussion of Section 2). By rebinning the one-day averages over a longer time interval, it is possible to obtain light curves with good signal-to-noise ratios. Even though rebinning reduces the number of data points and conceals short-term variability, it is still meaningful to acquire long-timescale variability of AGNs. This is also in accordance with our purpose of estimating long-timescale variances to differentiate the two PSD models hypothesized for AGNs. To ensure the use of $\chi^2$ statistics and to substantially increase the signal-to-noise ratio, we rebin the one-day-averaged light curves with a binsize of $\Delta t = 300$ days as a compromise. The count rate in each new bin is obtained by taking a weighted average of all the original one-day averages in that bin. This procedure of rebinning results in 17 data points in the 300-day-averaged light curve for each source. The values of $\sigma_{\text{NXS}}^2$ calculated with the rebinned light curves are listed in Table 1.

The rebinned light curves have a binsize of $\Delta t = 300$ days and a length of $T = 5100$ days. Their variances would be approximately equal to the predicted variances derived from integrating the PSD between $v_{\text{min}} = 2.27 \times 10^{-8}$ Hz and $v_{\text{max}} = 1.93 \times 10^{-8}$ Hz. More important, Equation (8) predicts that the lowest value of $v_b$ is approximately $1.12 \times 10^{-7}$ Hz ($\sim 1.50 \times 10^{-7}$ Hz if $v_b$ scales with $M_{\text{BH}}$ only) for the largest-mass-object in our AGN sample (3C 390.3). Therefore, the binsize of 300 days guarantees that $v_{\text{max}}$ is significantly lower than $v_b$ for all of our AGNs. As a result, the soft-state PSD predicts that the observed variances of our AGNs would be the same and thus independent of $M_{\text{BH}}$. In the hard-state PSD model, however, the assumption of $v_b/\nu_{t\text{FB}} \sim 20$ implies $v_{\text{max}} < \nu_{t\text{FB}}$ for AGNs with $M_{\text{BH}} \lesssim 2 \times 10^8 M_\odot$. The observed variances of these AGNs would linearly increase with mass. The 300-day rebinned light curves are therefore more effective to distinguish the two AGN PSD models.

4.1. Relationship Between $\sigma_{\text{NXS}}^2$ and $M_{\text{BH}}$

Figure 5 shows the relationship between the estimated $\sigma_{\text{NXS}}^2$ and $M_{\text{BH}}$. BLS1 and NLS1 do not occupy different regions. Although the scatter is large, it appears that the variance does not depend on mass. The Pearson’s correlation coefficient between

$$\log \sigma_{\text{NXS}}^2 \text{ and } M_{\text{BH}} = r = -0.23,$$

and the null probability is $p = 0.25$, suggesting that the variance may not correlate with $M_{\text{BH}}$. The blue solid line in Figure 5 plots the variance–mass relationship predicted by the hard-state PSD model, in which we adopt the best-fit parameters ($\text{PSD}_{\text{amp}} = 0.024$, $C_b = 43$ Hz, $M_{\text{BH}}$, and $L_{\text{bol}} = 20$) obtained by O’Neill et al. (2005) from the short-timescale variance–mass relationship. It is clear that the predicted relation is not at all in agreement with the observed one. In fact, the hard-state PSD predicts that the variances linearly increase with mass for $M_{\text{BH}} \lesssim 10^8 M_\odot$. The predicted variance–mass relationship flattens when $M_{\text{BH}} > 2 \times 10^8 M_\odot$.

