WAVELET ANALYSIS OF AGN X-RAY TIME SERIES: A QPO IN 3C 273?
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ABSTRACT

Quasi-periodic signals have yielded important constraints on the masses of black holes in galactic X-ray binaries, and here we extend this to active galactic nuclei (AGNs). We employ a wavelet technique to analyze 19 observations of 10 AGNs obtained with the XMM-Newton EPIC pn camera. We report the detection of a candidate 3.3 ks quasi period in 3C 273. If this period represents an orbital timescale originating near a last stable orbit of 3Rs, it implies a central black hole mass of 7.3 × 10^6 M☉. For a maximally rotating black hole with a last stable orbit of 0.6 Rs, a central black hole mass of 8.1 × 10^7 M☉ is implied. Both of these estimates are substantially lower than previous reverberation-mapping results, which place the central black hole mass of 3C 273 at about 2.35 × 10^8 M☉. Assuming that this reverberation mass is correct, the X-ray quasi period would be caused by a higher order oscillatory mode of the accretion disk.

Subject headings: galaxies: active — galaxies: individual (3C 273) — X-rays: galaxies

Online material: color figures

1. INTRODUCTION

Quasi-periodic oscillations (QPOs) are thought to originate in the inner accretion disk of a black hole or neutron star in an X-ray binary (XRB) system (van der Klis 2000). Consequently, QPOs have been used in galactic XRBs to place important constraints on the masses of the central black holes of these systems.

Previous work has revealed that AGNs and XRBs are alike: noise power spectra have shown that similar physical processes may be underlying the X-ray variability in both (Edelson & Nandra 1999; Uttley et al. 2002; Markowitz et al. 2003; Vaughan et al. 2003; McHardy et al. 2004, 2005). Taking this resemblance into account and assuming that accretion onto a stellar-mass black hole is comparable to accretion onto a supermassive black hole, one would expect some AGNs to exhibit QPOs similar to those observed in XRBs. In supermassive black holes (10^6–10^9 M☉), these QPOs would be at much lower frequencies than those we find in stellar-mass black holes (~10 M☉). Low-frequency quasi periods (LF QPOs) in XRBs range from 50 to 30 Hz; scaling from a ~1 Hz QPO in a 10 M☉ XRB, a LF QPO in an AGN would occur on timescales of days to months (Vaughan & Uttley 2005), too long to be detectable for the AGNs in our sample. On the other hand, high-frequency QPOs (HF QPOs) in XRBs have values ≥ 100 Hz and assuming a 1/MBH scaling of frequencies, fHFQPO ~ 3 × 10^{-3}(MBH/10^6 M☉)^{-1} Hz (Abramowicz et al. 2004), corresponding to timescales greater than 400 s for AGNs.

While this parallel between AGNs and XRBs seems promising, no claim of an X-ray quasi period in an AGN has been found to be statistically robust. Vaughan & Uttley (2006) remark that many false detections arise from assuming an inappropriate background noise power spectrum. X-ray variations of AGNs have intrinsically red-noise power spectra (i.e., the power spectra have a continuum resembling a power law with a steep slope; Press 1978); however, many purported QPOs in AGNs are compared against an assumed background of white noise (i.e., Poisson photon noise or a flat spectrum). For example, in a ~5 day Advanced Satellite for Cosmology and Astrophysics (ASCA) observation of IRAS 18325−5926, the significance of the candidate periodicity was estimated with white noise (Iwasawa et al. 1998). After including red noise in the periodogram fitting, Vaughan (2005) found that the candidate periodicity was no longer significant at the 95% level. Fiore et al. (1989) also claimed high-significance (>99%) peaks in NGC 4151; however, after fitting red-noise and Poisson photon noise components of the spectrum, Vaughan & Uttley (2006) showed that the significances of the QPOs fell below the 95% confidence level. It is also difficult to constrain the significance of possible QPOs due to power spectrum effects (Vaughan & Uttley 2006). European X-Ray Observatory Satellite (EXOSAT) data of NGC 5548 were reported to have a significant period (Papadakis & Lawrence 1993), but Tagliaferri et al. (1996) later showed that the significance of the candidate QPO was lower than previously reported once the uncertainties in modeling the spectrum were taken into consideration. This lack of statistically significant evidence for QPOs in AGNs has led to questions of whether existing X-ray observations of AGNs are sensitive enough to detect QPOs even if they are present (Vaughan & Uttley 2005).

Here we use a different technique to search for significant periodic structures in the time variability data that have been collected for AGNs with XMM-Newton. We use a wavelet transform technique, which can have certain advantages relative to periodograms and Fourier power spectra, the methods that have previously dominated the literature. The wavelet technique, which has become widely used in other branches of science, is particularly useful in identifying signals in which the period or its amplitude changes with time. This technique is applied to the XMM-Newton data from 10 bright AGNs with special care taken to properly treat the noise characteristics and error analysis, and we find a candidate 3.3 ks quasi period in 3C 273.

