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The Seyfert galaxy NGC 6814 – a highly variable X-ray source

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Abstract. The Seyfert galaxy NGC 6814 is a highly variable X-ray source despite the fact that it has recently been shown not to be the source of periodic variability. The 1.5 year monitoring by ROSAT has revealed a long term downward trend of the X-ray flux and an episode of high and rapidly varying flux (e.g. by a factor of about 3 in 8 hours) during the October 1992 PSPC observation. Temporal analysis of this data using both Fourier and autoregressive techniques have shown that the variability timescales are larger than a few hundred seconds. The behavior at higher frequencies can be described by white noise.

Key words: X-rays: galaxies – galaxies: Seyfert – methods: statistical – galaxies: NGC 6814

1. Introduction

The Seyfert galaxy NGC 6814 was long believed to be the only firm example of an Active Galactic Nuclei (AGN) with a persistent periodicity in the X-ray flux of about 3.4 hours (Mittaz and Branduardi 1989, Done et al. 1990). From ROSAT observations in October 1992 (Staubert et al. 1994) and April 1993 (Madejski et al. 1993) it was concluded that a so far unknown galactic object in the near vicinity of the Seyfert galaxy was emitting the periodically modulated flux. This new object RX J1940.1-1025 which is located about 37 arc min to the west of NGC 6814 was identified as an asynchronous magnetic cataclysmic variable (Staubert et al. 1994; Patterson et al. 1995; Friedrich et al. 1996; Watson et al. 1995).

X-ray flux from the direction of NGC 6814 was dicovered by ARIEL V in 1974 (Cooke et al. 1978) and identified with the Seyfert galaxy which was the most prominent optical counterpart in the satellites field-of-view, eventhough, the likelihood of this correlation was not very good (Elvis et al. 1978).

Considering the limited spatial resolution of the collimated proportional counter instruments ARIEL V, HEAO-A2, Ginga LAC and EXOSAT ME (FOV of $1\overset{\circ}{.}9\times0\overset{\circ}{.}4$, $1\overset{\circ}{.}7\times0\overset{\circ}{.}3$, $1\overset{\circ}{.}1\times2\overset{\circ}{.}0$, $0\overset{\circ}{.}75\times0\overset{\circ}{.}75$, FWHM respectively), the misidentification of the periodic source is not surprising and an imaging instrument such as ROSAT was needed to solve the puzzle.

ROSAT is able to study the radiation from NGC 6814 as an individual source without contamination. NGC 6814 is not an X-ray source with constant X-ray brightness, but shows strong variability. We have analyzed all ROSAT PSPC observations of the galaxy using Fourier techniques (Scargle 1982) and Linear State Space Models, denoted as SSM (Koen and Lombard 1993, König and Timmer 1996). Although NGC 6814 is no more a periodic source, it remains one of the most variable extragalactic X-ray sources.

2. ROSAT observations

ROSAT has performed four pointed observations of NGC 6814 in April and October 1992 and 1993, respectively. The countrate of NGC 6814 varies between 0.007 and 0.177 counts/sec (1σ errors) within the ROSAT PSPC observations (0.1 – 2.4 keV energy range) and the mean countrate of 0.092 counts/sec corresponds to an X-ray flux of $1.35\cdot10^{-12}$erg/s/cm^2 assuming a single power law with fixed $N_{\rm H} = 0.98\cdot10^{21}$ cm^2 (galactic 21cm column density taken from Elvis et al. 1989). The mean 1 keV intensity is $5.8\cdot10^{-4}$ phot/cm^2/s/keV with a photon index $\Gamma = 1.47$ in the 0.1 – 2.4 keV energy range (see Fig. 1).

Data reduction and spectral model fitting was done within the MIDAS/EXSAS package (provided by ESO/MPE Garching). The source counts were extracted from the raw data within a circle centered on the source (with a radius of 400 – 600 sky pixels corresponding to source intensity) and the background counts were derived from a ring around that source circle (all visible X-ray sources within this background ring have been removed). Deadtime and effective area correction has been applied to the data set. Subsequently, the time dependent background was subtracted from the source lightcurve.

3. Flux and spectral variability

The long term behavior of the X-ray flux as measured by ROSAT exhibits a downward trend with a flare-like feature in the October 1992 data (Fig. 2). Over the 1.5 year time baseline of the four observations the mean countrate decreases by about 60%. All four individual observations were tested for variability. Only

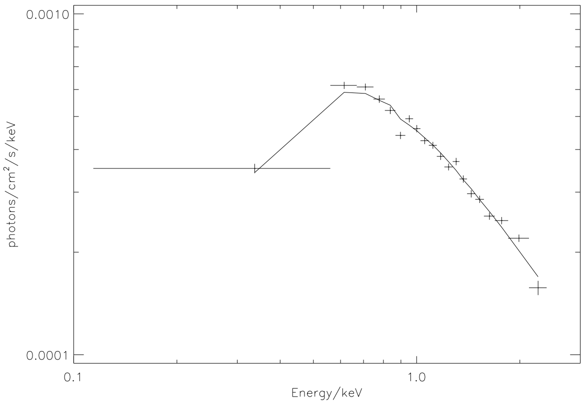

Fig. 1. Energy spectrum of merged ROSAT data from NGC 6814 (see Section 2 for the parameters of the power law fit).