This means that AGNs of $M_{\text{BH}} \lesssim 10^8 M_\odot$ have $v_{\text{max}} < \nu_{t\text{FB}}$, whereas those of $M_{\text{BH}} \gtrsim 2 \times 10^8 M_\odot$ have $v_{\text{min}} < \nu_{t\text{FB}} < v_{\text{max}}$. However, the failure of the hard-state PSD prediction merely shows that a very specific version of the hard-state PSD model does not fit the data. This does not prove that the hard-state PSD model, with another set of parameter values, cannot fit the data (to some extent). Among the three parameters, $C_b$, the scaling of $v_b$ with mass, is best determined and mostly impossible to change very much. As we will discuss in Section 4.3, the value of $\text{PSD}_{\text{amp}}$, primarily due to the intrinsic scatter of variance measurements, may range from 0.008 up to 0.052. In Figure 5, we again plot the hard-state PSD predictions by changing the values of $\text{PSD}_{\text{amp}}$ to 0.008 and 0.052. The $\text{PSD}_{\text{amp}} = 0.008$ prediction (the bottom blue dashed line) fails completely. Although the $\text{PSD}_{\text{amp}} = 0.052$ prediction is on top of the $\text{PSD}_{\text{amp}} = 0.024$ one, it still cannot adequately “fit” the data. As a result, it is rather unlikely that the hard-state PSD predictions can explain the data by altering the values of PSDamp.

In fact, the hard-state PSD predictions, within the $\text{PSD}_{\text{amp}}$ range adopted above, are about 1–2 orders of magnitude smaller than the observed variances for $M_{\text{BH}} \lesssim 10^8 M_\odot$. This indicates
that, down to frequencies of \( \sim 10^{-9} \) Hz, the PSDs of these AGNs should not show the second low-frequency breaks. In order to test this assumption, we show in Figure 5 (the magenta solid line) the hard-state PSD prediction by setting \( C_{LFB} = 2000 \), which explains the data much better than the case of \( C_{LFB} = 20 \). Thus, our long-timescale variance–mass relationship does not favor \( C_{LFB} = 20 \), as assumed by O’Neill et al. (2005) for the short-timescale variance–mass relationship. However, our data show that the second breaks of AGN PSDs, if they exist, should be close to or beyond the frequency of \( v_{\text{min}} \approx 2.27 \times 10^{-9} \) Hz. Similarly, the low-frequency end reached by the presently known high-quality AGN PSDs (e.g., McHardy et al. 2004, 2005) has extended through to \( \sim 10^{-8} \) Hz, at which the PSDs do not show the second breaks, either. Hence, both the variance and PSD data imply that the ratio of \( v_b \) to \( v_{LFB} \) should be larger than \( \sim 2000 \) for the second breaks of AGN PSDs to exist.

The black dashed line in Figure 5 plots the soft-state PSD prediction by using \( C_b = 43 \) Hz \( M_{\odot} \) and \( \text{PSD}_{\text{amp}} = 0.024 \), the same as those used for the hard-state PSD prediction. The soft-state PSD prediction is independent of mass due to \( v_{\text{max}} < v_b \) for all of our AGNs, which is roughly in agreement with the data. The mass-independent variance predicted by the soft-state PSD is \( 5.14 \times 10^{-2} \), slightly smaller than the average value (\( 6.64 \times 10^{-2} \), the red dashed line) of the observed variances of 27 AGNs (see Section 4.3). The red dashed line is also identical to the soft-state PSD prediction derived by using \( \text{PSD}_{\text{amp}} = 0.03 \), obtained from the averaged variance in Equation (11) (see Section 4.3), and \( C_b = 43 \) Hz \( M_{\odot} \). Consequently, our long-timescale variance–mass relationship seems to favor the soft-state PSD for AGNs.

With the present data, the soft-state PSD prediction is actually identical to the hard-state PSD prediction with \( C_{LFB} \gtrsim 2000 \). However, the value of \( C_{LFB} \gtrsim 2000 \) is remarkably larger than the presently approved values \( \sim (10–100) \) analogous to the GBH hard-state PSDs. This suggests that such a large value of \( C_{LFB} \) would not be physical for AGNs. As a result, our long-timescale variance–mass relationship is very likely to agree with the soft-state PSD prediction rather than with the hard-state PSD prediction.

