X-ray Periodicity in AGN

Karen M. Leighly
The University of Oklahoma

Abstract. Significant (marginal) detections of periodic signals have been recently reported in 3 (4) Active Galactic Nuclei. Three of the detections were obtained from long EUVE light curves of moderate-luminosity Seyfert galaxies; the fourth was discovered in Chandra data from the low-luminosity Seyfert 1 galaxy NGC 4395. When compared with Cyg X-1, I find that the period is related to the luminosity as \( P \propto L^{2/3} \) rather than the expected one-to-one relationship. This result might be explained if the QPO is associated with the inner edge of the optically thick accretion disk, and the inner edge radius depends on the source luminosity (or black hole mass). A discussion of uncertainties in the period detection methodology is also discussed.

Keywords: X-ray variability, NGC 4395, Ton S180, RX J0437.1−4711, 1H 0419−577

1. Introduction

Quasiperiodic oscillations are a characteristic feature of solar-mass black hole X-ray variability, especially when the objects are in the very high (or transition) state. Active Galactic Nuclei are similar to stellar-mass black holes in that they are both powered by accretion onto a central black hole. Therefore, it seems plausible, or at least possible, that quasiperiodic oscillations should be observed in active galaxies as well.

The search for periodic signals in AGN light curves has a long and checkered history, however. A number of claims of periodicity have been put forward, only to later be proved faulty. The problems fall into three categories. The first and most common problem involves claims in which the confidence level of the detection is overestimated. An example is the recent claim of a periodic signal with frequency of \( 2.4 \times 10^{-4} \) Hz in XMM-Newton data from Mrk 766 (Boller et al. 2001). It was later shown by Benlloch et al. (2001) that the simulated light curves used to establish the significance of the detection were not properly randomized. The second problem involves detector artifacts. An example of this problem was the apparent discovery of a decreasing period in RXTE data from IRAS 18325−5926 that was eventually demonstrated to be due to detector background (Fabian et al. 1998a,b). A final problem that this author has personal experience with is that of source confusion. EXOSAT and Ginga data revealed a 12,000 second periodicity in the Seyfert 1 galaxy NGC 6814 (e.g., Leighly et al. 1994). Imaging observations later showed that the signal was dominated by...
a cataclysmic variable star only 40 arcminutes away (Madejski et al. 1993).

These misadventures do not, however, preclude the possibility that periodicity or quasiperiodicity could be present in AGN light curves. It may be that we simply are not looking in the right place, or that we don’t have the right data. In this contribution, I discuss the significant (marginal) detection of periodicity X-ray data from three (four) Seyfert 1 galaxies.

2. Methodology

A standard Monte Carlo procedure was used to detect periodicity in the AGN light curves, with small differences between the procedure used in Halpern, Leighly & Marshall (2003), which discusses analysis and results of the EUVE light curves, and in Moran et al. 2005, which discusses the Chandra result. First, the slope and normalization of the assumed underlying power-law continuum was determined. In Halpern, Leighly & Marshall (2003), 100 long light curves were generated, using the method of Timmer & König (1995), for each point on a grid of trial power-law slopes and normalizations. These long light curves were resampled and rebinned in the same way as the real light curves, appropriate Poisson noise was added, and the periodogram was computed and rebinned. The average and standard deviation periodogram from the situations at each point in the grid was then compared with that of the real data using $\chi^2$. The minimum $\chi^2$ was assumed to locate the best-fitting values of the slope and normalization of the continuum. The procedure used for the analysis of the Chandra data from NGC 4395 differed in one respect. Light curves were produced for a range of slopes, but only one normalization. Following Vaughan, Fabian & Nandra (2003), the result was scaled to different normalizations, and appropriate Poisson noise computed and added.

Knowing the shape of the power spectrum continuum, 10,000 suitably rebinned and sampled light curves were generated using the method of Timmer & König (1995). The power spectra from these were used to assessed the local confidence level of the detection, first by counting the number of incidents in which the power of the simulations exceeded the power of the real data, and second by comparing with a $\chi^2$ distribution (e.g., Leahy et al. 1983). As discussed in Benlloch et al. (2001), one must account for the number of independent frequencies searched to obtain an estimate of the global significance by multiplying the single-trial confidence by that number.
3. Results and Discussion

Halpern, Leighly & Marshall (2003) present an atlas of EUVE light curves from Seyfert galaxies. Three objects had exceptionally long light curves: 33 days for Ton S180, 26 days for 1H 0419−577, and 20 days for RX J0437.1−4711. Periodicity analysis as outlined above revealed evidence for a 2.08-day signal in Ton S180 with global confidence level of 98%, a 0.908-day signal in RX J0437.4−4711, and a 5.8-day signal in 1H 0419−577 with a global confidence level of only 64%. Interestingly, the periodic signal in RX J0437.1−4711 appears to be transient; periodicity analysis of the first and second halves of the light curve showed no detectable signal, and a signal at 0.89-day with global confidence of 96%, respectively.