In § 2, we present our observations and data reduction steps. In § 3, we provide an overview of the two wavelet techniques used in our analysis, the continuous wavelet transform and the cross-wavelet transform. The results of these two techniques, as well as significance tests, are presented. We also discuss structure function analysis for the AGNs in our sample. In § 4 we argue that this 3.3 ks quasi period in 3C 273 is consistent with what we would
WAVELET ANALYSES OF AGNs

TABLE 1
Log of Observations

| Object | Observation ID | Start Date | Length (ks) | Counts |
|--------|----------------|------------|-------------|--------|
| 3C 273 | 126700301      | 2000 Jun 13 | 66          | 140    |
| 3C 273 | 126700801      | 2000 Jun 17 | 60.6        | 120    |
| 3C 273 | 136550101      | 2003 Jan 5  | 88.6        | 160    |
| 3C 273 | 159960101      | 2003 Jul 7  | 58          | 230    |
| IRAS 13349+2438 | 096010101 | 2000 Jun 20 | 44.6        | 10     |
| M81    | 111800101      | 2001 Mar 22 | 130         | 20     |
| MCG −6-30-15 | 029740701 | 2001 Aug 2  | 127         | 70     |
| MCG −6-30-15 | 029740801 | 2001 Aug 4  | 125         | 120    |
| Mrk 421| 099280101      | 2000 May 25 | 32.5        | 740    |
| Mrk 421| 099280301      | 2000 Nov 13 | 46.6        | 1060   |
| Mrk 766| 109141301      | 2001 May 20 | 128.5       | 90     |
| NGC 3516| 107460601 | 2001 Mar 10 | 129         | 20     |
| NGC 3516| 107460701      | 2001 Nov 9  | 128         | 12     |
| NGC 4151| 112310101     | 2000 Dec 21 | 30          | 20     |
| NGC 4151| 112830201      | 2000 Dec 22 | 57          | 25     |
| NGC 5548| 089960301      | 2001 Jul 9  | 93.4        | 75     |
| NGC 5548| 089960401      | 2001 Jul 12 | 37          | 90     |
| PKS 2155−304| 124930201 | 2000 May 31 | 59          | 280    |
| PKS 2155−304| 124930301 | 2001 Nov 30 | 44.6        | 380    |

Note.—Events are grouped in 5-s bins.

2. OBSERVATIONS AND DATA REDUCTION

The 10 AGNs in our sample were selected because they are bright and have XMM-Newton EPIC pn camera observations that exceed 30 ks. In total, we have 19 observations, and each observation’s ID, date, length, and average counts are listed in Table 1. All observations are in the energy range 0.75–10 keV, and most were taken in small-window mode, which has a readout time of 6 ms. The only exception is NGC 4151 ObsID 0112830201, which was taken in full-frame mode with a readout time of 73.4 ms.

Observation data files (ODFs) were obtained from the online XMM-Newton Science Archive and later reduced with the XMM-Newton Science Analysis Software (SAS, vers. 7.0.0, 6.1.0, and 5.4.1). Source light curves, with 5-s bins, were extracted for a circular region centered on the source (~20”). Background light curves were obtained from a nearby rectangular source-free region and subtracted from the source light curves. These rectangular background regions were larger than the source regions and were accordingly scaled down. Due to strong flaring, the last few ks of data are excluded from most observations. The count rates for the target sources are orders of magnitude greater than the background count rate in the detection cell, so a rise in the background is unimportant. We removed these last few ks of data from the data stream just to be very cautious. We note that in the observation of 3C 273 with the claimed detection, including the periods with flaring does not change our results.

Some of the observations in our sample are affected by pileup. Pileup occurs when more than one X-ray photon arrives in a pixel before the pixel is read out by the CCD, making it difficult to distinguish one high-energy photon from two lower energy photons. Pileup can also occur when photons striking adjacent pixels are confused with a single photon that deposits charge in more than one pixel. Depending on how many pixels are involved, this is called a single-, double-, triple-, or quadruple-pixel event. The SAS task EPATPLOT measures the pileup in an observation, and the results for our target with the highest count rate, Mrk 421 (Table 1), are shown in Figure 1. When we compare the expected fractions of pixel events (solid lines) with those actually measured in the data (histograms) for the range 0.75–10 keV, we see that a larger than expected fraction of double events (third histogram from top) is measured, as well as a larger fraction of triple and quadruple events (bottom two histograms), although to a lesser degree, while single events (second histogram from top) are lower than expected, indicating the presence of pileup. Pileup leads to a general reduction in the mean count rate, as well as a reduction in the magnitude of variations. We explore the influence of pileup on our data in more detail when we discuss structure functions in § 3.2.1.

FIG. 1.—Pileup measurement from the SAS task EPATPLOT for Mrk 421 ObsID 00999280101. The expected fractions of pixel events are shown by the solid lines, and the measured pixel events are shown by the histograms (the labels s, d, t, and q stand for single, double, triple, and quadruple events, respectively). In the range 0.75–10 keV we see that a larger than expected fraction of double events (third histogram from top) is measured, indicating that pileup is present in this source. [See the electronic edition of the Journal for a color version of this figure.]
3. DATA ANALYSIS AND RESULTS

3.1. Wavelet Analysis

3.1.1. The Continuous Wavelet Transform

The continuous wavelet transform (CWT) is the inner product of a dilated and translated mother wavelet and a time series $f(t)$, the idea being that the wavelet is applied as a bandpass filter to the time series. The continuous wavelet transform maps the power of a particular frequency (i.e., dilation) at different times in translation-dilation space, giving an expansion of the signal in both time and frequency. Hence, the continuous wavelet transform not only tells us which frequencies exist in the signal, but also when they exist, allowing us to see whether a timescale varies in time. This is the wavelet technique’s advantage over Fourier transforms in detecting quasi periods. In addition, the Fourier transform is not suited for detecting quasi periods, since nonperiodic outbursts will spread power across the spectrum, and windowing will cause power to appear at low frequencies, potentially obscuring quasi-periodic signals.

