Astron. Astrophys. 326, L25–L28 (1997)

ASTRONOMY AND ASTROPHYSICS

LETTER

Letter to the Editor

Correlation between variability time scale and X-ray spectral index in AGN

M. König, R. Staubert, and J. Wilms

Institut für Astronomie und Astrophysik, Astronomie, University of Tübingen, Waldhäuser Str. 64, D-72076 Tübingen, Germany

Received 26 June 1997 / Accepted 8 July 1997

Abstract. We have analysed EXOSAT ME X-ray light curves of a sample of AGN assuming a stochastic process in these sources. The result is a significant anti-correlation between the relaxation timescale τ, derived from this stochastic model fit, and the photon index Γ of the X-ray spectrum. This establishes for the first time a relationship between variability properties and spectral properties of the emitted X-ray flux of AGN. Even though the physical mechanism for the variations is far from clear, models employing the stochastic superposition of discrete events appear most promising. We propose Comptonization as a possible cause for the relationship.

Key words: X-rays: galaxies

1. Introduction

Rapid X-ray variability of active galactic nuclei (AGN) has been considered a valuable source of information (Wallinder, Kato & Abramowicz 1992) about the physics at work in the vicinity of the supermassive black holes (BH) believed to exist in their centers (Rees 1984). The traditional method in analysing variability has been to generate power spectra in frequency space (Wallinder, Kato & Abramowicz 1992). The power spectra of observed X-ray light curves of AGN usually show three components: a flat part at high frequencies, representing the Poisson noise of the measurement process, increasing power towards lower frequencies, and a flat top at the low frequency end of the spectrum (McHardy & Czerny 1987). The intermediate part, modeled by $1/f^{\alpha}$ with a slope α ranging between 0 and 2, is often taken as characteristic for the variability of the object (Lawrence & Papadakis 1993). A general problem with power spectral analysis in the frequency domain is that the window function (the Fourier transform of the observational sampling) is convolved with the true spectrum of the source. Especially in the case of X-ray satellite light curves which suffer from Earth occultations of the source, artefacts can be produced in the power spectrum complicating its interpretation (Priestley 1996). In addition, the $1/f^{\alpha}$ model fails to describe the flattening of the power spectra at low frequencies.

Send offprint requests to: M. König

2. The Linear State Space Model

We apply an alternative analysis method which works in the time domain thus avoiding problems with window functions and employ an autoregressive analysis (Yule 1927) (hereafter AR). The AR model expresses the temporal correlations of the time series in terms of a linear function of its past values plus a noise term and is closely related to the dynamics of the system. Actual physical processes can often be well represented by an AR model whereas a small number of parameters defines the stochastic differential equations of the system dynamics (Scargle 1981). In the simplest AR model, the damped temporal dependence of consecutive time series values yields an exponential decaying autocorrelation function characterized by the relaxation time τ. We use the AR processes in the generalised form of the linear state space model (Gantert, Honerkamp & Timmer 1992; König & Timmer 1997) (hereafter LSSM) by explicitly modelling observational noise. If an LSSM fit succeeds in describing the light curve dynamics, the temporal correlation of the time series can be expressed by a stochastic superposition of different relaxators or damped oscillators, depending on the order p of the AR[p] process.

To give an example, we present the observed light curve of NGC 5506 (Fig. 1a), and the estimated source light curve (Fig. 1b) – that is the observed light curve freed from observing noise under the assumption of an AR process. The time series of the difference between the observed and the estimated values is distributed like Gaussian white noise of the magnitude expected from counting statistics. These residuals of the LSSM estimation and the observation were tested for white noise behaviour by a Kolmogorov Smirnov test leading to a probability of 99.8% for uncorrelated residuals (König & Timmer 1997). We have

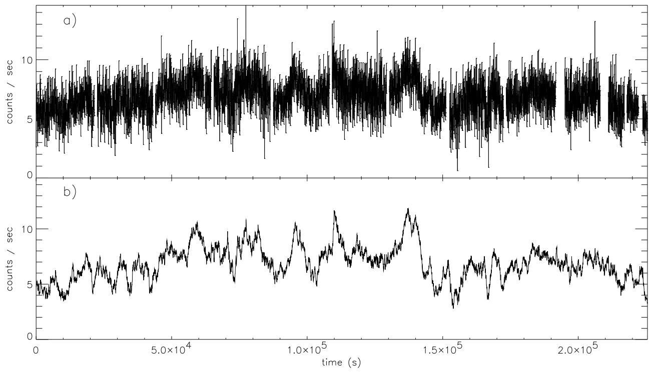

Fig. 1. a EXOSAT ME X-ray lightcurve of NGC 5506 (30sec/bin, Jan. 1986), **b** Hidden AR[1]-process, estimated with the LSSM fit. Both lightcurves are shown without error bars for clarity.

