LOW-LUMINOSITY ACTIVE GALACTIC NUCLEI AS ANALOGS OF GALACTIC BLACK HOLES IN THE LOW/HARD STATE: EVIDENCE FROM X-RAY TIMING OF NGC 4258

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ABSTRACT

We present a broadband power spectral density function (PSD) measured from extensive RXTE monitoring data of the low-luminosity active galactic nucleus (LLAGN) NGC 4258, which has an accurate, maser-determined black hole mass of \( (3.9 \pm 0.1) \times 10^7 M_\odot \). We constrain the PSD break timescale to be greater than 4.5 days at >90% confidence, which appears to rule out the possibility that NGC 4258 is an analog of black hole X-ray binaries (BHXRBs) in the high/soft state. In this sense, the PSD of NGC 4258 is different from those of some more luminous Seyfert galaxies, which appear similar to the PSDs of high/soft state X-ray binaries. This result supports previous analogies between LLAGNs and X-ray binaries in the low/hard state based on spectral energy distributions, indicating that the AGN/BHXRB analogy is valid across a broad range of accretion rates.

Subject headings: galaxies: active — galaxies: individual (NGC 4258) — X-rays: galaxies

1. INTRODUCTION

The aperiodic X-ray variability in Seyfert active galactic nuclei (AGNs) has been well quantified over multiple timescales. Seyfert broadband fluctuation power spectral density functions (PSDs) show characteristic breaks at temporal frequencies corresponding to timescales of a few days or less (Uttley et al. 2002; Markowitz et al. 2003; M’Hardy et al. 2004). Markowitz et al. (2003) and M’Hardy et al. (2004) have shown that the PSD break timescales measured so far are consistent with scaling roughly linearly with black hole mass \( M_\text{BH} \). Remarkably, the mass-timescale relation is consistent with an extrapolation to stellar-mass black hole X-ray binaries (BHXRBs), and AGN and BHXRB broadband PSD shapes are similar, suggesting that a similar variability process is at work over at least 6 decades in black hole mass.

In BHXRBs, the PSD shape and characteristic break timescales are known to correlate with the X-ray spectral state, which is thought to depend on the global accretion rate relative to the Eddington rate, \( L/L_{\text{Edd}} \approx \sim 10^{-4} \); e.g., Lasota et al. (1996), using monitoring data obtained in 1997–2000 by the Rossi X-Ray Timing Explorer (RXTE). NGC 4258’s black hole mass of \( (3.9 \pm 0.1) \times 10^7 M_\odot \) is highly accurately measured via VLBI studies of its water megamaser (Miyoshi et al. 1995; Herrnstein et al. 1999), allowing us to make an accurate comparison with the PSD expected from both high/soft and low/hard accretion states.

2. OBSERVATIONS AND DATA REDUCTION

We constructed a high dynamic range PSD for NGC 4258 by combining monitoring on complementary timescales (e.g., Edelson & Nandra 1999). NGC 4258 was monitored regularly once every 2–3 days by RXTE from 1997 December 27 to 2000 March 1 (“long-term” monitoring). Each visit lasted ~1 ks. There was also intensive, simultaneous RXTE and ASCA monitoring during 2000 May 15–20, when the source was observed every orbit (“short-term” monitoring). For consistency we only use the short-term RXTE PCA data here, binned to 5760 s (i.e., single-orbit) intervals, but note that the 2–10 keV ASCA short-term light curve is consistent with the RXTE light curve. Data were obtained from RXTE’s proportional counter array (PCA), using standard extraction methods and selection criteria appropriate for faint sources (see Markowitz et al. 2003 for further details). Light curves were generated over the 2–10 keV bandpass. All count rates quoted herein are normalized to 1 proportional counter unit (PCU). The light curves are plotted in

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Figure 1. One can see that NGC 4258 displays minimal variability on short timescales; other observations (e.g., Pietsch & Read 2002) also show minimal variability on ≤1 day timescales. In contrast, there is strong variability on long timescales. The fractional variability amplitude $F_{\text{var}}$, as defined in e.g., Vaughan et al. (2003), is $4.2\% \pm 0.8\%$ and $27.9\% \pm 0.2\%$ for the short- and long-term light curves, respectively.\(^3\)

The 2–10 keV X-ray emission is dominated by the direct nuclear emission in this source (e.g., Fiore et al. 2001). Variability due solely to variations in the intrinsic column density is negligible, as the column density is not strongly variable, even on timescales of years (Risaliti et al. 2002). Furthermore, a plot of the binned 2–4 keV flux versus the 7–10 keV flux (which, for brevity, we do not show here) shows a continuous, virtually linear distribution of points, suggesting a lack of strong absorption events during the monitoring.