### 4.2. Relationship Between \( \sigma_{\text{NXS}}^2 \) and \( L_{\text{bol}} \)

On short timescales, the observed variance anti-correlates with the X-ray luminosity of AGNs (e.g., Nandra et al. 1997), whereas it weakly increases with larger bolometric luminosity (Zhou et al. 2010). Figure 6 plots the relationship between our long-timescale \( \sigma_{\text{NXS}}^2 \) and \( L_{\text{bol}} \) for 20 AGNs. It appears that the variance does not depend on \( L_{\text{bol}} \). The Pearson’s correlation coefficient between \( \log \sigma_{\text{NXS}}^2 \) and \( \log L_{\text{bol}} \) is \( r = -0.09 \), and the null probability is \( p = 0.70 \), indicating that the variance does not correlate with \( L_{\text{bol}} \). This independence of variance from bolometric luminosity presents additional evidence for the soft-state PSD shape of AGNs. Because all our AGNs show \( v_{\text{max}} < v_b \), the soft-state PSD naturally predicts that the variance is independent of \( L_{\text{bol}} \), suggesting that Equation (8) is consistent with the lack of any correlation between \( \sigma_{\text{NXS}}^2 \) and \( L_{\text{bol}} \). However, the hard-state PSD with \( C_{LFB} = 20 \) would predict that the variance decreases with increasing bolometric luminosity.

### 4.3. Scatter of \( \sigma_{\text{NXS}}^2 \) and Constant \( \text{PSD}_{\text{amp}} \)

For the soft-state PSD model, Equation (11) shows that the value of \( \text{PSD}_{\text{amp}} \) can be directly estimated from the observed variance of an object if its \( v_b \) is larger than \( v_{\text{max}} \). Because \( v_b > v_{\text{max}} \) for all objects in our sample, their observed variances, independent of \( M_{\text{BH}} \) and \( L_{\text{bol}} \), are expected to be the same. Therefore, a constant \( \text{PSD}_{\text{amp}} \) (same for all AGNs) can be obtained with the observed variances of these objects. However, Table 1 (also Figure 5) shows that the observed variances exhibit quite large scatter, about one order of magnitude, indicating that the derived values of \( \text{PSD}_{\text{amp}} \) have an identical degree of scatter from object to object. This is inconsistent with the assumption that the value of \( \text{PSD}_{\text{amp}} \) is the same for all AGNs. However, the large scatter of the observed variances is probably due to the intrinsic scatter (probably very large) of the variance measurements (e.g., see Section 5 in Vaughan et al. 2003 and the entries in their Table 1; also see Section 3.2 in O’Neill et al. 2005). Consequently, the scatter of the estimated variances does not imply the intrinsic scatter of \( \text{PSD}_{\text{amp}} \). The way to reduce the intrinsic scatter of variance measurements is to average a number of estimated variances. As a result, in order to obtain the constant \( \text{PSD}_{\text{amp}} \) and reduce its uncertainty, we average the observed variances of our 27 AGNs and derive the standard deviation, which is \( (6.44 \pm 4.76) \times 10^{-2} \). With Equation (11), we obtain \( \text{PSD}_{\text{amp}} = 0.030 \pm 0.022 \). Based on the short-timescale variance–mass relationships, which are not sensitive enough to differentiate the soft-state and hard-state PSD predictions, Papadakis (2004) and O’Neill et al. (2005) obtained \( \text{PSD}_{\text{amp}} \sim 0.02–0.03 \), similar to the one we obtained.

