THE X-RAY POWER SPECTRAL DENSITY FUNCTION AND BLACK HOLE MASS ESTIMATE FOR THE SEYFERT ACTIVE GALACTIC NUCLEUS IC 4329a

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ABSTRACT

We present the X-ray broadband power spectral density function (PSD) of the X-ray-luminous Seyfert IC 4329a, constructed from light curves obtained via Rossi X-ray Timing Explorer monitoring and an XMM-Newton observation. Modeling the 3–10 keV PSD using a broken power-law PSD shape, a break in power-law slope is significantly detected at a temporal frequency of $2.5^{+2.5}_{-1.7} \times 10^{-6}$ Hz, which corresponds to a PSD break timescale $T_b$ of 4.6$^{+1.0}_{-2.3}$ days. Using the relation between $T_b$, black hole mass $M_{BH}$, and bolometric luminosity as quantified by McHardy and coworkers, we infer a black hole mass estimate of $M_{BH} = 1.3^{+1.0}_{-0.3} \times 10^6 M_\odot$ and an accretion rate relative to Eddington of 0.21$^{+0.06}_{-0.10}$ for this source. Our estimate of $M_{BH}$ is consistent with other estimates, including that derived by the relation between $M_{BH}$ and stellar velocity dispersion. We also present PSDs for the 10–20 and 20–40 keV bands; they lack sufficient temporal frequency coverage to reveal a significant break, but are consistent with the same PSD shape and break frequency as in the 3–10 keV band.

Key words: galaxies: active – galaxies: individual (IC 4329a) – galaxies: Seyfert – X-rays: galaxies

Online-only material: color figures

1. INTRODUCTION

The rapidly variable, aperiodic X-ray continuum emission from Seyfert AGNs has long supported the notion that the X-ray emission originates from within a few tens of Schwarzschild radii of the central supermassive black hole. In the late 1980s, EXOSAT probed X-ray variability on timescales of a few days or less, yielding power spectral density functions (PSDs) covering temporal frequencies down to $10^{-5}$ Hz. These PSDs established the scale-invariant “red-noise” nature, i.e., larger variability amplitudes toward larger timescales, characterized by a PSD which increases toward lower temporal frequencies. However, no characteristic timescale, such as a “break” in the PSD power-law slope, was detected (e.g., Lawrence et al. 1987; McHardy & Czerny 1987; Green et al. 1993).

The Rossi X-ray Timing Explorer (RXTE) was launched in 1995; its unique attributes (large effective area, high throughput, fast slewing, and flexible scheduling) permitted multi-timescale monitoring campaigns that probed X-ray variability on timescales from hours to years (temporal frequencies from $10^{-4}$ to $10^{-8}$ Hz). The resulting Seyfert broadband PSDs yielded evidence for breaks at temporal frequencies $f_b$ and PSD power-law slopes breaking from $\sim 2$ to $\sim 1$ above and below $f_b$, respectively; the break frequencies corresponded to break timescales $T_b$ of a few days or less (e.g., Edelson & Nandra 1999; Pounds et al. 2001; Uttley et al. 2002 (hereafter U02); Markowitz et al. 2003b (hereafter M03); Papadakis et al. 2003; McHardy et al. 2004, 2005; Uttley & McHardy 2005).

It was noted by M03 that a small sample of Seyfert PSDs was consistent with a relation between $T_b$ and black hole mass $M_{BH}$ estimated via reverberation mapping, in the sense that relatively larger-mass black holes are associated with PSDs with larger values of $T_b$, albeit with some scatter. Using a larger sample, McHardy et al. (2006) demonstrated that the scatter could be explained by an additional dependence of $T_b$ on $L_{bol}/L_{Edd}$, the accretion rate relative to Eddington, in that for a given $M_{BH}$, sources accreting at relatively higher rates have PSDs shifted toward higher $f_b$ (smaller values of $T_b$). In the absence of an accurate estimate of $M_{BH}$ by other means, X-ray timing can thus be used to estimate $M_{BH}$, if $T_b$ and bolometric luminosity $L_{bol}$ are both known.