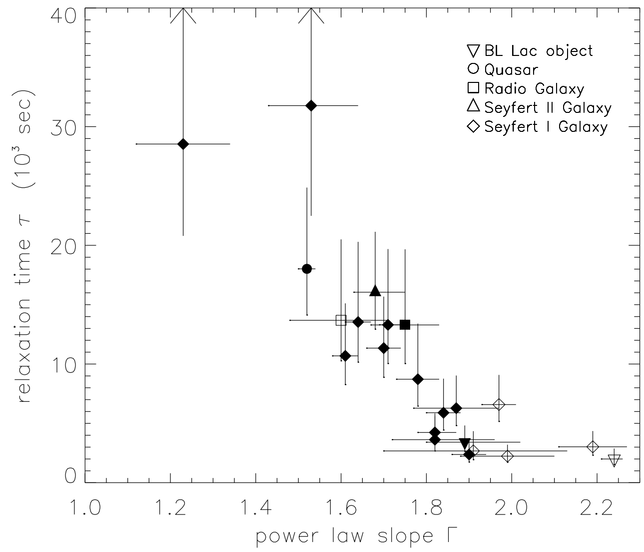

Fig. 2. Correlation plot of estimated relaxation time τ and photon spectral slope Γ (spectral information was taken from Malaguti, Bassani & Caroli (1994, and references therein) and references therein). Filled symbols indicate "good" LSSM fits with a probability $> 70\%$ for white noise residuals.

found that the light curve dynamics can be well modelled by an LSSM AR[1] process with a relaxation time of $\tau = 1.64$ hours for the NGC 5506 EXOSAT ME light curve. Higher order LSSM AR[p] models do not improve the fit significantly which means that more complex models are not needed to describe the dynamics in this AGN. This is true for all analysed light curves. The dynamics of the AR[1] process can be associated with a stochastic superposition of individual shots with only one relaxation time. We also note that the AR[1] process provides all features seen in AGN power spectra, including the flat top at low frequencies which is not covered by the $1/f^{\alpha}$ model (König & Timmer 1997). Note that Fig. 1b cannot be derived from Fig. 1a by a smoothing technique: smoothing removes high frequencies from the light curve, the LSSM approach does not.

3. The EXOSAT AGN Sample

The sample of AGN used here was derived from EXOSAT ME observations longer than 24 ksec which have been proven to be stationary and variable following criteria defined by Green *et al.* (Green, McHardy & Lehto 1993). Altogether, the sample consists of 22 X-ray light curves in the energy range from 1 to 9 keV. The results of the LSSM analysis are presented in Table 1. All light curves of the sample give good LSSM AR[1] fits. This means that the entire variability of each source can be described by a single parameter, the characteristic relaxation time τ of the stochastic process. Table 1 lists the objects and gives details about the EXOSAT observations, the X-ray luminosity and the power law spectral index Γ of the energy spectrum (both taken from the literature) and the relaxation time scale τ resulting from our analysis. For a consistency test, we subdivided long observations into 2 to 5 equally long parts and analysed them individually using LSSM (the time base for the subsets were chosen to be at least 10 times the relaxation time τ determined form the total data set). The individual relaxation times were always consistent with that determined from the entire light curve. We further note that the same applies to cases were EXOSAT has observed the same source more than once (see Table 1): the relaxation times of the process are the same within their uncertainties. We interpret this result as indicating a remarkable stability of the dynamical process on timescales from hours to years. Even when the AGN X-ray flux undergoes strong variations on timescales of hours (König & Timmer 1997) or long term modulations, the characteristics of the stochastic process remain the same.

In Fig. 2 we plot the relaxation time τ versus the photon spectral index Γ. A significant correlation between these two parameters is apparent: the variability is dominated by shorter timescales when the energy spectrum becomes softer (our characteristic timescale τ decreases with increasing photon power law index Γ). Selecting high quality LSSM fits (the filled symbols in Fig. 2, that is those 16 observations for which the Kolmogorov Smirnov test probability for white noise residuals is larger than 70% – see Table 1) we have the following linear relationship: $\tau = (85.9 \pm 10.6)\,\text{ksec} - (43.3 \pm 6.2)\,\text{ksec} \cdot \Gamma$. The formal correlation coefficient of -0.745 (Kendalls tau) corresponds to a probability of $5.7 \cdot 10^{-5}$ that there is actually no correlation between τ and Γ. This correlation establishes for the first time a relationship between a variability time scale and the shape of the X-ray spectrum in AGN. We note that we find no correlation between our variability timescale τ and other characteristic AGN parameters, such as the X-ray luminosity or the power spectral slope (Lawrence & Papadakis 1993; Green, McHardy & Lehto 1993).

