X-RAY VARIABILITY IN ACTIVE GALACTIC NUCLEI

Two Things That Everybody Should Know

KAREN M. LEIGHLY
Columbia Astrophysics Laboratory, Columbia University
538 West 120th Street, New York, NY 10027
leighly@ulisse.phys.columbia.edu

1. Introduction

X-ray variability is a distinguishing property of Active Galactic Nuclei (AGN), and the energetics and time scales of the emission dictate that the X-rays must originate very close to the central engine. In this review I discuss two basic topics from AGN variability research. The first is the correlation of the variability time scale with the X-ray luminosity, and the second is the structure of the X-ray light curve. In each case, I first review the old results that have been known for approximately the last 10 years and then I discuss very new results which may force us to modify our ideas about the origin of AGN X-ray variability. Note that I am discussing the variability of non-blazar type AGN.

2. AGN Variability Time Scales

2.1. THE OLD RESULTS

No matter how you measure it, the time scale of X-ray variability is always observed to be inversely correlated with the 2–10 keV luminosity. Lower luminosity Seyfert galaxies vary on very short times scales, sometimes shorter than 1000 seconds, while higher luminosity AGN vary significantly only on much longer time scales of days. This result was first reported by Barr & Mushotzky (1986) who estimated the doubling time scale by extrapolating observed variability, but the correlation is also found when the time scale is measured in other, more robust ways. Lawrence & Papadakis (1993) found that the amplitude of the variability power spectrum (PDS) at a particular frequency is inversely proportional to the luminosity. This parameter is related to the variability time scale if all AGN have the same shape PDS, as was found in their sample. More recently, from a sample of *ASCA* observations of Seyfert galaxies, Nandra et al. (1997) found that the excess variance, defined as the measured variance of the light curve minus the variance due to measurement error, is inversely proportional to the 2–10 keV luminosity. Since the slope of the PDS is steep down to at least 1×10^{-3} Hz (see Section 3.1), the measured excess variance will be larger for longer observations. However, this parameter can be used for *ASCA* light curves since all the observations are about the same length and have approximately the same sampling pattern.

What could be the physical origin of this correlation? The time scale of variability can be related to the source size, since the emission region must be smaller than the time scale times the speed of light. Then the Schwartzschild radius relates the source size to the black hole mass. If accretion onto a black hole powers AGN and if the emission is isotropic, the luminosity must be smaller than the Eddington value, also related to the black hole mass. Therefore, if the luminosity is the same fraction of the Eddington value in all objects, it is natural for more luminous objects to vary more slowly. However, the dependence does not appear to be exactly one-to-one, possibly a result of a shallow increase in Eddington fraction in more luminous objects; see Lawrence & Papadakis 1993 and Nandra et al. 1997 for further discussion.

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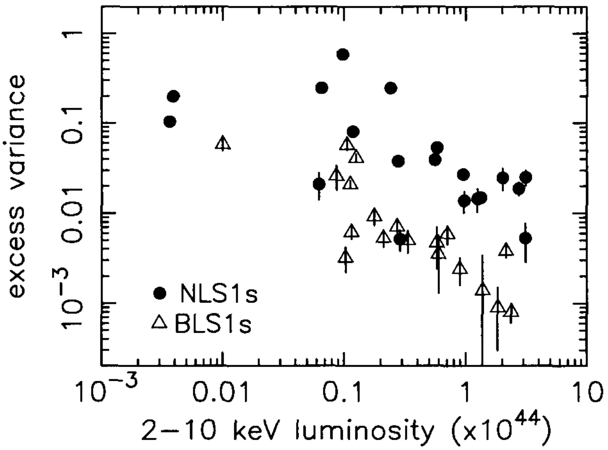

Figure 1. The excess variance versus 2–10 keV X-ray luminosity from *ASCA* observations of AGN. The open triangles, from Nandra et al. 1997, mark AGN with broad optical lines and trace the established correlation of variability time scale with luminosity. The solid circles mark the narrow-line Seyfert 1s (Leighly et al. 1997b). There also seems to be a rough inverse correlation with luminosity but for a given luminosity the excess variance from the NLS1s is generally significantly larger than that from AGN with broad optical lines.