In this paper, we present the broadband 3–10 keV PSD of IC 4329a, an X-ray bright and variable Seyfert located at a redshift of $z = 0.01605$ (Willmer et al. 1991). IC 4329a had been monitored in the optical with the intent of using reverberation mapping to estimate $M_{BH}$ in this object, but the constraints were quite poor (Winge et al. 1996; Peterson et al. 2004). Here, we demonstrate that there is significant evidence for a break in the X-ray PSD of IC 4329a. We also present PSDs for the 3–5, 5–10, 10–20, and 20–40 keV bands. Section 2 reviews the multi-timescale sampling strategy and describes the observations, data reduction, and light curve sampling. Section 3 describes the methods of measurement and modeling of the PSDs. The results of model fits to the PSDs are presented in Section 4. In Section 5, the PSD break frequency is used to yield an estimate of $M_{BH}$ based on X-ray timing, which we compare to estimates obtained by various other methods.

2. OBSERVING STRATEGY, OBSERVATIONS, AND DATA REDUCTION

We followed the observing strategy of Edelson & Nandra (1999), U02, M03, etc., in which a source is monitored with even, regular sampling on multiple timescales such that the resulting set of light curves yields individual PSDs covering complementary temporal frequency ranges. With the reasonable assumption that the underlying PSD shape has remained constant throughout all the monitoring observations, the individual PSDs are combined to produce the final broadband PSD. IC 4329a was monitored with RXTE once every 4.26 days (64 orbits) for a duration of 4.3 years, from 2003 April 8 to 2009 April 9.

1 The X-ray PSDs of black hole X-ray binaries are observed to vary (display strong non-stationarity) on timescales of hours to days and longer. Scaling with $M_{BH}$ and/or X-ray luminosity, we expect significant changes in the shapes of AGN PSDs only on timescales of centuries to millennia.
2007 August 7 (Modified Julian Day (MJD) 52737–54319; observation identifiers 80152-03-* , 90154-01-* , 91138-01-*, and 92108-01-*). This sampling, which probes variability on timescales from ~ a week to a few years, is henceforth called “long-term” sampling. Each observation lasted approximately 1 ks. There were four gaps due to sun-angle constraints in October–November of each year; each gap was ~50 days long. More intensive monitoring with RXTE was done to probe variability on timescales from several hours to a month (“medium-term” sampling). RXTE observed IC 4329a once every ~17.1 ks (three orbits) for a duration of 34.1 days, from 2003 July 10 at 18:05 UT to 2003 August 13 at 20:35 UT (MJD 52830.75–52864.86; observation identifiers 80152-04-*). Again, each visit lasted ~1 ks. Finally, a continuous, 133 ks observation of IC 4329a with XMM-Newton (Section 2.3) allowed us to probe variability on timescales from ~ an hour to 1 day.

2.1. PCA Data Reduction

The Proportional Counter Array (PCA; Swank 1998) consists of five large-area, collimated proportional counter units (PCUs). Reduction of the PCA data followed standard extraction and screening procedures, using HEASOFT version 6.5.1 software. PCA STANDARD-2 data were collected from PCU 2 only; PCUs 1, 3 and 4 have been known to suffer from repeated breakdown during on-source time, and PCU 0 lost its propane veto layer in 2000. Data were rejected if they were gathered at less than 10° from the Earth’s limb, within 30 minutes of satellite passage through the South Atlantic Anomaly (SAA), if the satellite’s pointing offset was greater than 0.2, or if ELECTRON2 was >–0.1. As the PCA is a non-imaging instrument, the background was estimated using the “L7-240” background models, appropriate for faint sources; see e.g., Markowitz et al. (2003a) and Edelson & Nandra (1999) for details on PCA background subtraction, the dominant source of systematic uncertainty (e.g., in total broadband count rate) in these data. Spectral fitting for each observation was done using XSPEC version 11.3.2ag, assuming a Galactic column of 4.6 × 10^20 cm^-2 (Kalberla et al. 2005). As the response of the PCA slowly hardens slightly over time due to the gradual leak of xenon gas into the propane layer in each PCU,2 response files were generated for each separate observation. Fluxed light curves were extracted in the 3–10 keV band by fitting a power law to that band only (2–10 keV is a “standard” hard X-ray measurement band, but the 2–3 keV effective area of the PCA is extremely small, so we use 3–10 keV here). Light curves for the 3–5 and 5–10 keV sub-bands and the 10–20 keV band were also extracted. Errors on each light curve point were derived from the standard error of 16 s count rate light curve bins within each observation. The total number of data points after screening was 372 points for each long-term light curve, with 14.5% of the data missing due to, e.g., sun-angle constraints or screening. Each medium-term light curve contained 173 points, with only 4.1% of the data missing. The 3–10 keV light curves are plotted in Figure 1.