3. THE PSD OF NGC 4258

3.1. Constraints on PSD Break Timescale

We used the PSRESP Monte Carlo method of Uttley et al. (2002; see also Markowitz et al. 2003) to constrain the shape of the PSD. Monte Carlo simulations are required to take account of aliasing effects due to sparse and/or irregular sampling, which distorts the PSD shape. Furthermore, simulations are essential to properly determine confidence limits and the goodness of fit of models while using the full dynamic range of the PSD, since the lowest frequencies in the PSDs of the long- and short-term light curves are not well sampled enough to allow standard, Gaussian errors to be assigned to the PSD. The method is fully described in Uttley et al. (2002) and Markowitz et al. (2003), but see also M’Hardy et al. (2004).\(^4\) The long- and short-term PSDs spanned the temporal frequency ranges $2 \times 10^{-5} - 3 \times 10^{-7}$ and $4 \times 10^{-5} - 9 \times 10^{-7}$ Hz, respectively.

\(^3\) The errors on $F_{\text{var}}$ account for observational noise only, not intrinsic stochastic variability.

\(^4\) We note here that to improve the signal-to-noise ratio, the long-term light curve was binned up in 2 week intervals. Model fits were carried out using grids of PSD model parameter values, and at each point in the grid, 400 simulated light curves were generated for each light curve (long and short term), resampled to match the sampling of the observed light curves (and rebinned to 2 week bins in the case of the long-term simulated data), and 4000 combinations of the resulting simulated PSDs were used to estimate the goodness of fit for that set of model parameters.

The power due to Poisson noise over the 2–10 keV bandpass was 860 and 8.3 Hz\(^{-1}\) for the long- and short-term PSDs, respectively.

To constrain the location of any PSD break, we employed a broken power-law model of the form $P(f) = A(f/f_c)^{-\beta}$, $f \leq f_c$, and $P(f) = A(f/f_s)^{-\alpha}$, $f > f_s$, where the normalization $A$ is the PSD amplitude at the break frequency $f_c$, and $\beta$ is the high-frequency power-law slope, with the constraint $\beta > 1$. This simple model provides a good description of the PSDs of Seyfert galaxies measured so far, with PSD breaks detected in nine of those AGNs. The range of $\beta$ tested was 1.0–2.3 in increments of 0.1. Break frequencies were tested from $10^{-8}$ to $10^{-5}$ Hz, in multiplicative steps of 1.5. The best-fitting model is one with a break at $2.25 \times 10^{-8}$ Hz, although an unbroken power law is also formally acceptable (i.e., the break frequency could lie out of the observed range). The best-fitting $\beta = 2.3, A = (3.3 \pm 0.3) \times 10^6$ Hz\(^{-1}\), and the “rejection probability” (corresponding to the fraction of simulated PSD sets that are a better fit to the assumed model than the real data) is 0.43; i.e., the model is formally acceptable. Contour plots showing the rejection probabilities for a given $\beta$ and $f_c$ are shown in Figure 2. On the contour plot we also show the expected break frequencies assuming linear scaling with mass from typical values of the break timescale in the low/hard and high/soft states of the BHXB Cyg X-1 (assuming a $10 M_\odot$ black hole in Cyg X-1 [e.g., Herrero et al. 1995] and the well-determined maser mass of $(3.9 \pm 0.1) \times 10^7 M_\odot$ in NGC 4258). The high/soft state break frequency (corresponding to 4.5 days) is ruled out at >90% confidence, while the low/hard state break (∼45 days) is acceptable at this level of confidence.

Fiore et al. (2001) report a 1998 December BeppoSAX 3–10 keV light curve of NGC 4258 that shows almost a factor 2 change in flux in 1 day. This behavior is atypical of the source, which shows much smaller variations on timescales of a few days in both the RXTE long-term monitoring and the much more intensive monitoring. We investigated whether or not this relatively large variation in the BeppoSAX observation was consistent with the PSD derived from RXTE monitoring, by including the BeppoSAX light curve (obtained directly from the public archive) in our fits. We find that the rejection probability for the broken power-law PSD is increased to 0.77 but...
that the overall confidence contours for \( f \) and \( \beta \) are only made marginally wider. We conclude that the BeppoSAX light curve is consistent with the RXTE PSD and simply represents a statistical outlier in the stochastic variability process.