4. Discussion

Any model which attempts to describe the physical processes in the centers of AGN must not only reproduce the emerging spectra and the variability behaviour individually but must in addition explain the relationship between these two apparently

Table 1. LSSM fit results of the EXOSAT AGN sample

AGN	AGN type[a]	observation ddd/yy	$T_{\rm tot}$[b] ksec	$L_{2\text{–}10\,\rm keV}$[c] $\log_{10}$ erg/s	τ[d] 10^3 s	$\rm KS_{test}$[e]	$\Gamma^f_{2\text{–}10\,\rm keV}$
Mrk 501	BL	74/86	91.28	43.941	$2.00^{+0.88}_{-0.47}$	0.41	$2.24^{+0.02}_{-0.03}$
Mrk 335	S1	202/85	74.06	43.204	$2.24^{+0.96}_{-0.52}$	0.49	$1.99^{+0.11}_{-0.11}$
NGC 4051	S1	337/85	143.84	41.182	$2.38^{+1.38}_{-0.64}$	0.81	$1.90^{+0.04}_{-0.04}$
Mrk 335	S1	335/85	28.13	43.253	$2.68^{+1.66}_{-0.74}$	0.67	$1.91^{+0.22}_{-0.21}$
Akn 120	S1	24/85	23.93	43.821	$3.02^{+1.33}_{-0.71}$	0.61	$2.19^{+0.08}_{-0.08}$
Mrk 421	BL	338/84	26.59	44.439	$3.41^{+1.41}_{-0.77}$	0.98	$1.89^{+0.13}_{-0.09}$
MCG-6-30-15	S1	28/86	183.69	42.659	$3.63^{+1.98}_{-0.95}$	0.77	$1.82^{+0.14}_{-0.10}$
NGC 4593	S1	176/85	32.49	42.217	$4.24^{+1.60}_{-0.91}$	0.94	$1.82^{+0.05}_{-0.04}$
NGC 5506	S2	24/86	225.56	42.777	$5.89^{+2.88}_{-1.46}$	0.99	$1.84^{+0.04}_{-0.04}$
Fairall 9	S1	286/83	30.60	43.791	$6.28^{+2.75}_{-1.47}$	0.84	$1.87^{+0.10}_{-0.10}$
Mrk 766	S1	364/85	193.90	42.917	$6.59^{+2.50}_{-1.42}$	0.36	$1.97^{+0.04}_{-0.04}$
NGC 4593	S1	9/86	95.65	42.613	$8.72^{+4.69}_{-2.26}$	0.80	$1.78^{+0.05}_{-0.05}$
NGC 5548	S1	62/86	85.88	43.430	$10.69^{+4.43}_{-2.42}$	0.86	$1.61^{+0.03}_{-0.03}$
3C 120	S1	228/83	44.61	43.896	$11.34^{+4.34}_{-2.46}$	0.85	$1.70^{+0.04}_{-0.04}$
Cen A	RG	44/84	44.22	42.147	$13.29^{+6.37}_{-3.26}$	0.94	$1.75^{+0.08}_{-0.08}$
3C 120	S1	276/84	44.52	44.029	$13.30^{+6.38}_{-3.26}$	0.97	$1.71^{+0.03}_{-0.02}$
NGC 5548	S1	19/86	63.75	43.545	$13.54^{+6.75}_{-3.38}$	0.96	$1.64^{+0.03}_{-0.03}$
3C 390	RG	33/85	30.30	43.975	$13.69^{+6.82}_{-3.42}$	0.44	$1.60^{+0.11}_{-0.12}$
NGC1068	S2	8/85	54.35	41.262	$16.05^{+5.09}_{-3.12}$	0.83	$1.68^{+0.07}_{-0.05}$
3C 273	Q	17/86	145.20	46.402	$18.02^{+6.85}_{-3.89}$	0.98	$1.52^{+0.02}_{-0.02}$
NGC 4151	S1	192/83	86.66	42.327	$28.54^{+16.90}_{-7.74}$	0.75	$1.23^{+0.11}_{-0.11}$
NGC 4151	S1	27/85	94.45	42.393	$31.77^{+22.33}_{-9.29}$	0.91	$1.53^{+0.11}_{-0.10}$

[a] BL – BL Lac, S1/2 – Seyfert 1/2, Q – Quasars, RG – Radio Galaxies, [b] total observation time, [c] X-ray luminosity in the 2–10 keV energy range, [d] AR relaxation time, [e] Kolmogorov Smirnov test probability on white noise residuals, [f] slope Γ of the power law fit of the photon spectrum in the 2–10 keV energy range (energy $E \propto E^{-\Gamma}$), taken from Malaguti, Bassani & Caroli (1994).

correlated properties. We propose that the underlying physical mechanism responsible for the observed correlation is Comptonization since it seems to naturally satisfy the above requirements. Comptonization models have been sucessfully used to explain the observed X-ray spectra of AGN (Svensson 1996; Madejski et al. 1995), we also expect them to reproduce our relationship: In Comptonization, low-energy UV photons, presumably generated by shocks or coronal flares in a cold ($\approx$ 100 eV) accretion disk, are upscattered via the inverse Compton effect in a hot ($\approx$ 100 keV) electron plasma. The shock lifetime is determined by the dynamical time scale of the accretion disk (few seconds for a central mass of $10^6\,\rm M_\odot$). The characteristic time scale of the produced X-ray emission gets longer for harder X-ray spectra, since a larger number of Compton collisions is required to produce the high-energy photons in the hard spectrum. This is in line with our observational result.