The AGN PSDs obtained with high-quality RXTE and XMM-Newton light curves indicate that the values of \( \text{PSD}_{\text{amp}} \) also show large scatter by up to one order of magnitude for different AGNs (e.g., Markowitz et al. 2003; Done & Gierlinski 2005; Uttley & McHardy 2005). The uncertainty in the best-fit \( \text{PSD}_{\text{amp}} \) probably does not indicate a range of intrinsic \( \text{PSD}_{\text{amp}} \), but rather the true uncertainty with which one can estimate the constant \( \text{PSD}_{\text{amp}} \) with the present PSDs. Nevertheless, one could average the known values of \( \text{PSD}_{\text{amp}} \) from the best fits to the high-quality PSDs of a few AGNs as an approximate value of the constant \( \text{PSD}_{\text{amp}} \). The averaged value of \( \text{PSD}_{\text{amp}} \sim 0.02–0.03 \) is also similar to the one we obtained from the average of the observed variances of a number of AGNs, assuming a soft-state PSD shape.

### 4.4. The \( \sigma_{\text{NXS}}^2–M_{\text{BH}}–L_{\text{bol}} \) Plane

Equation (8) shows that \( v_b \) depends on both \( M_{\text{BH}} \) and \( L_{\text{bol}} \). It is therefore inadequate to study the \( \sigma_{\text{NXS}}^2–M_{\text{BH}} \) and \( \sigma_{\text{NXS}}^2–L_{\text{bol}} \) relationships.
relationships separately. Taking into account the scaling of $\nu_b$ with $M_{\text{BH}}$ and $L_{\text{bol}}$ synchronously, we have to compare the observed variances with the ones predicted by the PSD models, i.e., a projection of the $\sigma_{\text{NS}}^2-M_{\text{BH}}-L_{\text{bol}}$ (or $C_{\text{LFB}}$) plane. The predictions are calculated with the soft-state and hard-state PSDs with the values of $\nu_b$ calculated with Equation (8) and $\text{PSD}_{\text{amp}} = 0.03$ estimated in Section 4.3. For the hard-state PSD predictions, $C_{\text{LFB}}$ is still assumed to equal 20.

Figure 7 plots the observed $\sigma_{\text{NS}}^2$ against the predicted $\sigma_{\text{NS}}^2$ (the black solid circles for the soft-state PSD predictions and the red solid squares for the hard-state PSD ones) for 20 AGNs. We especially emphasize that the black solid line in Figure 7 is not a best-fit line to the relation between the observed and predicted variances (for the two PSD models, respectively). It is the line on which an object will lie exactly if the predicted variance is equal to the observed one. In the same way, the two black dashed lines indicate $\sigma$ deviations from the black solid line, showing the positions to which the black solid line will shift if the predicted variances are calculated with $\text{PSD}_{\text{amp}} = 0.052$ (the upper black dashed line) and $\text{PSD}_{\text{amp}} = 0.008$ (the lower black dashed line), respectively. The predicted variances by the soft-state PSD are the same for all objects (the magenta solid circle indicates the average value of the observed variances). The error bars on the observed variances are not shown for the soft-state PSD model, but they are identical to the ones for the hard-state PSD model because the observed variances are the same for the two PSD models. Most of the AGNs reside far from the three lines for the hard-state PSD predictions, whereas they lie close to the lines for the soft-state PSD predictions.

(A color version of this figure is available in the online journal.)

![Figure 7](image)

Figure 7. Observed $\sigma_{\text{NS}}^2$ is plotted against the predicted $\sigma_{\text{NS}}^2$ for the soft-state (black solid circles) and hard-state (red solid squares) PSD models, respectively. For the soft-state and hard-state PSD predictions, we adopt $\text{PSD}_{\text{amp}} = 0.03$, and the PSD break frequency ($\nu_b$) scales with black hole mass and bolometric luminosity via Equation (8). The ratio of $\nu_b$ to $\nu_{\text{LFB}}$ ($C_{\text{LFB}}$) is assumed to be 20 for the hard-state PSD model. The black solid line is not a best-fit line to the relationship between the observed and predicted variances, but rather the position on which an object will lie if the predicted variance is equal to the observed one. The two black dashed lines indicate $\sigma$ deviation from the solid line, representing the positions to which the solid line will shift if the predicted variance is calculated with $\text{PSD}_{\text{amp}} = 0.052$ (the upper black dashed line) and $\text{PSD}_{\text{amp}} = 0.008$ (the lower black dashed line), respectively. The predicted variances by the soft-state PSD are the same for all objects (the magenta solid circle indicates the average value of the observed variances). The error bars on the observed variances are not shown for the soft-state PSD model, but they are identical to the ones for the hard-state PSD model because the observed variances are the same for the two PSD models. Most of the AGNs reside far from the three lines for the hard-state PSD predictions, whereas they lie close to the lines for the soft-state PSD predictions.