Throughout this paper, we follow Hughes et al. (1998) and Kelly et al. (2003) and references within. In previous studies (Hughes et al. 1998; Kelly et al. 2003; Liu et al. 2005; Kadler et al. 2006), we have found the Morlet wavelet

$$\psi_{\text{Morlet}} = \pi^{-1/4} e^{i k_0 t} e^{-|t|^2/2}$$

with $k_0 = 6$ to be an excellent choice. This value of $k_0$ is a satisfactory compromise between a value small enough that we have good resolution of temporal structures and large enough that the admissibility condition is satisfied, at least to machine accuracy (Farge 1992). The wavelet, being continuous and complex, permits a rendering in transform space that highlights temporally localized periodic activity—oscillatory behavior in the real part and a smooth distribution of power in the modulus—and being progressive (zero power at negative frequency), is optimal for the study of causal signals. We have deliberately avoided any form of weighting, such as that introduced by Foster (1996) to allow for uneven sampling or Johnson (2006) to rescale within the cone of influence, in order to facilitate our interpretation of the cross-wavelet and to allow the use of existing methods of significance analysis.

From this mother wavelet, we generate a set of translated $(t')$ and dilated $(l)$ wavelets

$$\psi_{l,t}(t) = \frac{1}{\sqrt{l}} \psi\left(\frac{t - t'}{l}\right), \quad l \in \mathbb{R}^+, \quad t \in \mathbb{R},$$

and we then take the inner product with the signal $f(t)$ to obtain the wavelet coefficients

$$\tilde{f}(l,t') = \int_{\mathbb{R}} f(t) \psi_{l,t}(t) \, dt.$$

The wavelet coefficients are later mapped in wavelet space, which has as coordinates translation and dilation, and so periodic behavior shows up as a pattern over all translations at a specific dilation.

By way of example, Figure 2 shows the real part and the power of the continuous wavelet transform (second and bottom panels, respectively) for a sinusoidal signal of varying frequency (top). Here the real part of the transform shows oscillatory behavior corresponding to the two periodicities of the sinusoidal signal at dilations of 3 and 6 s, with a break in translation at 50 s corresponding to the time when the change in frequency occurs.

The bottom panel in Figure 2 shows that the power of the continuous wavelet transform is concentrated at these two frequencies as well.

The hatched area in both panels of Figure 2 represents the cone of influence, the region where edge effects become important. It arises because discontinuities at the beginning and end of a finite time series result in a decrease in the wavelet coefficient power. Also shown in the header of Figure 2 are the number of dilations used ($N_l$) and the ranges of dilations explored. We discuss $\alpha$ and the normalization of Figure 2 in § 3.1.2.

3.1.2. Significance Tests

Significance tests can be created for the continuous wavelet transform, and here we follow Torrence & Compo (1998). First, one compares the wavelet power with that of an appropriate background spectrum. We use the univariate lag-1 autoregressive [AR(1)] process given by

$$x_n = \alpha x_{n-1} + z_n,$$

where $\alpha$ is the assumed lag-1 autocorrelation and $z_n$ is a random deviate taken from white noise. Note that $\alpha = 0$ gives a white-noise process. Throughout this paper, we use “white noise” to refer to an AR(1) process with $\alpha = 0$. Red noise is sometimes used to refer to noise with $\alpha = 1$; however, throughout this paper we apply the term to any nonzero $\alpha$.

The normalized discrete Fourier power spectrum of this process is

$$P_l = \frac{1 - \alpha^2}{1 + \alpha^2 - 2 \alpha \cos(2\pi \delta t/\tau_l)},$$

where $\tau_l$ is the associated Fourier period for a scale $l$. We use equations (4) and (5) to model a white-noise or red-noise spectrum.
The global wavelet power spectrum (GWPS) is obtained by averaging in time

\[ \tilde{f}_G(l_j) = \frac{1}{N_j} \sum_{i=l_j}^{l_j+1} \tilde{f}(l_i, t_f)^2, \]  