Recently, Kazanas et al. (Kazanas, Hua & Titarchuk 1997) have expressed the same expectation, namely that a relationship should exist between temporal and spectral properties in Comptonized radiation. They, however, refer (without reference to observational data) to the power spectral slopes as variability indicator for which there is no correlation in our data.

In addition to these arguments, preliminary results of Monte Carlo simulations of the time dependent Comptonization process support our hypothesis. Using such simulations, we intend to arrive at a scalable Comptonization model that is able to reproduce the empirical relationship. If the Comptonization model is correct we would also expect a time-lag between different spectral energy bands. Since the more energetic X-ray photons emerging from the cloud have undergone more interactions than the emerging softer photons, they stay in the cloud for a longer time and are consequently delayed with respect to the lower energy X-ray photons (Payne 1980; Nowak & Vaughan 1996). Although this time-lag has not yet been observed in AGN, it has been observed in galactic black hole candidates, which are thought to have similar radiation mechanisms on similar principles as AGN (Miyamoto et al. 1992; Nowak et al. 1997).

We also would like to stress that in order to explain the short term variability of AGN there is no need to require short term fluctuations in the mass accretion rate. A varying accretion rate only results in a varying shot rate but does not influence the relaxation time of the emission process (König & Timmer 1997). This is in line with our observation that there is no correlation, from object to object, of τ with X-ray luminosity, which we take to be proportional to the mass accretion rate. Presumably, only long term variability on timescales from months to years is caused by changes in the global accretion rate, following the typical viscous timescales of AGN accretion disk models (Mushotzky, Done & Pounds 1993). We therefore speculate that τ might be connected to the black hole's mass. Starting from the Γ-τ-relationship it might be possible to scale the results of time dependent Comptonization models and use a combination of temporal and spectral arguments to estimate the mass of the central black hole.

In addition, we do not find any dependence of the Γ-τ-relation on AGN type. This might be interpreted as a fingerprint of a physical mechanism common to all AGN – possibly in support of the unifying model of Active Galactic Nuclei.

Acknowledgements. We would like to thank J. Timmer for his assistance concerning the LSSM analysis method and C. Gantert for writing the LSSM code which has been kindly provided from the Freiburger Zentrum für Datenanalyse und Modellbildung. This research has made use of data obtained through the HEASARC Online Service, provided by NASA-GSFC.

References

Gantert, C., Honerkamp, J., Timmer, J., 1992, Biolog. Cyber., 66, 479
Green, A. R., McHardy, I. M., Lehto, H. J., 1993, MNRAS, 265, 664
Kazanas, D., Hua, X., Titarchuk, L., 1997, ApJ, 480, in press
König, M., Timmer, J., 1997, A&AS, 124, 1
Lawrence, A., Papadakis, I. E., 1993, ApJ, 414, L85
Madejski, G., Zdziarski, A. A., Turner, T. J., et al., 1995, ApJ, 438, 672
Malaguti, G., Bassani, L., Caroli, E., 1994, ApJS, 94, 517
McHardy, I., Czerny, B., 1987, Nat, 325, 696
Miyamoto, S., Kitamoto, S., Iga, S., et al., 1992, ApJ, 391, L21
Mushotzky, R. F., Done, C., Pounds, K. A., 1993, ARA&A, 31, 717
Nowak, M. A., Vaughan, B. A., 1996, MNRAS, 280, 227
Nowak, M. A., Vaughan, B. A., Dove, J., Wilms, J., 1997, in D. Wickramasinghe, L. Ferrario, G. Bicknell (eds.), Accretion Phenomena and Related Outflows, IAU Coll. 163, in press
Payne, D. G., 1980, ApJ, 237, 951
Priestley, M. B., 1996, Spectral Analysis and Time Series, San Diego: Academic Press, 9th edition
Rees, M. J., 1984, ARA&A, 22, 471
Scargle, J. D., 1981, ApJS, 45, 1
Svensson, R., 1996, A&AS, 120, 475C
Wallinder, F. H., Kato, S., Abramowicz, M. A., 1992, A&AR, 4, 79
Yule, G. U., 1927, Phil. Trans. R. Soc., 226, 267

This article was processed by the author using Springer-Verlag LaTeX A&A style file *L-AA* version 3.