5. DISCUSSION AND CONCLUSIONS

With the ASM data accumulated over 14 years, we estimate the normalized excess variances of 27 AGNs in the X-ray band on the longest reported timescale ($\Delta t = 300$ days and $T = 5100$ days) so far. Although the observed variances show quite large scatter, they do not appear to depend on the black hole mass and bolometric luminosity of AGNs. This phenomenon has already been noticed by Markowitz & Edelson (2004) with PCA light curves of $\Delta t = 34.4$ days and $T = 1296$ days. The short-timescale variance–mass relationship has been able to constrain the PSD amplitude and the scaling law of the PSD high-break frequency with black hole mass (Papadakis 2004; O’Neill et al. 2005), but it cannot be used to effectively distinguish the hard-state and soft-state PSD models hypothesized for AGNs (as they have the same predictions on short timescales) in general. Relatively, the long-timescale variance–mass relationship is more valid to determine whether the AGN PSDs have the second, low-frequency breaks.

With the best-fit parameters obtained by O’Neill et al. (2005), the soft-state PSD prediction is much more consistent with our long-timescale variance–mass relationship than the hard-state PSD prediction. On the longest timescale so far, the hard-state PSD predicts that the variance increases with mass, whereas the soft-state PSD predicts mass-independent variance. In fact, the variance predicted by the hard-state PSD model is remarkably smaller than the observed variances for most of our AGNs. Furthermore, by taking into account the scaling factor of the PSD high-break frequency with black hole mass and bolometric luminosity together, the soft-state PSD predictions are more likely to agree with the observed variances than the hard-state PSD predictions. Therefore, the long-timescale variances appear to favor the soft-state rather than the hard-state PSD shape for AGNs. It is reasonable to assume that the variances predicted by the best-fit PSD parameters of O’Neill et al. (2005), not the hard-state PSD in general, are not consistent with the data. However, we have demonstrated that changes in PSD amplitude within the widest possible range do not improve the “fit” to the data. Rather, the hard-state PSD model could probably agree with the data, but it would require a range of PSD amplitude values that has not been observed so far when a proper fitting to the PSDs of a few sources has been performed. Although the hard-state PSD predictions with $\nu_b/\nu_{\text{LFB}} > 2000$ can explain the data as well as the soft-state PSD predictions, such a large value of $\nu_b/\nu_{\text{LFB}}$ is very probably nonexistent by scaling from GBHs to AGNs. Moreover, the hard-state PSD with $\nu_b/\nu_{\text{LFB}} > 2000$ is actually identical to the soft-state PSD for the present data.
Up to now, the best fits show that the high-quality PSDs of a few AGNs have one only high-frequency break, except for Ark 564, which exhibits the second, low-frequency break. Therefore, our variance analysis of a larger sample of AGNs agrees with the direct PSD analysis of a smaller sample of AGNs, both of which imply the soft-state PSD shape for AGNs. For example, the PSDs of NGC 4051 and MCG-6-30-15, having the smallest mass among our sample, show only one break down to a frequency of $\sim 10^{-8}$ Hz at quite a high confidence level (McHardy et al. 2004, 2005). At the same time, Figure 5 shows that the estimated variances of the two objects, roughly consistent with the soft-state PSD predictions, are remarkably larger than the variances predicted by the hard-state PSD model. Compared to the PSD analysis, however, our variance analysis lowers the frequencies by more than one order of magnitude. Therefore, our results further strengthen the standpoint, first suggested by the PSD analysis, that AGN PSDs might have only one break.