(6)

where \( i \) and \( f \) are the indices of the initial and final translations \( t_f \) outside the cone of influence at a given scale \( l \) and \( N_j \) is the number of translations \( t_f \) outside the cone of influence at that scale. Assuming a background spectrum given by equation (5), we estimate the autocorrelation coefficient \( \alpha \) by calculating the lag-1 and lag-2 autocorrelations \( \alpha_1 \) and \( \alpha_2 \). The autocorrelation coefficient is then estimated as \( \alpha = (\alpha_1 + \sqrt{\alpha_2})/2 \). The background spectrum \( P_l \) then allows us to compute the confidence levels. It is assumed that the time series has a mean power spectrum given by equation (5), and so if a peak in the wavelet power spectrum is significantly above this background spectrum, then the peak can be assumed to be a true feature. If the values in the time series \( f(t) \) are normally distributed, we expect the wavelet power \( |\tilde{f}|^2 \) to be \( \chi^2 \) distributed with 2 degrees of freedom \( \chi^2_2 \). The square of a normally distributed variable is \( \chi^2_2 \) distributed with 1 degree of freedom, and the second degree of freedom comes from the fact that both the real and imaginary parts of the complex \( f \) are normally distributed. For example, to determine the 95% confidence level, one multiplies the background spectrum (eq. [5]) by the 95th percentile value for \( \chi^2_2 \). In Figure 3 we show the GWPS of a time series, along with the 99% and 95% confidence levels for a red-noise process and the 99% confidence level for a white-noise process.

The distribution for the local wavelet power spectrum is

\[ \frac{|\tilde{f}(l_j, t_f)|^2}{\sigma^2} \rightarrow P_j \frac{\chi^2_2}{\nu}, \]  

(7)

where the arrow means “distributed as,” \( \sigma^2 \) is the variance, and \( \nu \) is the number of degrees of freedom, which is 2 here. The indices on the scale \( l \) are \( j = 1, 2, \ldots, J \), where \( J \) is the number of scales, and the indices on the translation \( t_f \) are \( i = 1, 2, \ldots, N_{\text{data}} \). We evaluate this equation at each scale to get 95% confidence contour lines, and in this paper our continuous transforms are normalized to the 95% confidence level for the corresponding red-noise process. Doing this allows one to see the strength of the wavelet coefficients relative to the 95% confidence level of a red-noise process.

3.1.3. The Cross-Wavelet Transform

Although the continuous wavelet transform is useful in examining how a time series varies in time and scale, it does not tell us how the time series varies in dilation over a range of scales when assigning a characteristic timescale. Since a quasi-periodic signal has no unique dilation, we use the cross-wavelet transform (XWT), which filters out noise and reveals the QPO more clearly. Here we use the XWT introduced by Kelly et al. (2003).

After the continuous transform determines that a periodic pattern exists in the data, the dilation that characterizes this period is obtained from the global wavelet power spectrum and is used to create a sinusoidal mock signal. The continuous wavelet transform coefficients of the data signal \( f_d(t) \) are then multiplied by the complex conjugate of the continuous transform coefficients of a mock signal \( f_m(t) \). The results are mapped out in wavelet space and analyzed for a correlation.

The cross-wavelet transform takes the form

\[ \tilde{f}_c(l, t_f) = \tilde{f}_d(l, t_f) \tilde{f}_m^*(l, t_f), \]  

(8)

where the continuous wavelet coefficients \( \tilde{f}_d \) and \( \tilde{f}_m \) are given by equation (3).

Figure 4 shows the cross-wavelet for the same sinusoidal signal of varying frequency used in Figure 2. The mock signal was calculated using the 6 s period found in the wavelet power spectrum (see Fig. 3), and as the concentrations in the real and power panels of Figure 4 show, the cross-wavelet finds that this 6 s period exists in the first half of the time series, illustrating the cross-wavelet’s ability to highlight a QPO. The reader may refer to Kelly et al. (2003) for a full review of the cross-wavelet technique used here.

3.2. Structure Function Analysis

Since the global wavelet power spectrum compares the observed signal to the expected levels of red noise and white noise, we created structure functions (SFs) for each of our observations to see which noise process dominates the signal at different times. A structure function calculates the mean deviation of data points, providing an alternate method of quantifying time variations. Here we use a structure function of the first order (Simonetti et al. 1985),

\[ \text{SF}(\delta t) = \langle [F(t) - F(t + \delta t)]^2 \rangle, \]  

(9)
where $F(t)$ is the flux at time $t$ and $\delta t$ is a time lag. The slope $\alpha$ of the SF curve in $\log SF - \log \delta t$ space depends on the noise processes underlying the signal, giving us an indication of the nature of the process of variation. If $\alpha = 1$, red noise dominates, and for flatter slopes of $\alpha = 0$, Poisson photon noise is significant. A plateau at a short time lag is due to measurement noise. The point of turnover from power law to plateau at longer time lags corresponds to a maximum characteristic timescale.

### 3.2.1. Effects of Pileup

We measure the presence of pileup in our observations by using the SAS task EPATPLOT and find that the majority of our sources show varying degrees of pileup. For example, as previously shown in §2, Mrk 421 ObsID 0099280101 has a modest amount of pileup (see Fig. 1). In the structure function of this observation (Fig. 5, left), the flat portion of the structure function curve should have a value of $\log SF = 1$, which corresponds to the Poisson photon noise inherent in the photon statistics. However, here it falls below the Poisson photon noise level. To remove the pileup, we exclude the central core of the source in the event file, since pileup is more likely to occur here. For these subtracted data, the EPATPLOT output indicates that there is no pileup, and the SF curve is then at the expected value for Poisson photon noise (Fig. 5, right). Pileup affects the SF because it lowers the overall count rate, and thereby Poisson photon noise is underreported.

