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X-ray Fluctuation Power Spectral Densities of Seyfert 1 Galaxies

A. MARKOWITZ et al.
University of California, Los Angeles

Abstract

By combining complementary monitoring observations spanning long, medium and short time scales, we have constructed power spectral densities (PSDs) of six Seyfert 1 galaxies. These PSDs span $\sim$4 orders of magnitude in temporal frequency, sampling variations on time scales ranging from minutes to years. In at least four cases, the PSD shows a "break," a significant departure from a power law, typically on time scales of order a few days. This is similar to the behavior of Galactic X-ray binaries (XRBs), lower mass compact systems with breaks on time scales of seconds. NGC 3783 shows tentative evidence for a doubly-broken power law, a feature that until now has only been seen in the (much better-defined) PSDs of low-state XRBs. When one previously-observed object is added to make a small sample of seven, an apparently significant correlation is seen between the break time scale T and the putative black hole mass $M_{\rm BH}$, while none is seen between break time scale and luminosity. The data are consistent with the linear relation $T = M_{\rm BH}/10^{6.5}\,{\rm M}_\odot$; extrapolation over 6–7 orders of magnitude is in reasonable agreement with XRBs. All of this strengthens the case for a physical similarity between Seyfert 1s and XRBs.

1.1 Introduction: Seyfert X-ray Variability

Seyfert nuclei exhibit rapid, aperiodic flux variability over a wide range of time scales. Some authors characterized the rapid X-ray variability in Seyferts by measuring the variability amplitude, and noting an anticorrelation with luminosity (Barr & Mushotzky 1986; Nandra et al. 1997; Turner et al. 1999; Markowitz & Edelson 2001). If we assume that all Seyferts accrete at the same fraction of the Eddington limit, then this anticorrelation is consistent with higher luminosity sources being associated with larger black hole masses with larger Schwartzschild radii, larger X-ray emission regions, and hence a longer time required to achieve a given amplitude of flux variability. However, these variability amplitudes were all measured over a fixed duration, and it is known that the fraction of Eddington at which these source accrete does differ across the Seyfert range. The solution is to quantify the variability using the power spectral density (PSD) in order to identify a characteristic variability time scale.

EXOSAT established the 'red-noise' nature of Seyfert PSDs, with stronger scale-invariant variability at longer time scales and power law slopes of ~ -1.5 (e.g., Lawrence & Papadakis 1993). No characteristic time scales were found, however, due to the limited dynamic range of these PSDs.

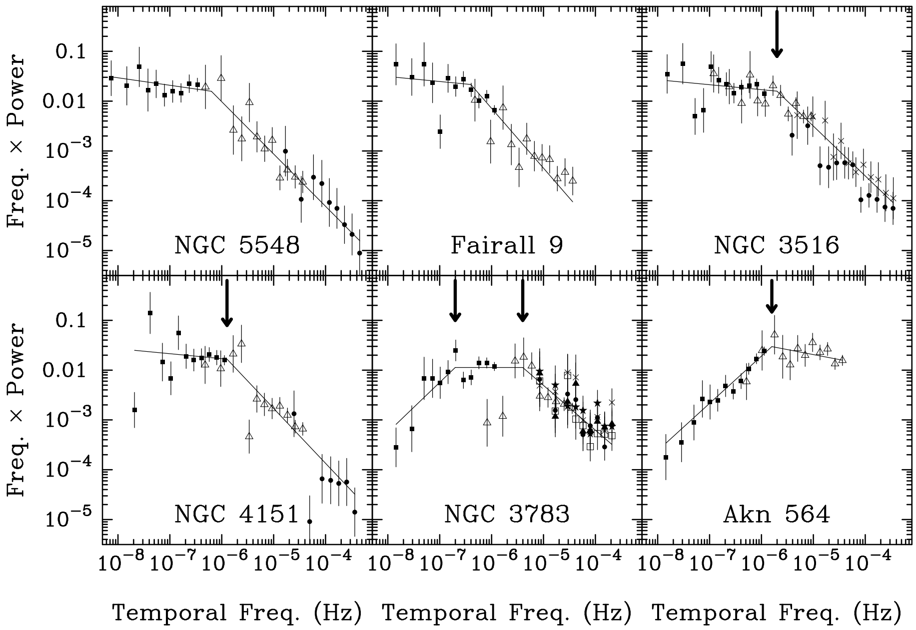

Fig. 1.1. Broadband PSDs for our six targets, ranked by black hole mass estimate. The best fitting singly-broken power law (doubly-broken for NGC 3783) is shown. Downward arrows indicate significant detection of PSD break. Solid lines show the instrinsic underlying PSD model shape. The plots are 'unfolded' in that the PSD measurement distortion effects of aliasing and red-noise leak, as well as the contant level of power due to Poisson noise, have been removed.