We also extracted 20–40 keV PCA light curves, as it would have been desirable to have PCA data simultaneous with the 20–40 keV High-Energy X-Ray Timing Experiment (HEXTE) light curves (see below), but in this band, the source was only ~7% of the total PCA background; ±2% systematic uncertainties in

The PCA background on timescales of ~1–2 ks (Jahoda et al. 2006, Figure 29) yield uncertainties of ~ ±30% uncertainties in the net source count rate, and so we do not consider the PCA above 20 keV.

2.2. HEXTE Data Reduction

The HEXTE aboard RXTE consists of two independent clusters (A and B), each containing four NaI(Tl)/CsI(Na) phoswich scintillation counters (see Rothschild et al. 1998) which share a common 1° FWHM field of view. Each of the eight detectors has a net open area of about 200 cm2. Source and background spectra were extracted from each individual RXTE visit using Science Event data and standard extraction procedures. The same good time intervals used for the PCA data (e.g., Earth elevation and SAA passage screening) were applied to the HEXTE data. To measure real-time background measurements, the two HEXTE clusters each undergo two-sided rocking to offset positions, in this case, to 1.5 off-source, switching every 32 s. There is a galaxy cluster (Abell 3571, located at a redshift of z = 0.039) located about 2° south of IC 4329a, at R.A. = 13°47.50°, decl. = −32°52′. This source is detected in the RXTE all-sky surve-

SXS; Revnivtsev et al. 2004), which shows the 8–20 keV flux of this source to be about half that of IC 4329a (at 2° off-axis, the count rate in the PCA is negligible, and thus the effect of contamination from Abell 3571 on PCA light curves and PSDs is negligible; Jahoda et al. 2006). However, BeppoSAX–PDS observations have shown no detection of Abell 3571 above 15 keV (Nevalainen et al. 2004). The 8–20 keV emission seen by the XSS must therefore be emission only between 8 and ≤15 keV, and in this paper we use the 20–40 keV band, so the presence of A3571 can be safely ignored as far as contaminating HEXTE background data obtained within ~1–2° of the center of A3571 is concerned. Cluster A data taken during the following times were excluded, as the cluster did not rock on/off-source: 2004 December 13–2005 January 14, 2005 De-

cember 12–2006 January 4, during 2006 January 25, and after 2006 March 14. Detector 2 aboard cluster B lost spectral capabilities in 1996; these data were excluded. Light curves were extracted in 16 s bins in the 20–40 keV band. Dead-time corrections were applied to account for cluster rocking, pulse analyzer electronics, and the recovery time following scintillation pulses caused by high-energy charged particles; typically, the HEXTE dead-time is ~30%–40%. The light curves were then binned to every 12.79 days (long-term) or 50.2 ks (medium-term). This action minimized variability associated with background systematics. The HEXTE background is relatively stable over long timescales but rapidly variable within a single satellite orbit as the spacecraft moves in the geomagnetic environment. For a typical background rate, the Poisson error in a ~600 s good time exposure is ≥1% (Gruber et al. 1996). In the case of IC 4329a, the net source flux is roughly 9% of the total background in the 20–40 keV band, and each observation was only 1 ks in duration, yielding a ~10% systematic uncertainty in the net source count rate. In addition, there are likely sys-

tematic uncertainties associated with the dead-time correction, ≤0.5% in a 1 ks duration observation.3 Errors on each point were determined by the standard error of the 16 s points. For observations using both clusters, light curves from clusters A and B were added; all light curves are in units of counts s^{-1} detector^{-1} (that is, counts s^{-1} per 7 detectors when both clusters were in operation, or per 3 detectors when only cluster

2 In two previous papers, Markowitz et al. (2006, 2009), the cause of the evolution in response was incorrectly listed as propane leaking into the xenon layers.

3 See http://hnamasc.ucsd.edu/hexte/status/hexte_deadtime.html.
B was operating normally; there were no observations where cluster A was the only cluster operating normally). The long-term light curve had 125 points, with 13 points (10.4%) missing; the medium-term light curve had 60 points, with no points missing.