We correct for pileup in the rest of our data by adding a fixed value to $\log SF$, moving the flat part of the structure function curve up to 1. All of our observations had less than 5% pileup, except for PKS 2155–304 ObsID 124930301 (6.5%) and both observations of Mrk 421 (~10%). Overall, the percentage of pileup in our sample increases with the number of counts, except

![Figure 5](image_url)

**Fig. 5.—** Effect of pileup on structure functions of Mrk 421 ObsID 0099280101. The flat portion of the structure function curve affected by pileup (left) falls below $\log SF = 1$, which corresponds to Poisson photon noise. In the right panel, the central core of the source has been removed (i.e., pileup is greatly reduced), and the SF curve is then at the expected value for Poisson photon noise.

![Figure 6](image_url)

**Fig. 6.—** Continuous wavelet transform for 3C 273 ObsID 126700301. The real part of the transform shows an oscillatory behavior at 3.3 ks. There is also a concentration in the power plot at 3.3 ks. The 3.3 ks signal is circled in both panels. The light curve (top) is binned up from 5 to 100 s for clarity. The value of $\alpha$ for the unbinned 5 s data is 0.14. The hatched area is the cone of influence, the region where edge effects become important. [See the electronic edition of the Journal for a color version of this figure.]

![Figure 7](image_url)

**Fig. 7.—** Global wavelet power spectrum for 3C 273 ObsID 126700301. The solid line is the power spectrum of the signal, which is compared to the power spectra of white- and red-noise random processes (broken lines). The 3.3 ks detection exceeds the expected level of red noise with a 99.979% probability of detection.
for NGC 4151 ObsID 112830201, which is 5% piled up and has an average of only 25 counts.

3.3. Results

3.3.1. Wavelet Analysis Results

Of the observations that we analyzed, only one showed a quasi period of interest (at 3.3 ks), and this occurred in an observation of 3C 273 (ObsID 126700301). The continuous wavelet transform result for this observation is shown in Figure 6, with the quasi period circled in the real and power plots (second and third panels, respectively). One can see that the quasi period appears in the last two-thirds of the observation. In the real plot, the concentrations match up with peaks in the light curve, and the power is concentrated at $4.2 \times 10^4$ s. The wavelet is sampled with 220 dilations ($N_l$) ranging between $207.2$ and $2.3 \times 10^4$ s. We note that the data in Figure 6 are binned from 5 to 100 s for clarity and that we show only the first 56 ks due to background flaring at the end of the observation. We note that including the periods with background flaring does not change our results. The value of $\alpha$ found from autocorrelation analysis for the unbinned data is 0.14, and this value is used to reach the conclusions in this paper.

The 3.3 ks quasi period is also evident in the global wavelet power spectrum (GWPS; Fig. 7), which is calculated by summing

![Cross-wavelet transform for 3C 273 ObsID 126700301](image)

Fig. 8.— Cross-wavelet transform for 3C 273 ObsID 126700301. We use the cross-wavelet to compare a mock sinusoidal signal with a period of 3282 s with the observation. The concentrations in the real and power plots show that a $\sim 3300$ s period exists in the data. [See the electronic edition of the Journal for a color version of this figure.]

![Global wavelet power spectra for all observations in our sample with log(global power spectrum)](image)

Fig. 9.— Global wavelet power spectra for all observations in our sample with log(global power spectrum). The period is in seconds.
up the wavelet power spectra at all times. In searching for quasi-periodic behavior, we excluded timescales above 25% of the time series length, where, using spectral methods, too few periods to provide a convincing result would be present and where the cone of influence becomes important for the wavelet coefficients. On short timescales, experience has shown that sources often exhibit a broad distribution of power, with local maxima not well separated from the mean power level. We selected a lower bound for our search, by visual identification of such behavior in the GWPS, in conjunction with a concomitant change in behavior of the SF. The solid line in Figure 7 is the power spectrum of the signal, which is compared to the power spectrum of white- and red-noise random processes (broken lines). One can see that the 3.3 ks detection exceeds the expected levels of white and red noise at the 99% significance level; i.e., the probability of the detection is higher than 99% of the noise random processes (the significance of this signal is 99.979% relative to red noise with $\alpha = 0.14$). The origins of the white- and red-noise power spectra were discussed in § 3.1.2.

The cross-wavelet analysis for 3C 273 (Fig. 8) supports the conclusion that a period of 3.3 ks is indeed present. Here the XWT (see § 3.1.3) compares a mock sinusoidal signal of period 3282 s with the 3C 273 light curve. The concentration in the cross-wavelet transform shows that the 3.3 ks signal is present throughout the observation. As one can see by comparing the cross-wavelet signals in juxtaposed bands, the 3.3 ks periodicity can be traced over the entire interval. In the CWT (Fig. 6) the 3.3 ks signal is particularly strong at late times, and so, due to the limited dynamic range of the rendering, it is not evident early in the time interval in that figure.

This periodicity is not detected in the other three observations of this object. In the 58 ks (ObsID 159960101) and 60 ks (ObsID 126700801) observations of 3C 273, there is a signal at 5000 s, but it does not rise above the 99% red-noise confidence level (Fig. 9). We note that a Fourier analysis of 3C 273 yielded a feature at 3.3 ks, but with a lower significance ($<3 \sigma$) than is found with the wavelet technique.