To measure high-dynamic range PSDs, we use the observing technique of Edelson & Nandra (1999), which combines three complementary, overlapping sampling patterns: *RXTE* is used to obtain virtually-continuous long- and medium-term sampling, and combined with a short-term intensive long-look from *Chandra* or *XMM-Newton*. Each light curve is Fourier transformed to produce an individual PSD; these are combined to yield high-quality, high-dynamic range PSDs, typically spanning 3–4 orders of magnitude in temporal frequency, and sampling variations on time scales from tens of minutes to over a year. The Monte Carlo method introduced by Uttley, McHardy & Papadakis (2002) is used to account for PSD measurement distortion effects, assign PSD errors, and determine the underlying, intrinsic PSD shape.

The broadband PSD results are shown in Figure 1.1, with the best-fitting singly-broken power law model shown. Four targets (Akn 564, NGC 3783, NGC 3516 and NGC 4151) show significant evidence for flattening on the longest time scales, showing PSD breaks (evident as a significant departure from a pure red-noise power law) on time scales of a few days. NGC 3783 is tentatively best-fit by a doubly-broken power law, showing preliminary evidence for **two** PSD breaks, a feature that until now has only been seen in X-ray Binary

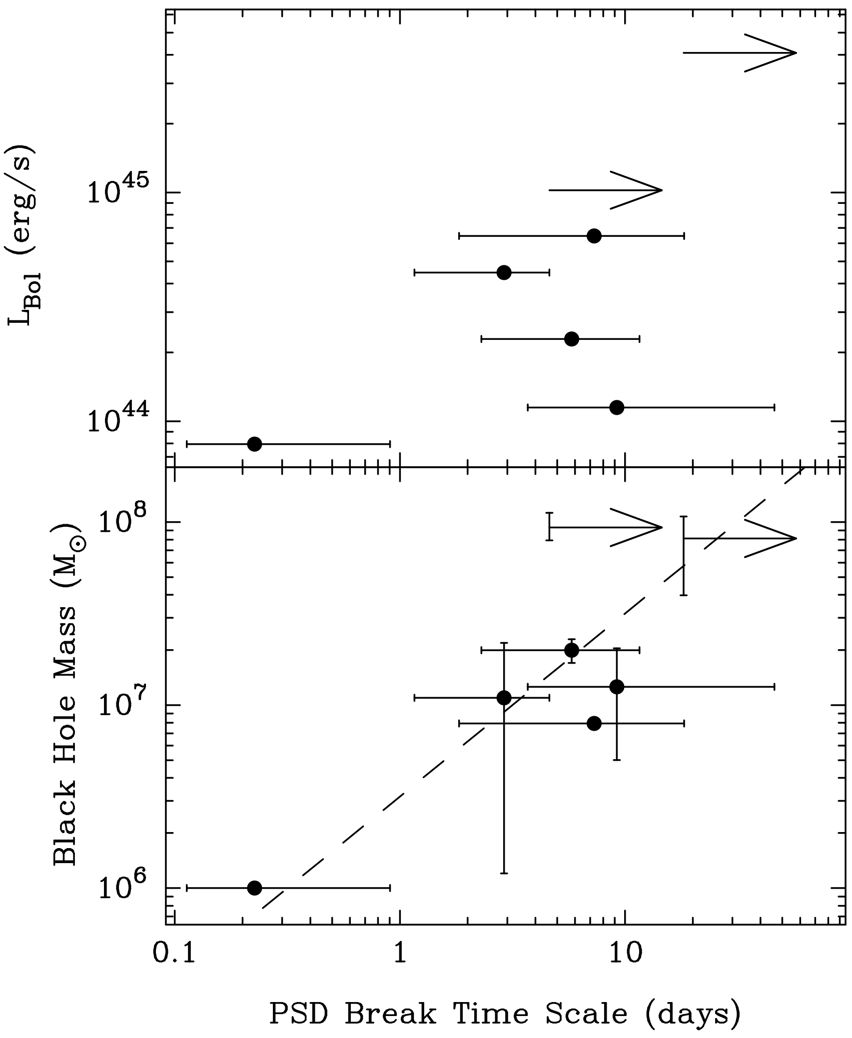

Fig. 1.2. Bolometric luminosity (top) and black hole mass estimate (bottom) plotted against PSD break time scale; the MCG–6-30-15 PSD break is from Uttley, McHardy & Papadakis (2002). Mass estimates are e.g., reverberation-mapped mass estimates (e.g., from Kaspi et al. 2000). The dashed line denotes the linear mass–time scale relation $T_{\rm (days)} = M_{\rm BH}/10^{6.5}\,{\rm M}_\odot$

(XRB) PSDs (e.g., Nowak et al. 1999a, 1999b). Upper limits to PSD break frequency were obtained for NGC 5548 and Fairall 9, the two most luminous targets in our sample.