The 20–40 keV light curves are plotted in Figure 1. The HEXTE gain and response are both very stable over timescales of years, permitting us to work in units of count rates. However, the HEXTE light curves, plotted in Figure 1, have had count rates converted to fluxes for consistency with the way the PCA light curves are plotted; we use a conversion rate of 1 counts s$^{-1}$ per HEXTE detector in 20–40 keV corresponding to $2.6 \times 10^{-10}$ erg cm$^{-2}$ s$^{-1}$ for a source with a photon index of 1.7. Visually, there appears to be some mild variability in the 20–40 keV light curves not present in the 3–10 keV light curve, likely from the aforementioned systematic uncertainties associated with background subtraction and dead-time correction. However, we note that the overall shape of the resulting long- and medium-term combined PSD (see Section 4) is roughly consistent with that obtained for the 10–20 keV band at the temporal frequencies probed, and we are confident that the systematic effects associated with HEXTE background subtraction and dead-time correction do not significantly affect our conclusions for the 20–40 keV PSD.

2.3. XMM-Newton Data Reduction

XMM-Newton observed the nucleus of IC 4329a during 2003 August 6–7 (observation identifier 0147440101), for a duration of 136 ks. In this paper, we only consider data collected using the European Photon Imaging Camera (EPIC) pn camera. Light curves were extracted using XMM Science Analysis Software version 7.1.0, XSELECT version 2.4a, and the latest calibration files. Source photons were extracted from a circular region of radius 40′′; backgrounds were extracted from circles of identical size, centered ∼3′ away from the core. Hot, flickering, or bad pixels were excluded. We inspected the 10–13 keV pn background light curve for flares, and excluded periods when the 10–13 keV background rate exceeded 0.1 counts s$^{-1}$. We extracted a light curve in the 3–10 keV band binned to 2000 s; variability at shorter timescales was dominated by Poisson noise. The light curve had 67 points, with 3 points, or 4.5%, missing due to the above background screening. It is plotted in Figure 1. Light curves for the 3–5 and 5–10 keV sub-bands were also extracted, binned to 5000 s (27 points).

3. PSD MEASUREMENT

Light curve sampling parameters, including mean net source and background count rates, for all light curves are listed in Table 1.
medium- and short-term sampling. As in Section 2. Table 2 lists PSD measurement parameters. The curve, it is not immediately obvious how much variability is consistent with this trend (in the case of the 20–40 keV light described in Section 3.1. However, as described in Section 3.2, coverage above 12 keV, there is no short-term sampling to accommodate three periodogram points. The 3–5 lowest temporal frequency bins were widened to accommodate three periodogram points. The ~5 lowest-temporal frequency bins in each individual PSD typically contained <15 periodogram points, precluding us from assigning normal errors.

The individual long-, medium-, and short-term PSDs were combined to yield the final, broadband observed PSDs \( P(f) \), which are plotted in Figure 2, as well as in the top panels of Figures 3–5 in \( f \times P_f \) space. No renormalization of the individual PSDs was done. The constant level of power due to Poisson noise was not subtracted from these PSDs, but instead modeled in the Monte Carlo analysis below.

### 3.2. Monte Carlo Simulations

Visual inspection of Figure 2 supports, at first glance, the notion that all five PSDs are at least roughly consistent in broadband shape. However, to account for PSD measurement effects (the reader is referred to U02 and M03 for descriptions of aliasing and red-noise leak, and how the method accounts for them) and to assign proper errors, we use a version of the Monte Carlo technique “PSRESP” introduced by U02.
We summarize this technique as follows: one first assumes an underlying broadband model PSD shape, and, for each individual observed light curve sampling pattern, one uses the algorithm of Timmer & König (1995) to generate a given temporal frequency bin. The constant level of power due to Poisson noise is calculated. The best-fitting renormalization of the observed PSD, using poorly determined errors from the observed PSD, is achieved by renormalizing the average PSD, respectively. Filled diamonds denote PSDs derived from long-, medium-, and short-term monitoring, respectively.

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

Figure 2. Observed PSDs for the 3–10 (black), 3–5 (red), 5–10 (blue), 10– 20 (green), and 20–40 keV (orange) PSDs. Filled circles, open squares, and filled diamonds denote PSDs derived from long-, medium-, and short-term monitoring, respectively.