We performed Monte Carlo simulations in order to estimate the probability that the wavelet technique would claim a spurious detection. As a baseline, we created 1000 simulated light curves for Poisson photon noise (Fig. 10) to represent random observational errors, i.e., photon-counting statistics. The simulated light curves were 56 ks long with 5 s intervals, and we multiplied the mean deviation $\sigma_0$ by 40 to produce an average spread in the $y$-axis of 40 counts to resemble the 3C 273 light curve. Most of the false detections occur at timescales less than 2000 s, which corresponds to 3.6% the length of the observation and supports our earlier point that one can select the lower limit to search for periodicities by visual identification of broad distributions of power on short timescales in the GWPS. On average, the wavelet technique claims a detection (at or above the significance level reported by the wavelet analysis for 3C 273) 0.4% of the time (Fig. 10).

The Monte Carlo simulations suggest a significantly higher rate of false detections than is implied by the statistics based on the GWPS. However, they are consistent with the latter estimates within the margin of error, given that only 1000 realizations of a time series were generated. Better simulation statistics could be achieved by increasing the number of time series realizations by several orders of magnitude, but devoting time and resources to this is not warranted. Visual inspection of the simulated light curves reveals that they differ qualitatively from the actual time series; a better correspondence can be achieved with the addition of randomly distributed Gaussian profile bursts of fixed, small amplitude. Evidently, the process under study is not strictly a stationary, first-order one, and the formal statistical measures of significance should be regarded as only indicative of the high likelihood of a quasi-periodic phenomenon in this source. A more detailed analysis, allowing for nonstationary processes, is beyond the scope of this paper. While we have performed 19 independent experiments and found only 1 detection, we point out that of our 19 data sets only 7 have average counts (Table 1) equal to or more than the observation in which we find the QPO. One cannot expect to see with equal likelihood a periodicity of equal strength in these weaker AGNs.

We note that, independently, the XWT finds evidence for power throughout the observation at 3.3 ks (Fig. 8). We measured the 3.3 ks signal strength across the time series from the power plot of Figure 8. The power of the 3.3 ks signal is ~4000 times stronger than shorter and longer dilations, illustrating that the 3.3 ks period is well constrained. We also ran the XWT on this time series with analyzing signals of 2.3 and 4.3 ks. The average power of these signals is ~2 times less than the average power of the 3.3 ks signal. This demonstrates that the XWT is picking out a well-defined persistent signal and will not misleadingly report a signal where there is none.

We did not find any significant detections for the other nine AGNs in our sample. No features had a significance that exceeded the 99% confidence levels for both white-noise and red-noise processes (see Figs. 9 and 11) and appeared at either too short (i.e., at timescales shorter than 3.6% the length of the observation) or too long (i.e., at timescales greater than half the length of the observation) a timescale. Some of the AGNs in our sample have been studied before, and previous reports of QPOs exist in the literature. We discuss those results in more detail in § 4.3.
3.3.2. Structure Function Results

After correcting for pileup, we subtract a constant level corresponding to Poisson photon noise from the structure functions (Figs. 12 and 13). The slopes are measured by fitting a power law to the SF curve using the least-squares method in log SF-log δt space. Slopes are listed in Table 2, along with the characteristic timescales of variability, which were measured by identifying the times of turnover from plateau to power law and vice versa in the SF curve. All of our structure functions have a flat plateau at short timescales, corresponding to Poisson photon noise, most have a power-law portion, and some have a plateau at long timescales. We include light curves in Figures 14 and 15 for comparison with the structure functions.

The structure functions for all four observations of 3C 273 are shown in the top four panels of Figure 12. The observation with the 3.3 ks quasi period (Fig. 12, top left) is dominated by whitish noise around 3000 s, as inferred from its flat slope; however, the SF is unsuited to quantifying the autocorrelation coefficient precisely. Recall that the wavelet analysis finds an autocorrelation coefficient of \( \alpha = 0.14 \), relatively small and consistent with a flattish structure function. We note that this observation also has the greatest excess of such noise above the photon noise compared to the other three observations, consistent with this being a time series unique among all those analyzed.

4. DISCUSSION

4.1. Mass Estimates of 3C 273

There are several mass estimates for 3C 273 obtained from different methods. One method is reverberation mapping, whereby one uses the time lag of the emission-line light curve with respect to the continuum light curve to determine the light crossing size of the broad-line region (BLR) and then assumes Keplerian conditions in the broad-line region gas motion (i.e., \( M_{\text{BH}} = v^2 R_{\text{BLR}} / G \); Peterson & Wandel 2000).