3.2. Comparison with Other AGNs

The PSD of the LLAGN NGC 4258 does indeed appear to be better explained by scaling from a low/hard state PSD than from a high/soft state PSD, unlike the PSDs of some of the Seyfert galaxies measured so far that rule out a low/hard state interpretation and are consistent with a high/soft state interpretation (e.g., NGC 4051, MCG 6-30-15: M’Hardy et al. 2004, 2005; NGC 3227: Uttley & M’Hardy 2005). To demonstrate this difference in the PSDs, we show in Figure 3 a relatively model-independent comparison between the PSD of NGC 4258 and that of a normal Seyfert galaxy with nearly identical black hole mass, NGC 3516 \( (M_{\text{BH}} = (4.3 \pm 1.5) \times 10^7 M_\odot; \text{Peterson et al.} 2004) \), together with the PSDs of Cyg X-1 in low/hard and high/soft states for further comparison. NGC 3516’s accretion rate is likely \( \sim \)5% of the Eddington rate, given its 2–10 keV luminosity of \( 10^{40} \) ergs s\(^{-1} \) and assuming the X-ray–to–bolometric luminosity scaling of Padovani & Ranalli (1988). Within the errors, the PSD break timescale of NGC 3516 is more consistent with linearly scaling from the high-frequency break of Cyg X-1 in the high/soft state, although scaling from the low/hard state cannot be ruled out. From the figure, although its amplitude at low frequencies is similar to that of NGC 3516, NGC 4258’s PSD is consistent with being shifted downward in temporal frequency by a factor of \( \sim \)100 relative to NGC 3516’s PSD. Given the similarity in black hole mass between the two objects and the overlapping temporal-frequency range of the PSDs, the fact that a PSD break was unambiguously detected in the PSD of NGC 3516 but not in that of NGC 4258 reinforces this notion. Furthermore, the fact that NGC 4258 shows similar levels of long-timescale variability to normal Seyfert galaxies of comparable mass \( (F_{\text{Edd}} \sim 30\% ; \text{Markowitz & Edelson} 2004) \) rules out the possibility that the normalization of NGC 4258’s PSD is significantly lower than that for normal Seyfert galaxies. The PSDs are thus consistent with the notion that for a given mass, a PSD shifted toward relatively lower temporal frequencies is associated with a lower accretion rate. NGC 4258 and, by extension, other LLAGNs may thus be low accretion rate versions of normal Seyfert galaxies, as far as X-ray continuum variability is concerned.

4. DISCUSSION AND CONCLUSIONS

We have shown that the PSD of NGC 4258 is consistent with having the same shape and normalization as the PSDs of more luminous Seyfert galaxies, but with a break on longer timescales than expected by scaling from the high/soft state of Cyg X-1, unlike a Seyfert galaxy with similar mass, NGC 3516. From a purely phenomenological point of view, this result may help to explain the differences in short-term (\(<1\) day) variability amplitude between LLAGNs and Seyfert galaxies reported by Ptak et al. (1998), who showed that LLAGNs do not follow the well-known anticorrelation between X-ray luminosity and short-term variability amplitude that is shown by normal Seyfert galaxies (e.g., Nandra et al. 1997) but instead populate the low-luminosity, low-variability part of the variance-luminosity diagram. NGC 4258 also shows a very low variability amplitude on short timescales, and our PSD suggests that this is due to a long break timescale in this AGN, rather than a low overall normalization of the PSD. The same might also be true of other LLAGNs.

The comparison with break timescale expected from the mass scaling of the timescales from Cyg X-1 and the comparison with the PSD of NGC 3516 both suggest that the break timescale in NGC 4258 is intrinsically longer (given its mass) than in more luminous AGNs. This difference may reflect the low accretion rate in NGC 4258. NGC 4258 appears to be consistent with scaling from the low/hard state PSD of Cyg X-1, although it is possible that the break timescale is even longer than that scaling would suggest. An analogy with other BHXRBs that display a larger range of \( L/L_{\text{Edd}} \) than Cyg X-1 supports this possibility. For example, in the outburst decays of transient BHXRB candidates, after the transition from the high/soft spectral state to the low/hard spectral state, there is evidence that PSD timescales, particularly quasi-periodic oscillations, continue to migrate toward lower frequencies as the luminosity and accretion rate of the source decrease and as the source approaches quiescence (van der Klis 2005; Kalemci et al. 2004; Rodriguez et al. 2004; Nowak et al. 2002).