Moran et al. (2005) present analysis of the Chandra data from the low-luminosity Seyfert 1 galaxy NGC 4395. A period of 396 seconds was found in the light curve with estimated global significance of 97.6%. In this case, we again found evidence that the signal is transient; no signal appears in the first half of the observation, but in the second half a strong signal appears with estimated global confidence of 99.95% at a period of 396 seconds.

It is interesting to note that the presence of a QPO does not appear to depend on Seyfert type. Ton S180 is a narrow-line Seyfert 1 galaxy, 1H 0419−577 is a Seyfert 1.5, and both NGC 4395 and RX J0437.1−4711 are both classified as ordinary Seyfert 1 galaxies.

Figure 1. Log of the period as a function of the log of the 2–10 keV luminosity for 4 AGN and Cyg X-1. The dotted and dashed lines have slopes of 1 and 2/3, respectively.
As noted in Halpern, Leighly, & Marshall (2003), there is a correspondence between the X-ray luminosity and the period such that more luminous objects have longer periods. This correspondence is expected if the luminosity and characteristic time scales both scale with the black hole mass. Things get interesting when I compare the period and luminosity of NGC 4395 and Cyg X-1 in the hard state, as shown in Fig. 1. For Cyg X-1, we use the pre-RXTE period of 5.6 s (e.g., Tanaka 1995), but note that using the RXTE values of 0.5–1 s (e.g., Gilfanov et al. 2000) would not change this figure much because it is logarithmic. Remarkably, the linear relationship between the log of the period and luminosity is maintained over the 8 decades of luminosity between Cyg X-1 and 1H 0419−577. However, the slope of the relationship is 2/3, rather than 1, as would be expected for fixed $L/L_{\text{Edd}}$ and emission $R/R_S$. One possibility is that the QPO is associated with the truncation radius of the optically thick, geometrically thin accretion disk, and the dependence on luminosity is a secondary effect, in that the Seyferts are radiating closer to $L/L_{\text{Edd}}$ than does Cyg X-1 in the hard state, in which $L/L_{\text{Edd}} = 0.02$. If that were the case, and if $R = 3R_S$ for Ton S180, we infer that $R = 23R_S$ for NGC 4395, and $R = 95R_S$ for Cyg X-1. Interestingly, $R \approx 100R_G$ is approximately the inferred radius of the inner edge of the optically thick accretion disk when Cyg X-1 is in the hard state (e.g., Gilfanov, Churazov & Revnivtsev 2000).

4. Caveats and Cautions

What do these results say about the incidence of periodicity in X-ray light curves from AGN? There are thousands of X-ray light curves that have not been tested for periodicity, so one might argue that these are isolated incidents and not representative. However, as discussed in Halpern, Leighly, & Marshall (2003), if the characteristic period of Seyfert 1 galaxies is one day or longer, most of those thousands of light curves will be not suitable for periodicity searches. The EUVE light curves were exceptionally long, and thus the fact that some evidence for periodicity was found in the three longest ones suggests perhaps that periodicity is common in AGN. Then what about NGC 4395? It is notable for being the lowest luminosity Seyfert 1, with a 2–10 keV luminosity of only $8 \times 10^{39}$ erg s$^{-1}$ (Moran et al. 2005), much lower than a typical Seyfert 1 galaxy. The fact that we observe the period to scale with the luminosity in the EUVE sample suggests that NGC 4395 should have an exceptionally low period; therefore, since it is unique, luminosity-wise, it makes sense that it is unique, period-wise.
On the other hand, we observe that the periodicity appears to be transient in both NGC 4395 and RX J0437.1--4711 in that in both cases it is detected only in the second halves of the light curves. This suggests that even if periodicity were common in AGN, it may be difficult to observe even in much better data than currently available, simply because too few cycles will be present to detect.