Table 3

| Bandpass (keV) | $\alpha$ | $A_0$ (Hz$^{-1}$) | $L_{\text{unbr}}$ (%) |
|---------------|----------|-------------------|----------------------|
| 3–10          | $1.7^{+0.4}_{-0.3}$ | $2.5 \pm 0.5 \times 10^3$ | 2.2 |
| 3–5           | $1.5^{+0.4}_{-0.3}$ | $3.0^{+0.4}_{-0.3} \times 10^3$ | 9.4 |
| 5–10          | $1.3^{+0.5}_{-0.2}$ | $2.3^{+0.3}_{-0.2} \times 10^3$ | 4.0 |
| 10–20         | $1.2 \pm 0.2$ | $2.1 \pm 0.2 \times 10^3$ | 17.5 |
| 20–40         | $1.1 \pm 0.3$ | $5.5^{+0.9}_{-0.8} \times 10^3$ | 22.3 |

Notes. Results from fitting the PSDs with unbroken power-law model. $A_0$ is the amplitude at $f = 10^{-6}$ Hz. $L_{\text{unbr}}$ is the likelihood of acceptance for this model, defined as one minus the rejection probability.

4. PSD FIT RESULTS

We tested PSD model shapes consisting of simple unbroken power-law models and singly broken power-law models; the quality of each PSD precludes more complex shapes such as single or multiple Lorentzian components or quasi-periodic oscillations routinely modeled in the PSDs of X-ray binary systems.

The unbroken power-law model was of the form $P(f) = A_0 (f/f_0)^{-\alpha}$, where $\alpha$ is the power-law slope and the normalization $A_0$ is the PSD amplitude at $f_0$, arbitrary chosen to be $10^{-6}$ Hz. $P_{\text{obs}}$ is added to each simulated PSD but is not explicitly listed here since $P_{\text{obs}}$ is different for each PSD segment. The model was tested by stepping through $\alpha$ from 0.0 to 3.2 in increments of 0.1, each time with $N_{\text{trial}} = 300$ simulations done to calculate $P_{\text{sim}}(f)$. The best-fitting models are plotted in the second panels of Figures 3–5. The best-fitting values of $\alpha$, $A_0$, and likelihood of acceptance $L_{\text{unbr}}$ are listed in Table 3. The errors on $\alpha$ correspond to values $\sigma$ above the rejection probability $L_{\text{unbr}}$ for the best-fit value on a Gaussian probability distribution; for example, if the best-fit model had $R_{\text{unbr}} = 95.45\%$ (2.0$\sigma$ on a Gaussian probability distribution), errors correspond to $R_{\text{unbr}} = 99.73\%$ (3.0$\sigma$). The errors on $A_0$ were determined from the rms spread of the $10^4$ randomly selected sets of simulated PSDs.

The high rejection probabilities for the 3–10, 3–5, and 5–10 keV PSDs (each $>90\%$) and the residuals plotted in Figures 3(b) and 4(b) suggest that a more complex PSD model shape may be appropriate for these three PSDs. The 10–20 keV and 20–40 keV PSDs cover less dynamic range in temporal frequency than their $<10$ keV counterparts due to the lack of short-term sampling; the rejection probabilities are consequently much lower, $<90\%$, along with smaller residuals (Figure 5(b)).

To test for the presence of breaks in the PSD, we then tested a singly broken PSD model shape of the form

$$P(f) = \begin{cases} A_1 (f/f_b)^{-\alpha_0}, & f \leq f_b \\ A_1 (f/f_b)^{-\alpha_1}, & f > f_b \end{cases},$$

where the normalization $A_1$ is the PSD amplitude at the break frequency $f_b$, and $\alpha_0$ and $\alpha_1$ are the low- and high-frequency power-law slopes, respectively, with the constraint $\alpha_0 < \alpha_1$. (We also tested a more slowly bending PSD model of the form $P(f) = (A_1 f^{-\alpha_0}) (1 + f/f_b)^{\alpha_0}$, but given the PSD quality, there were degeneracies between $f_b$, $\alpha_0$, and $\alpha_1$ such that reasonable constraints on $f_b$ could not be attained.) The range of slopes tested was 0.0–3.2 in increments of 0.1. Break frequencies were tested in the log from –7.4 to –4.9 in increments of 0.1, corresponding to $f \to 1.26 f$ in the linear

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Figure 3. Top panel shows the observed 3–10 keV PSD, plotted in $f \times P(f)$ space to visually emphasize the turnover. Filled circles, open squares, and filled diamonds denote PSDs derived from long-, medium-, and short-term monitoring, respectively. The solid line denotes the best-fit singly broken power-law model folded through the sampling window (i.e., containing the distortion effects of PSD measurement and power due to Poisson noise). The middle and bottom panels show the residuals to the best-fit unbroken and broken power-law models, respectively.