Despite the consistency with BHXRB behavior, it is still not clear whether the dependency of the mass-timescale relation on the AGN accretion rate is a continuous scaling or whether it exists in the form of a high versus low accretion rate dichotomy akin to that seen in BHXRBs. However, there are differences in the observed energy-spectral features of LLAGNs and normal Seyfert galaxies that are suggestive of differing accretion modes in the two classes of objects. Specifically, LLAGNs are more radio-loud compared to normal Seyfert galaxies, and the so-called optical/UV big blue bump in normal Seyfert galaxies, inferred to be thermal accretion disk emission, is absent in LLAGNs (Ho 1999). Similar discrepancies arise when comparing the spectral energy distributions of low/hard and high/soft state BHXRBs (although, in this case, due to the much smaller, hotter disks of BHXRBs, the thermal emission appears in the X-ray band). Nagar et al. (2005) have suggested that both LLAGNs and low/hard state BHXRBs are low-efficiency accreting sources, as both classes of objects are often associated.
with strong radio jet emission and low levels of thermal disk emission. Higher efficiency accreting sources, namely, normal Seyfert galaxies and high/soft state BHXRBs, meanwhile, usually lack strong radio emission but have a strong disk signature, with the supermassive systems also having gas-rich nuclei. Additionally, a fundamental plane between $M_{\text{BH}}$ and X-ray and radio luminosities is seen in both stellar-mass and supermassive systems (Merloni et al. 2003; Falcke et al. 2004). However, this relation breaks down for high-state objects; radio power is reduced, e.g., for high/soft state BHXRBs and normal Seyfert galaxies (Gallo et al. 2003; Maccarone et al. 2003), further supporting the notion of a similar dichotomy of states for both AGNs and BHXRBs. Finally, based on the distributions of $M_{\text{BH}}$ and bolometric luminosities, Jester (2005) has suggested that in AGNs, there is tentative evidence for the existence of a critical accretion rate, $L/L_{\text{Edd}} \sim 0.01$, which separates high- and low-efficiency accretion modes. The number of low-efficiency accreting sources in that sample was small, but all were LLAGNs.

For LLAGNs and low/hard state BHXRBs, the longer variability timescales for a given mass, the reduced emission from the optically thick, radiatively efficient disk, and the relative weakness of Fe Kα emission (e.g., Pietsch & Read 2002; Gilfanov et al. 1999) are all consistent with the suggestion that the inner accretion disk is truncated, possibly existing at smaller radii as an optically thin, radiatively efficient disk, and the relative weakness of Fe Kα emission (e.g., Pietsch & Read 2002; Gilfanov et al. 1999). ADAF models have frequently been invoked to explain the spectral energy distributions in NGC 4258 and other LLAGNs (e.g., Yuan et al. 2002). As one example, one popular geometrical model for the accretion configuration is the so-called sphere + disk model of Dove et al. (1997) and Esin et al. (1997). This model features a geometrically thick, sometimes spherical, ADAF flow, at the innermost radii, surrounded by a radiatively efficient, geometrically thin disk. The transition radius between the ADAF and the thin disk appears at relatively larger radii for lower accretion rates. Also, considerations of how an ADAF/coronal accretion flow can form from the evaporation of the optically thick disk have suggested that the inner disk may evaporate completely into an optically thin flow if the accretion rate transitions from above to below a critical accretion rate (Różańska & Czerny 2000; Meyer-Hofmeister & Meyer 2003 and references therein). Further progress in this area can be made by firmly establishing whether or not such a critical accretion rate exists in AGNs and whether it is indeed responsible for the dominance of high- or low-efficiency accretion modes as a function of accretion rate. Measuring PSD breaks for a larger number of AGNs, including LLAGNs, is also necessary to critically test the dependence of the mass-timescale relation on accretion rate. Clarification of these issues in AGNs as well as in BHXRBs will help us to unify the behavior of stellar-mass and supermassive accreting black holes.

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