1.2 Discussion

1.2.1 Similarity to PSDs of low-state XRBs

All six PSDs studied are consistent in shape with (at least portions of) the PSDs of low-state XRBs; the doubly-broken power law model fit for NGC 3783 provides the closest match in PSD shape. Given that XRBs are, like Seyferts, accreting black hole systems, albeit at a lower mass (e.g., Cyg X-1: 10 $M_{\odot}$, Herraro et al. 1995), the similarity of PSD shapes suggests similar variability processes in low-state XRBs and Seyferts across 10^{6-7} in luminosity, mass and variability time scale.

1.2.2 Correlations between time scale, luminosity, and black hole mass

Figure 1.2 shows bolometric luminosity and black hole mass $M_{\rm BH}$ each plotted against PSD break time scale T. Black hole masses for our six targets are reverberation-mapped masses (e.g., from Kaspi et al. 2000). MCG–6-30-15 is included from Uttley, McHardy & Papadakis (2002). Though we are hampered by small-number statistics, there is an apparent significant correlation between $M_{\rm BH}$ and T, with the correlation coefficient $r = 0.79$ (corresponding to probability $P_r = 3.3 \times 10^{-2}$ for seven points.).

No such strong correlation is seen between bolometric luminosity and PSD break time scale ($r = 0.49$, corresponding to $P_r = 0.27$). This perhaps implies that black hole mass more closely governs the observed X-ray variability properties than does luminosity.

The apparent $M_{\rm BH}$–T scale correlation also supports the validity of the reverberation mapping method of black hole mass estimation. That is, it is encouraging to note that this agreement between X-ray variability time scale and reverberation mapping arises despite numerous caveats and assumptions in both analysis methods (e.g., the assumption of broad-line emission clouds being on Keplerian orbits, Peterson & Wandel 1999), each of which is expected to probe different regions of the central engine.

Along with the similarity of PSD shapes, the $M_{\rm BH}$–T correlation is consistent with a picture in which the Seyfert PSDs have a universal PSD shape (red-noise at high-frequencies, with flattening at low frequencies, similar to that of low-state XRBs) which moves towards lower temporal frequencies as the black hole mass increases.

The data are consistent with the linear relation $T = M_{\rm BH}/10^{6.5}\,M_{\odot}$. This relation can be extrapolated down to Cyg X-1's mass of $10\,M_{\odot}$, resulting in an inverse time scale that is remarkably closae to Cyg X-1's mean high-frequency PSD break of 3.3 Hz. This further argues for similar variability processes in Seyferts and XRBs, and suggests only a small departure from linearity of the $M_{\rm BH}$–T relation over 6–7 decades. If it is indeed the case that identical variability mechanisms exist in Seyferts and XRBs, then this presents a valuable constraint on models which attempt to explain the origin of the X-ray variability, as such models must now satisfy the linear $M_{\rm BH}$–T relation for both Seyferts and XRBs simultaneously.

References

Barr, P., & Mushotzky, R. 1986, Nature, 320, 421
Edelson, R., & Nandra, K. 1999, ApJ, 514, 682
Herrero, A., Kudritzki, R., Gabler, R., Vilchez, J., & Gabler, A. 1995, A&A, 297, 556
Kaspi, S., Smith, P., Netzer, H., Maoz, D., Jannuzi, B., & Giveon, U. 2000, ApJ, 533, 631
Lawrence, A., & Papadakis, I. 1993, ApJ, 414, L85
Markowitz, A., & Edelson, R., ApJ, 547, 684

Nandra, K., George, I. M., Mushotzky, R.F., Turner, T.J., & Yaqoob, T. 1997, ApJ, 476, 70
Nowak, M., Vaughan, B., Wilms, J., Dove, J., & Begelman, M. 1999a, ApJ, 510, 874
Nowak, M., Wilms, J., & Dove, J. 1999b, ApJ, 517, 355
Peterson, B., & Wandel, A. 1999, ApJ, 521, L95
Turner, T. J., George, I. M., Nandra, K., & Turcan, D. 1999, ApJ, 524, 667
Uttley, P., McHardy, I., & Papadakis, I. 2002, MNRAS, 332, 231