One hundred simulated PSDs were used to determine $P_{\text{sim}}(f)$. The best-fit model parameters, along with likelihoods of acceptance $L_{\text{brkn}}$, are listed in Table 4; residuals are plotted in the bottom panels of Figures 3 and 4 for the 3–10, 3–5, and 5–10 keV PSDs. Figure 6 shows contour plots of $\alpha_{\text{hi}}$ versus $f_b$ for these three PSDs at the respective best-fit values of $\alpha_{\text{lo}}$. We use the ratio of the likelihoods of acceptance $L_{\text{brkn}}/L_{\text{unbr}}$ between the broken and unbroken power-law model fits to establish if a break is significant (we use $L_{\text{brkn}}/L_{\text{unbr}}$ at least $\sim 10$). For the 3–10 keV PSD, we conclude that a break is significantly detected at $f_b = 10^{-5.6(\pm 0.5, -0.3)}$ Hz = $2.51^{+2.30}_{-1.75} \times 10^{-6}$ Hz, which corresponds to a timescale of $4.6^{+10}_{-2.1}$ days. Breaks are also significantly detected in each 3–5 and 5–10 keV sub-band PSD, with best values of $f_b$ also near $10^{-6}$ Hz. Because of the limited dynamic range in temporal frequency for the 10–20 and 20–40 keV PSDs, the improvement in fit when adding a break to the model is not high, with $L_{\text{brkn}}/L_{\text{unbr}} \sim 2$–3. Parameters for the broken power-law model are thus listed in parentheses in Table 4 for these two PSDs and data/model residuals are not plotted.

We next explored the possibility that all five PSDs could be consistent with the same PSD shape, namely that of the 3–10 keV PSD, with a low-frequency power-law slope equal to $-1.0$, a high frequency slope near $-2$, and a break frequency $\sim 1–2 \times 10^{-6}$ Hz. We re-tested the 3–5 and 5–10 keV PSDs with a broken power-law model, keeping $\alpha_{\text{lo}}$ fixed at 1.0. Acceptable fits were obtained, with best-fit values for $f_b$ and $\alpha_{\text{hi}}$, consistent with those measured for the 3–10 keV PSD; results are listed.
in Table 4. The 10–20 and 20–40 keV PSDs only cover up to roughly 10\(^{-5}\)–10\(^{-4}\) Hz, and there is not much “leverage” above \(\sim 10^{-5.5}\)–10\(^{-4}\) Hz to either confirm or refute the presence of a break at those temporal frequencies. However, the best-fit power-law slopes in the unbroken power-law fits are flat, 1.1–1.2 (compared to 1.5–1.7 for the <10 keV PSDs, which extend up to roughly 10\(^{-4}\) Hz, well above the best-fit 3–10 keV PSD break frequency). We conclude that the 10–20 and 20–40 keV PSDs are at least roughly consistent with the presence of breaks at or near that found in the <10 keV PSDs, and with the same \(\alpha_{0}\), and that the >10 keV PSDs probe temporal frequencies primarily below the break frequency.

5. DISCUSSION AND CONCLUSIONS

5.1. A New Black Hole Mass Estimate for IC 4329a from X-ray Timing

We have used complementary RXTE and XMM-Newton monitoring of the X-ray bright Seyfert AGN IC 4329a to measure the 3–10 keV PSD, and we find significant evidence for a break in the modeled power-law slope at a temporal frequency of 2.5\(^{+2.5}_{-1.7}\) \times 10\(^{-6}\) Hz, which corresponds to a break timescale \(T_b\) of 4.6\(^{+10}\)\(^{-2.3}\) days. Best-fit power-law slopes above and below the break are \(\alpha_{0} = 2.3^{+0.8}_{-0.4}\) and \(\alpha_{0} = 1.0^{+0.4}_{-0.3}\), respectively. For a discussion of candidate physical mechanisms to explain the turnover, the reader is referred to, e.g., Edelson & Nandra (1999) and Arévalo & Uttley (2006).