By analogy with the PSDs of GBHs in the high/soft state, both the variance and PSD analyses suggest that Seyfert-type AGNs are in the high accretion state. Therefore, AGNs are thought to be scaled-up GBHs in the high/soft state, characterized by the PSD break frequency scaling with black hole mass and bolometric luminosity (or Edgington accretion rate) from GBHs to AGNs (McHardy et al. 2006). Under these assumptions, the PSD break frequencies of all AGNs in our sample are substantially larger than the maximum frequency to which the 300-day binned light curves correspond, indicating that the estimated variances are the same for our AGNs. This motivates us to average the observed variances, from which we obtain a constant PSD amplitude of $0.030 \pm 0.022$ for AGNs, roughly consistent with those obtained from the direct PSD analysis and the short-timescale variance analysis.

There are a number of factors that may cause the large scatter of the observed variances. One main effect may come from the low-quality ASM light curves for AGNs (see Section 2). From the point of view of the PSD itself, the slopes above and below the break frequency are not exactly equal to $-2$ and $-1$ for most of the AGNs, as already seen from the known AGN PSDs (e.g., Uttley et al. 2002). At the same time, the AGN PSDs are better described by a bending power law (e.g., Uttley & McHardy 2005) than by an abruptly broken power law, as assumed here for simplicity. It is worth noting that, if the soft-state PSD model is applicable to AGNs, the observed variances should be the same. However, because the variance measurements have a known intrinsic scatter (Vaughan et al. 2003; O’Neill et al. 2005), which could be very large, the large scatter of the estimated excess variances is almost certainly due to the intrinsic scatter of the $\sigma_{XX}$ values themselves. In order to decrease the intrinsic scatter of variance measurements, it is necessary to perform high-quality observations on a longer timescale (and/or multiple observations) for AGNs. Averaging the multiple variances of an object (from segments of a long timescale or multiple observations) can reduce the intrinsic uncertainty of variance measurements. Due to shorter timescales, the AGNs with smaller or intermediate black hole mass more effectively differentiate the two PSD models.

In conclusion, the longest-timescale X-ray variability suggests that AGN PSDs have only one break, and further indicates that AGNs are in the high accretion state.

I thank the anonymous referee for the constructive suggestions and comments that significantly improved the paper. The data used in this paper are based on quick-look results provided by the ASM/RXTE team. This research has made use of data obtained through the High Energy Astrophysics Science Archive Research Center Online Service, provided by the NASA/Goddard Space Flight Center. This work is supported by the National Natural Science Foundation of China (Projects 10878011 and 10733010) and by the National Basic Research Program of China—973 Program 2009CB824800.