Reverberation-mapping results based on the optical continuum (i.e., Balmer lines) place the mass of the central black hole in 3C 273 at \( 2.35^{+0.35}_{-0.22} \times 10^8 M_\odot \) (Kaspi et al. 2000). In a different study, Pian et al. (2005) use Hubble Space Telescope UV luminosities to find the broad-line region size. To do so, they derive a relationship between \( R_{\text{BLR}} \) and UV luminosity using the empirical relationship found by Kaspi et al. (2000) between \( R_{\text{BLR}} \) and the optical luminosity. Pian et al. (2005) obtain a mass of \( 4.0^{+2}_{-2} \times 10^8 M_\odot \) for 3C 273, consistent with the Kaspi et al. (2000) value within errors. In another study, Paltani & Türler (2005) look at the strongest
broad emission UV lines ($\text{Ly}_\alpha$ and $\text{C IV}$) in archival *International Ultraviolet Explorer* observations and obtain a mass of $6.59^{+0.89}_{-0.86} \times 10^6 M_\odot$ for the central supermassive black hole in 3C 273.

There are also mass estimates for 3C 273 that do not come from reverberation mapping. Liang & Liu (2003) find a black hole mass of $2 \times 10^7 M_\odot$ by generalizing the Elliot-Shapiro relation to the Klein-Nishina regime for 3C 273’s gamma-ray flux obtained from EGRET. Another method is to use the McLure & Dunlop (2001) correlation between host galaxy luminosity and black hole mass, which obtains a mass of $1.6 \times 10^9 M_\odot$ with an uncertainty of 0.6 dex (Wang et al. 2004).

### 4.2. Underlying Physical Process for the QPO in 3C 273

If the 3.3 ks quasi period in 3C 273 represents an orbital timescale originating near a last stable orbit, it implies a central black hole mass of $7.3 \times 10^6 M_\odot$ for a nonrotating black hole or $8.1 \times 10^7 M_\odot$ for a maximally rotating black hole. These numbers agree with the Liang & Liu (2003) mass estimate of $2 \times 10^7 M_\odot$. However, these masses are substantially lower than those expected for supermassive black holes.

The Pian et al. (2005) estimate for the mass of the black hole in 3C 273 at $4.0 \times 10^8 M_\odot$ points to an orbital period of $\sim 200$ ks for a last stable orbit of $3 R_g$ and a period of $\sim 16$ ks for $0.6 R_g$ for a rotating black hole. Paltani & Türler (2005) estimate a mass for 3C 273 of $6.59 \times 10^6 M_\odot$, which points to an orbital period of 3000 ks for a last stable orbit of $3 R_g$ and a period of 270 ks for $0.6 R_g$. The 3.3 ks quasi period we find here is only about 2%–20% of the Pian et al. (2005) orbital timescale and 0.1%–1% of the Paltani & Türler (2005) orbital timescale, suggesting that this X-ray quasi period is not caused by dynamical motion in the inner accretion disk. Furthermore, the inverse scaling between frequency and black hole mass yields an expected period of $t \sim 300 M_\text{BH}/(10^6 M_\odot)$ based on the representative HF QPO in XRBs, namely, GRO J1655–40 (Orosz & Bailyn 1997; Remillard et al. 1999; Abramowicz et al. 2004). Using either the Pian et al. (2005) or Paltani & Türler (2005) mass estimates yields a period that is 1–2 orders of magnitude higher than what we observe.

Previous work has suggested that oscillations can occur in the innermost region of relativistic accretion disks due to their instability against axisymmetric radial oscillations, possibly due to a magnetic field (Kato & Fukue 1980). This has been proposed for X-ray binary systems, but the physical mechanism responsible for these oscillations can be applied to other accretion disk systems like AGNs. Perez et al. (1997) analyze modes of oscillation.
Table 2: Structure Function Slopes and Timescales

| Object          | Observation ID | Slopes | Transition Time (s) | Turnover Time (s) |
|-----------------|----------------|--------|---------------------|-------------------|
| 3C 273          | 126700301      | 1.23   | $1.5 \times 10^4$   | ...               |
| 3C 273          | 126700801      | 2.09   | $1.5 \times 10^4$   | ...               |
| 3C 273          | 136550101      | ...    | ...                 | ...               |
| 3C 273          | 159960101      | 1.68   | $2 \times 10^4$     | ...               |
| IRAS 13349+2438 | 096010101      | 1.68   | 1000                | ...               |
| M81             | 111800101      | 0.95   | 7000                | ...               |
| MCG-6-30-15     | 029740701      | 0.82   | ...                 | $10^4$            |
| MCG-6-30-15     | 029740801      | 1.11   | 200                 | ...               |
| Mrk 421         | 099280101      | 1.25   | 400                 | ...               |
| Mrk 421         | 099280301      | 1.13   | 350                 | 7000              |
| Mrk 766         | 109141301      | 0.67   | 100                 | $3 \times 10^4$   |
| NGC 3516        | 107460601      | 1.18, 1.39 | 2000               | ...               |
| NGC 3516        | 107460701      | 1.86   | $2 \times 10^4$     | ...               |
| NGC 4151        | 112310101      | ...    | ...                 | ...               |
| NGC 4151        | 112830201      | 1.19   | 7000                | ...               |
| NGC 5548        | 089960301      | 0.99, 1.64 | 1200              | ...               |
| NGC 5548        | 089960401      | 0.97, 2.75 | 1000             | ...               |
| PKS 2155–304    | 124930201      | 0.99, 0.59, 0.45, 1.69 | 2000         | ...               |
| PKS 2155–304    | 124930301      | 1.59   | 1100                | ...               |

Note.—Transition time corresponds to the time at which the SF curve changes from a plateau to a power law. Turnover time is the time at which the power-law portion of the SF curve changes to a plateau.
in terms of perturbations of the general relativistic equations of motion of perfect fluids within the Kerr metric. They look at the case of a thin accretion disk around a Kerr black hole in order to determine black hole mass and angular momentum for different trapped modes.