2.2. THE NEW RESULTS

New observations show that things do not appear to be as simple as we thought when you consider, surprisingly enough, the optical classification of the AGN. Narrow-line Seyfert 1 galaxies (NLS1s; not to be confused with NELGs, NLXGs, or Seyfert 2s) are identified by their narrow permitted lines which are only slightly broader than the forbidden lines (Hβ FWHM $< 2000\,\mathrm{km/s}$), low [O III]λ5007 to Hβ ratio, and typically strong Fe II emission (Osterbrock & Pogge 1985; Goodrich 1989). Observations using *ROSAT* revealed the first evidence that this class of AGN often exhibits high amplitude, rapid variability (e.g. Boller, Brandt & Fink 1996; Forster & Halpern 1996). Figure 1 shows the excess variance from *ASCA* observations of NLS1s overlaid on the results found by Nandra et al. for Seyferts with broader optical lines (Leighly et al. 1997b). There appears to be again a rough correlation between excess variance and luminosity; however, for a given luminosity, the NLS1 excess variance is typically an order of magnitude higher.

What could be the origin of this result? One possibility is that NLS1s are characterized by a relatively higher accretion rate. If a higher accretion rate relative to the Eddington value implies a higher luminosity, then for a particular X-ray luminosity the black hole mass can be smaller in NLS1s implying more rapid variability. This scenario is supported by the fact that the X-ray spectrum of NLS1s is also different from that of Seyfert 1s with broader optical lines. Characterized by a stronger and hotter soft X-ray excess component, and a steeper power law (Pounds, Done & Osborne 1995; Brandt, Mathur & Elvis 1997), this is reminiscent of the spectrum of high state Galactic black hole candidates, which are also believed to be accreting at a higher fraction of the Eddington rate.

3. The Structure of the X-ray Light curve

3.1. THE OLD RESULTS

The *EXOSAT* satellite (1983–1986) had a highly eccentric orbit which allowed it to continuously observe a target for up to three days. In contrast, more recent X-ray missions including *Ginga* and *ASCA* have nearly circular orbits and therefore observations are interrupted every ~ 96 minutes by earth occultation and regions of high particle background. Toward the end of the mission, *EXOSAT* made long observations of a handful of rapidly variable AGN. It is from these data that we have gained most of our knowledge about the structure of the X-ray light curve, due to the great difficulty

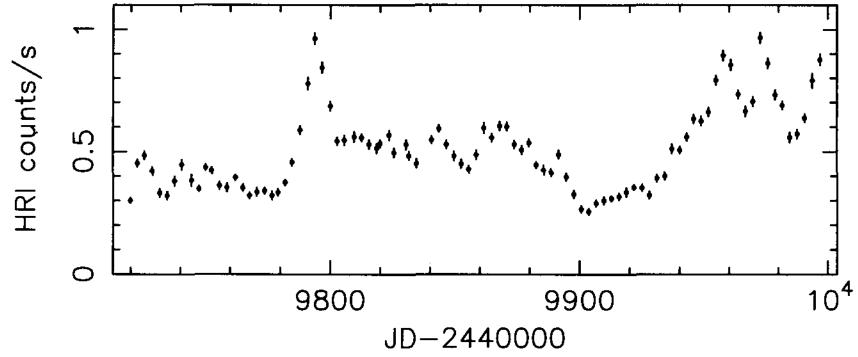

Figure 2. The soft X-ray light curve from the 1995 monitoring of the broad-line radio galaxy 3C 390.3 using the *ROSAT* HRI (Leighly et al. 1997a). The flares and quiescent periods before and after the flares are characteristic of nonlinear variability (Leighly & O'Brien 1997).

of doing time series analysis on light curves with gaps. The result is that the light curves can be described by a steep and essentially featureless power law with $P(\nu) \propto \nu^{-\alpha}$ where the slope $\alpha \approx 1.5$ between 10^{-5} and 10^{-3} Hz (Lawrence et al. 1987; McHardy & Czerny 1987; McHardy 1989; Green, McHardy & Lehto 1993; Lawrence & Papadakis 1993). Because the power law is featureless, the slope of the power law is the only information available to constrain physical models.