It has been suggested by Vaughan (2005) that the global confidence of the detections claimed in Halpern, Leighly & Marshall (2003) and in Moran et al. (2005) have been overestimated for two reasons. The first reason is that we oversample the periodogram; this was done to improve the sensitivity to frequencies other than the usual Fourier frequencies. This is potentially a problem because oversampling the periodogram will produce more higher peaks, and thus comparison of the real data, with spurious high peaks, with the simulated data will result in overly high single-trial probabilities, or false detections. We investigate this problem in Fig. 2, for the NGC 4395 data. We find almost the same values for the global significance for the total light curve, possibly because the peak for the oversampled power spectrum
is only 20% from one of the Fourier frequencies. For the second half of the light curve, where the periodicity appears stronger, the significance of the oversampled peak is much higher than for the Fourier peak. Perhaps this is because that peak lies almost exactly in between Fourier frequencies.

The second criticism raised by Vaughan (2005) is that the standard analysis does not take into account the uncertainty in the shape of the underlying continuum. That is, we assume that once we measure the underlying power-law spectral continuum, it is fixed, whereas in reality there is uncertainty in the slope, normalization, and even the Poisson noise level. This criticism appears to be well founded, and will no doubt lower the global confidence level of the periodicity detections. Quantifying the new global confidence levels is somewhat difficult, though; there is no direct way to do this.

Acknowledgements

KML gratefully acknowledges helpful discussions with Jules Halpern and Andrzej Zdziarski, thanks the organizers for the opportunity to speak on this topic, and acknowledges funding from NASA ADP grant NAG5-13110.

References

Benlloch, S., J. Wilms, R. Edelson, T. Yaqoob, and R. Staubert. Quasi-periodic Oscillation in Seyfert Galaxies: Significance Levels. The Case of Markarian 766. ApJ, 562, 121, 2001.

Boller, Th., R. Keil, J. Trümper, J., P. T. O’Brien, J. Reeves, and M. Page. Detection of an X-ray periodicity in the Narrow-line Seyfert 1 Galaxy Mrk 766 with XMM-Newton. A&A, 365, L146, 2001.

Fabian, A. C., J. C. Lee, K. Iwasawa, K. Jahoda, W. N. Brandt, and C. S. Reynolds. IRAS 18325−5926. IAUC, 6871, 3, 1998b.

Fabian, A. C., J. C. Lee, K. Iwasawa, W. N. Brandt, and C. S. Reynolds. IRAS 18325−5926. IAUC, 6835, 3, 1998a.

Gilfanov, M., E. Churazov, and M. Revnivtsev. Frequency-resolved spectroscopy of Cyg X-1: fast variability of the reflected emission in the soft state. MNRAS, 316, 923, 2000.

Halpern, J. P., K. M. Leighly, and H. L. Marshall. An Extreme Ultraviolet Explorer Atlas of Seyfert Galaxy Light Curves: Search for Periodicity. ApJ, 585, 665, 2003.

Leahy, D. A., W. Darbro, R. F. Elsner, M. C. Weisskopf, S. Kahn, P. G. Sutherland, and J. Grindlay. On searches for pulsed emission with application to four globular cluster X-ray sources – NGC 1851, 6441, 6624, and 6712. ApJ, 266, 160, 1983.
Leighly, K., H. Kunieda, Y. Tsusaka, H. Awaki, and S. Tsuruta. Evidence for X-ray flux and spectral modulation by absorption in NGC 6814. 1: The nature of the most rapid variability. ApJ, 421, 69, 1994.

Madejski, G., C. Done, T. J. Turner, R. F. Mushotzky, P. Serlemitsos, F Fiore, M. Sikora, and M. Begelman. Solving the Mystery of the Periodicity in the Seyfert Galaxy NGC 6814. Nature, 365, 626, 1993.

Moran, E. C., Eracleous, M., Leighly, K. M. Leighly, G. Chartas, A. V. Filippenko, L. C. Ho, and P. R. Blanco. Extreme X-ray Behavior and Quasi-Periodic Oscillations in the Low-Luminosity Active Nucleus of NGC 4395. ApJ, submitted, 2005.

Tanaka, Y. Physics of Neutron Stars and Black Holes. In X-ray Binaries, Cambridge University Press, 1995.

Timmer, J., and M. König On Generating Power Law Noise. A&A, 300, 707, 1995.

Vaughan, S. A simple test for periodic signals in red noise. A&A, in press, 2005.

Vaughan, S., A. C. Fabian, and K. Nandra. X-ray continuum variability of MCG–6-30-15. MNRAS, 339, 1237, 2003.