We propose that a $g$-mode oscillation of $m \geq 3$ is responsible for the 3.3 ks quasi period in 3C 273. A $g$-mode (inertial) oscillation can be characterized as a restoring force that is dominated by the net gravitational-centrifugal force. These modes are the most relevant observationally, since they appear to occupy the largest area of the disk and hence should be the most observable trapped modes (Perez et al. 1997).

Equation (5.4) of Perez et al. (1997) shows that the frequency of a quasi period should be observed at

$$f = \frac{714(M_\odot/M)}{a} F(a) \text{ Hz},$$

(10)

where $a$ is the angular momentum parameter and $M = M_{\text{AGN}}$. For $m = 0$ and $a = 0$, $F(0) = 1$, while $F(a_{\text{max}}) = 3.443$, where $a_{\text{max}} = 0.998$. This gives a mass that is too low. For $m = 3$, $F(a_{\text{max}}) \sim 59$ (see Fig. 5 of Perez et al. 1997), and this gives a mass for 3C 273 of $1.4 \times 10^8 M_\odot$. Perez et al. (1997) do not look at modes higher than 3.
4.3. Previously Reported QPOs for AGNs in Our Sample

Fiore et al. (1989) report a QPO in NGC 4151 around 5.8 ks with >99% significance based on three EXOSAT observations. Vaughan & Uttley (2006) reanalyzed these data sets and found that after fitting the red-noise significance and Poisson photon noise components of the spectrum, the QPOs fall below the 95% threshold. Our XMM-Newton observations show a ~4.8 ks feature. This appears in our 57 ks observation (ObsID 112830201) with 96% red-noise significance and in our 30 ks observation (ObsID 112310101) with 99.4% red noise (see Fig. 11). Even though this signal rises above the 99% red-noise level in this observation, we discount it because it appears as part of a larger power structure in the GWPS and is not a well-defined peak.

For NGC 5548, Papadakis & Lawrence (1993) claim a 500 s QPO in five out of eight EXOSAT observations. Tagliaferri et al. (1996) reanalyzed the same data and found that one observation had detector problems. Also, in every case they found less than 95% significance by taking into account the uncertainties in modeling the spectrum. In our XMM-Newton data of NGC 5548, we report a 500 s feature, but it has only a 93% red-noise significance and is seen in only one of our two observations (ObsID 089960401; Fig. 11).

For Mrk 766, Boller et al. (2001) claim a ~4200 s QPO in a 30 ks XMM-Newton observation. In our 128 ks observation, taken a year later, we see a signal at 4200 s with 99.5% red-noise significance, but it is dwarfed in the global wavelet power by a much stronger, wider broad peak (see Fig. 11), possibly due to a secular change in flux over the observation.

We do not detect any significant feature for MCG –6–30–15 (Lee et al. 2000), Mrk 421, or PKS 2155–304 (Osone & Teshima 2001), which have previously reported QPOs. To the best of our knowledge, there are no published QPO claims for any of the other objects in our sample. 3C 273, IRAS 13349+2438, or NGC 3516.

Halpern et al. (2003) reported the discovery of a 2.08 day quasi period in the narrow-line Seyfert 1 galaxy Ton S180 with a 33 day observation taken with the Extreme Ultraviolet Explorer (EUVE). Vaughan (2005) suggests that this periodogram is over-sampled, and so the significance is overestimated. Our wavelet analysis of these data shows a ~2 day period in the global wavelet power spectrum, which rises above the 99% white-noise level, but it has only a 89.5% red-noise significance (Fig. 11). Our wavelet analysis finds an α of 0.8 for this observation, and the structure function shows that red noise dominates, implying that this 2 day feature should be compared to red-noise significance and so is not significant.

5. SUMMARY AND CONCLUSIONS

We applied the wavelet analysis technique to XMM-Newton observations of 10 AGNs and detected a candidate 3.3 ks period in 3C 273. The cross-wavelet transform shows that the 3.3 ks signal is present throughout the entire observation.

If the 3.3 ks quasi period in 3C 273 represents an orbital timescale originating near a last stable orbit, it implies a central black hole mass of at least 7.3 × 10^6 M_☉, which does not agree with reverberation-mapping mass estimates. Kaspi et al. (2000) estimate the mass of the black hole in 3C 273 at 2.35 × 10^8 M_☉, and Paltani & Türl (2005) find a mass of 6.59 × 10^8 M_☉. This suggests that this X-ray quasi period is not caused by dynamical motion in the inner accretion disk.

We suggest that oscillations with modes of 3 or higher are occurring in the accretion disk of 3C 273, producing the detected 3.3 ks quasi period. Perez et al. (1997) shows that for m ≥ 3 and maximum angular momentum one can obtain a mass for 3C 273 of 1.4 × 10^8 M_☉, consistent with the lower mass estimate obtained from reverberation mapping.

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