What kinds of model can explain this result? Shot noise, composed of randomly occurring, exponentially decaying flares, cannot directly explain this result since $\alpha = -2$ is predicted. However, if there is a range of decay time scales a flatter slope would be found over a limited frequency range (Lehto 1989). The rotating hot spot model attempts to explain the variability in a more physical way. The emission from active regions distributed on a Keplerian accretion disk will be modulated by Doppler and gravitational effects and occultations, and the superimposed individual light curves will produce a steep power-law PDS (e.g. Abramowicz et al. 1991; Abramowicz et al. 1992; Zhang & Bao 1991; Bao & Østergaard 1995). AGN broad band continuum spectra support this model. Hard X-rays are thought to be produced in a corona lying above a disk, the source of the optical and UV emission. Since the UV luminosity L_{UV} is typically much larger than L_X the corona should not cover the disk completely but rather be patchy (Haardt, Maraschi & Ghisellini 1994).

3.2. NEW RESULTS

In 1995 we observed the broad-line radio galaxy 3C 390.3 every three days for nine months, obtaining the first well-sampled AGN X-ray light curve on these time scales (Leighly et al. 1997a; Figure 2). Considerable structure is seen, including flares and periods of quiescence before and after the flares where the variability is significantly reduced. This structure is characteristic of *nonlinear* variability (e.g. Vio et al. 1992). Here "nonlinear" is used in the mathematical sense and it means that the light curve can not be modeled as a sum of *independent* events. Time series analysis found that nonlinearity was detected with $> 6\sigma$ confidence (Leighly & O'Brien 1997). This result is important because it rules out shot noise and rotating hot spot models discussed in the previous section since in those models the events which superimpose to form the power-law PDS are independent.

The flares and reduction in variability before and after the flares is similar to that observed in *Ginga* light curves from the Galactic black hole candidate Cygus X-1 (Negoro et al. 1995). A self-organized critical (SOC) disk model was developed to explain this result (Mineshige, Ouchi & Nishimori 1994). The disk is assumed to be composed of numerous reservoirs, and when a critical density is reached in a reservoir, an instability is triggered, and an avalance of accretion results in a flare. The reservoirs are *coupled* providing the essential nonlinearity in this model. Large flares result when the instability is triggered in many adjacent reservoirs. A reduction in variability is produced after large flares because the reservoirs must fill again, while it is found before the large flares because they are more likely to occur if no small flares have happened to release the potential energy. This model cannot be directly applied to AGN, since the X-rays most likely do not originate in the disk; however, SOC models are quite general.

Nonlinear variability has been recently reported in a series of *ROSAT* monitoring observations of NLS1 IRAS 13224−3809 (Boller et al. 1997) and in fact it is also detectable in the *ASCA* light curve from this object (Leighly et al. 1997b). However, it was not detected in the set of *EXOSAT* long observations discussed in the previous section, although several groups have looked (Krolik, Done & Madejski 1993; Lehto, Czerny & McHardy 1993; Czerny & Lehto 1997). Low signal-to-noise is a possible problem. The SNR of the 3C 390.3 light curve is about 30, and if I degrade the data by adding and subtracting noise, I lose the nonlinearity detection at SNR $\approx$ 10. An alternative exciting possibility is that some objects exhibit linear while others exhibit nonlinear variability, and detection of nonlinearity could prove to be an important physical diagnostic.

4. Future Prospects

The field of AGN X-ray variability study is in a somewhat primitive state, especially compared to the study of variability of Galactic objects. The problem is that AGN generally have much lower fluxes than Galactic objects, and therefore low signal to noise can be a problem. A second problem is that AGN have much longer variability time scales and therefore the variability cannot be not adequately sampled in typical one-day observations. Finally, the gaps in the light curves from low earth orbit satellites are a severe impediment for detailed time series analysis. However, current and new missions soon to be launched should revolutionize the field. *AXAF* and *XMM* will have highly eccentric orbits like *EXOSAT* but much more sensitive detectors. Light curves from long observations of rapidly variable AGN will be amazing. *RXTE*, which has the advantage that about 1/2 of the sky is available during the entire year, is currently monitoring a handful of AGN with intervals of days over long periods of time. The results of these observations also should be very exciting. *ROSAT* is still being used to monitor soft AGN such as NLS1s. Finally, the next generation of all-sky monitors, including the proposed *Lobster* mission and *MAXI* which will be placed on the Japanese module of the space station, should be sensitive enough to obtain SNR=5 detections of 1000 AGN per day, and high SNR flux measurements of about 25.

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