REFERENCES

Arévalo, P., McHardy, I. M., & Summons, D. P. 2008, MNRAS, 388, 211
Axelsson, M., Borgonovo, L., & Larsson, S. 2006, A&A, 452, 975
Bentz, M. C., et al. 2006, ApJ, 651, 775
Bentz, M. C., et al. 2007, ApJ, 662, 205
Bian, W., & Zhao, Y. 2003, MNRAS, 343, 164
Denney, K. D., et al. 2006, ApJ, 653, 152
Denney, K. D., et al. 2009, ApJ, 702, 1353
Done, C., & Gierliński, M. 2005, MNRAS, 364, 208
Gierliński, M., Nikolajuk, M., & Czerny, B. 2008, MNRAS, 383, 741
Herrnstein, J. R., Greenhill, L. J., Moran, J. M., Diamond, P. J., Inoue, M., Nakai, N., & Miyoshi, M. 1998, ApJ, 497, 69
Klein-Wolt, M., & van der Klis, M. 2008, ApJ, 675, 1407
Liu, Y., & Zhang, S. N. 2008, A&A, 480, 699
Lu, Y., & Yu, Q. 2001, MNRAS, 324, 653
Maccarone, T. J., Gallo, E., & Fender, R. 2003, MNRAS, 345, L19
Markowitz, A. 2009, ApJ, 698, 1740
Markowitz, A., & Edelson, R. 2004, ApJ, 617, 939
Markowitz, A., et al. 2003, ApJ, 593, 96
McHardy, I. M., Gunn, K. F., Uttley, P., & Goad, M. R. 2005, MNRAS, 359, 1469
McHardy, I. M., Koerding, E., Knigge, C., Uttley, P., & Fender, R. P. 2006, Nature, 444, 730
McHardy, I. M., Papadakis, I. E., Uttley, P., Page, M. J., & Mason, K. O. 2004, MNRAS, 348, 783
McHardy, I. M., et al. 2007, MNRAS, 382, 985
Miniutti, G., Ponti, G., Greene, J. E., Ho, L. C., Fabian, A. C., & Iwasawa, K. 2009, MNRAS, 394, 443
Morales, R., & Fabian, A. C. 2002, MNRAS, 329, 209
Nandra, K., George, I. M., Mushotzky, R. F., Turner, T. J., & Yaqoob, T. 1997, ApJ, 476, 70
Nikolajuk, M., Czerny, B., & Gruyeronicked, P. 2009, MNRAS, 394, 2141
Nikolajuk, M., Czerny, B., Ziolkowski, J., & Gierliński, M. 2006, MNRAS, 370, 1534
Nikolajuk, M., Papadakis, I. E., & Czerny, B. 2004, MNRAS, 350, L26
O’Neill, P. M.; Nandra, K., Papadakis, I. E., & Turner, T. J. 2005, MNRAS, 358, 1405
Papadakis, I. E. 2004, MNRAS, 348, 207
Papadakis, I. E., Brinkmann, W., Negoro, H., & Gliozzi, M. 2002, A&A, 382, L1
Papadakis, I. E., Chatzopoulos, E., Athanasiadis, D., Markowitz, A., & Georganopoulos, I. 2008a, A&A, 487, 473
Papadakis, I. E., Ioannou, Z., Brinkmann, W., & Xilouris, E. M. 2008b, A&A, 490, 995
Peterson, B. M., et al. 2004, ApJ, 613, 682
Potschmidt, K., et al. 2003, A&A, 407, 1039
Pounds, K., Edelson, R., Markowitz, A., & Vaughan, S. 2001, ApJ, 550, L15
Reynolds, C. S. 1997, MNRAS, 286, 515
Romano, P., et al. 2004, ApJ, 602, 635
Summons, D. P., Arévalo, P., McHardy, I. M., Uttley, P., & Bhaskar, A. 2007, MNRAS, 378, 649
Timmer, J., & König, M. 1995, A&A, 300, 707
Uttley, P., & McHardy, I. M. 2005, MNRAS, 363, 586
Uttley, P., McHardy, I. M., & Papadakis, I. E. 2002, MNRAS, 332, 231
Vaughan, S., Edelson, R., Warwick, R. S., & Uttley, P. 2003, MNRAS, 345, 1271
Wang, T. G., Matsuoka, M., Kubo, H., Mihara, T., & Negoro, H. 2001, ApJ, 554, 233
Woo, J. H., & Urry, C. M. 2002, ApJ, 579, 530
Zhang, Y. H. 2002, MNRAS, 337, 609
Zhang, Y. H., Cagnoni, I., Treves, A., Celotti, A., & Maraschi, L. 2004, ApJ, 605, 98
Zhang, Y. H., Treves, A., Celotti, A., Qin, Y. P., & Bai, J. M. 2005, ApJ, 629, 686
Zhang, Y. H., et al. 2002, ApJ, 572, 762
Zhou, X. L., Zhang, S. N., Wang, D. X., & Zhu, L. 2010, ApJ, 710, 16