We can derive a new estimate for \(M_{\text{BH}}\) from the PSD break, using the empirical relation between \(T_b\), bolometric luminosity \(L_{\text{bol}}\), and \(M_{\text{BH}}\) quantified by McHardy et al. (2006), \(L_{\text{bol}}(\text{days}) = 2.1 \log(M_{\text{BH}}/10^{7} M_{\odot}) - 0.98 \log(L_{\text{bol}}/10^{44} \text{ erg s}^{-1}) - 2.32\). The average absorbed 3–10 keV flux from the long-term PCA monitoring is 11.18 \times 10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1}. To find the unabsorbed flux, we used a spectral model in XSPEC consisting of a power law with photon index 1.74 (Markowitz et al. 2006), absorbed by the Galactic column, and five layers of absorption modeled by Steenbrugge et al. (2005): a column of cold gas intrinsic to the host galaxy with column density \(N_{\text{H}} = 1.7 \times 10^{21} \text{ cm}^{-2}\), and four ionized absorbers, with column densities 1.3, 0.32, 6, and 2 \times 10^{21} \text{ cm}^{-2}\) and ionization parameters \(\log \xi = -1.37, 0.56, 1.92,\) and 2.70 erg cm s\(^{-1}\), respectively.\(^4\) (A fifth ionized absorber quantified by Markowitz et al. 2006, with best-fit modeled values of \(\log \xi = 3.73\) erg cm s\(^{-1}\) and \(N_{\text{H}} = 1.4 \times 10^{22} \text{ cm}^{-2}\), is expected to produce only a narrow Fe K absorption feature and is ignored.) To model each ionized absorber, an XSTAR component was used (Bautista & Kallman 2001). Using this model, a luminosity distance of 78.6 Mpc (Mould et al. 2000), and assuming a cosmology with \(H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}\) and \(\Omega_0 = 0.73\), the unabsorbed, rest-frame 2–10 keV luminosity \(L_{2-10}\) is thus estimated to be \(1.1 \times 10^{44} \text{ erg s}^{-1}\). Using Marconi et al. (2004), their Figure 3(b), \(L_{\text{bol}}/L_{2-10} = 30\), and \(L_{\text{bol}} = 3.3 \times 10^{45} \text{ erg s}^{-1}\). Using the relation of McHardy et al. (2006), we derive \(M_{\text{BH}} = 1.3^{+1.0}_{-0.3} \times 10^{7} M_{\odot}\) (a 7% uncertainty in the distance to IC 4329a (Mould et al. 2000) translates into an additional \sim 7% uncertainty on \(M_{\text{BH}}\)). The accretion rate relative to Eddington, \(L_{\text{bol}}/L_{\text{Edd}}\), is thus estimated to be 0.21\(^{+0.06}_{-0.10}\).

This estimate of \(M_{\text{BH}}\) is in agreement with several estimates obtained by other methods. Reverberation mapping has been known to yield highly accurate estimates of \(M_{\text{BH}}\), but only if the data are of sufficiently high quality. In the case of IC 4329a, the estimate of \(M_{\text{BH}}\) is poorly constrained due to relatively low-quality optical spectra, and formally only an upper limit, 9.90\(^{+17.80}_{-1.80}\) \times 10^{6} M_{\odot} (see Peterson et al. 2004 for details). However, many other methods of estimating \(M_{\text{BH}}\) in IC 4329a yield estimates closer to \(10^{7} M_{\odot}\). This includes other methods based on estimating the distance \(R_{\text{BLR}}\) from the central continuum source to the broad-line region, such as the empirical relation noted by Kaspi et al. (2000) between \(R_{\text{BLR}}\) and the optical continuum luminosity, “recalibrated” by Vestergaard & Peterson (2006; their Equation (5)). Using the value of \(H/\beta\) FWHM (rms) from Wandel et al. (1999), 5960 \pm 2070 km s\(^{-1}\), and a value for \(\lambda L_{\lambda}(5100 \text{ Å})\) of 1.64 \pm 0.21 \times 10^{41} \text{ erg s}^{-1} \text{ from Kaspi et al. (2000), the Vestergaard & Peterson (2006) equation yields \(M_{\text{BH}} = 1.2^{+1.4}_{-0.7} \times 10^{8} M_{\odot}\). Vestergaard & Peterson (2006; their Equation (6)) also provide a recalibrated formula for estimates of \(M_{\text{BH}}\) based on \(H/\beta\) luminosity and optical continuum luminosity. Winge et al. (1996) report a mean \(H/\beta\) flux of 3.331 \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1}; assuming a luminosity distance of 78.6 \pm 5.5 Mpc (Mould et al. 2000) yields an \(H/\beta\) luminosity of 2.45\(^{+0.36}_{-0.25}\) \times 10^{41} \text{ erg s}^{-1}. The resulting estimate of \(M_{\text{BH}}\) is thus 6.8\(^{+7.7}_{-4.3}\) \times 10^{7} M_{\odot}. A virial estimate based on the photoionization method (Wandel et al. 1999) is 2.2 \times 10^{7} M_{\odot}. The black hole mass can also be estimated via the well-known relation between stellar velocity dispersion \(\sigma_{*}\) and \(M_{\text{BH}}\). We use Equation (19) of Tremaine et al. (2002), \(M_{\text{BH}} = 10^{8.15 \pm 0.06} M_{\odot}/(\sigma_{*}/(200 \text{ km s}^{-1}))^{0.02 \pm 0.32}\). Oliva et al. (1999) report \(\sigma_{*} = 218 \pm 20 \text{ km s}^{-1}\) or 231 \pm 20 km s\(^{-1}\) using 1.59 \mu m Si or 1.62 \mu m CO(6,3) features, respectively. Using the average of these two values yields \(M_{\text{BH}} = 2.17^{+0.98}_{-1.05} \times 10^{8} M_{\odot}\.

\(^4\) The ionization parameter \(\xi = L_{\text{bol}} n_{e}^{-1} r^{-2}\), where \(L_{\text{bol}}\) is the isotropic 1–1000 Ryd ionizing continuum luminosity, \(n_{e}\) is the electron number density, and \(r\) is the distance from the central continuum source to the absorbing gas.
Several of the X-ray timing studies discussed in Section 1 have noted the remarkable similarity between Seyferts and black hole X-ray binaries in terms of their broadband PSD shapes; furthermore, the $T_{90}$–$M_{BH}$–$L_{bol}$ relation extrapolates down to stellar-mass black holes over 6–7 orders of magnitude in both $M_{BH}$ and X-ray luminosity. However, it is not immediately obvious from the shape of IC 4329a’s PSD and from the derived value of $L_{bol}$/$L_{Edd}$ if IC 4329a is an analog to a high/soft or low/hard state black hole X-ray binary system. There is not enough temporal frequency coverage below the break in the PSD of IC 4329a to determine if the power-law slope of $\sim$1 persists for several decades of temporal frequency below the break, which would identify it as an analog of Cyg X-1 in the high/soft state (e.g., Axelsson et al. 2005); monitoring covering temporal frequencies down to and below $10^{-8}$–$9$ Hz would be needed to determine the ultra-low temporal frequency PSD shape of IC 4329a.

### 5.2. The Energy-Dependent PSD Properties of IC 4329a

The PSDs presented here are roughly consistent with same underlying broadband PSD shape at all energies probed: a break near 2 $\times$ $10^{-6}$ Hz, and power-law slopes of $\sim$ 1.0 and $\sim$ 2.0 below and above the break frequency, respectively. The 10–20 and 20–40 keV PSDs are probing temporal frequencies primarily below the break frequency but are consistent with the presence of a break in the PSD up to 20–40 keV.

Arévalo & Uttley (2006) noted that an increase in $f_b$ with photon energy is expected in a model incorporating inwardly propagating variations in the local mass accretion rate modifying the central X-ray emission (Lyubarskii 1997; Kotov et al. 2001), with relatively harder X-ray bands associated with more centrally concentrated emissivity profiles. However, no significant breaks were detected in the 10–20 and 20–40 keV PSDs. The current 3–5 and 5–10 keV PSDs lack the necessary high temporal frequency resolution to discern any dependence of $f_b$ on photon energy. A much more dense temporal frequency sampling covering at least the range $10^{-7}$–$10^{-4.5}$ Hz would be required to adequately test any energy dependence of $f_b$ in this object.

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