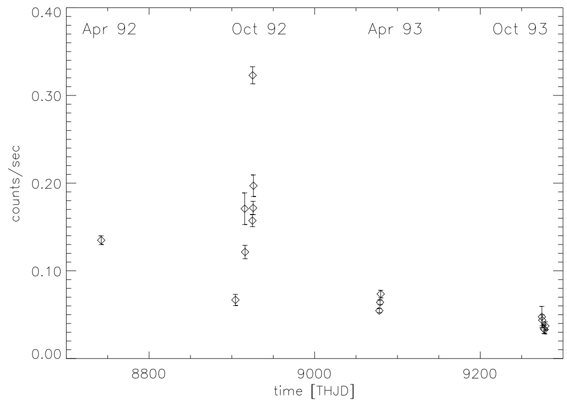

Fig. 2. Complete X-ray lightcurve of the Seyfert galaxy NGC 6814 (ROSAT PSPC, 0.1 – 2.4 keV energy range). The abscissa denotes the truncated heliocentric Julian Days. The ordinate values represent mean countrates of four consecutive orbits.

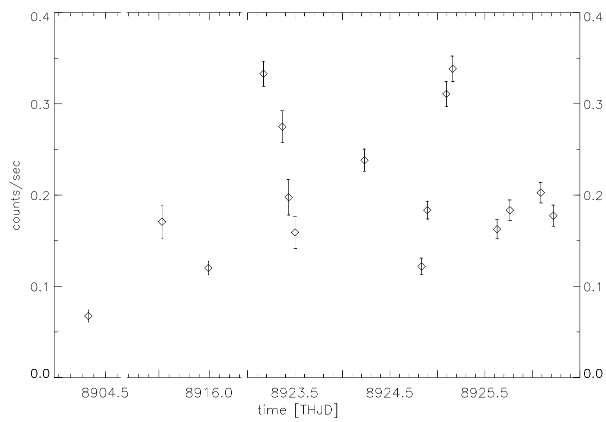

Fig. 3. ROSAT PSPC observation of October 1992 (mean countrates for individual orbits are shown, the abscissa is subdivided into three time intervalls with 0.1 day grids each).

the ROSAT observation of October 1992 indicates strong flux modulation on timescales of hours (see Table 1). The other three observations can be well modelled with a constant X-ray flux with white noise stochastic variations.

We have analyzed the October 1992 observation in detail (Fig. 3). The X-ray flux of NGC 6814 varies by a factor of 2.8 within a timescale of about 8 hours. The observed lightcurves of single orbits indicate variability on timescales of a few hundred seconds (see Section 4).

We have also investigated the spectral behavior of NGC 6814 by fitting single and double power laws to the individual ROSAT PSPC observations. The single power law fits were performed both with free and fixed hydrogen column density $N_{\rm H}$. For the latter we used $0.98 \cdot 10^{21}{\rm cm}^{-2}$ derived by Elvis et al. (1989). Also double power law fits were performed for free and fixed N_H with the hard photon index always fixed to $\Gamma = 1.5$ as derived by Turner et al. (1992) from Ginga observations[1]. The best fit, i.e. the lowest reduced χ^2 value was always obtained for a single power law with fixed $N_{\rm H}$. The results of these single power law fits for all individual ROSAT observations are listed in Table 1.

To test the hypothesis of a spectral hardening with decreasing flux (Yaqoob et al. 1989) , we separated the October 1992 observation in two groups, summing all orbits with high countrates (>0.25 counts/sec) and with low countrates (<0.15 counts/sec), respectively. Subsequently single power law spectra with N_H fixed to $0.98 \cdot 10^{21}{\rm cm}^{-2}$ were fitted to each data group. A photon index of 1.42 ± 0.11 for the 'low flux' data and one of 1.48 ± 0.13 for the 'high flux' data was obtained. This is consistent with a constant spectral shape while the X-ray flux varies by a factor of about three.

[1] However, one should keep in mind that the obervation is contaminated by the close X-ray binary RXJ1940.1-1025, which has a harder energy spectrum (with a power law slope of about 1) in the ROSAT energy range compared to the spectrum of the Seyfert galaxy NGC 6814.

4. Short term variability

A common phenomenon of AGN is the strong variability that can be found in their X-ray lightcurves. This is often described as flickering or $1/f^\alpha$ fluctuations (Lawrence et al. 1987). The $1/f^\alpha$ term describes the distribution of power as a function of frequency in the periodogram.

Any individual observation of the NGC 6814 can be interpreted as a single realization or better as an observation of the realization of a stochastic process. The observed most prominent modulation feature strongly depends on the observation. Therefore, a charaterization which is based on the variability on a single timescale (such as the flux doubling time e.g. McHardy 1988) could be misleading. A more fruitful approach is the examination of the distribution of all observed timescales which is done by computing the periodogram.

The lightcurve of the October 1992 ROSAT observation has a very poor duty cycle of 1.5%. The duty cycle describes the real on-source time relative to the temporal baseline of the to-

Table 1. Individual ROSAT observations of NGC 6814 with single power law spectral fits (fixed N_H^a). Uncertainties are standard errors as given by the EXSAS routines.

Observation/PI	HJD[b]	length (ks)	mean countrate (cts/s)	rms (cts/s)	χ^2_{red} [c]	Γ_{soft} [d]	I_{1keV} [e]	$\chi^2(dof)$
Apr 1992 / Staubert	244 8742.148	8.5	0.137	0.042	1.44	1.65 ± 0.16	0.85 ± 0.04	25.2 (19)
Oct 1992 / Staubert	244 8915.282	28.4	0.181	0.100	7.07	1.43 ± 0.08	1.20 ± 0.03	28.2 (29)
Apr 1993 / Madejski	244 9078.858	37.1	0.062	0.032	1.69	1.49 ± 0.13	0.39 ± 0.02	7.5 (16)
Oct 1993 / Staubert	244 9276.694	28.0	0.037	0.044	1.27	1.45 ± 0.37	0.20 ± 0.02	10.3 (13)

[a] $N_H = 0.98 \cdot 10^{21} cm^{-2}$ (Elvis et al. 1989)
[b] mean time of observation
[c] reduced χ^2 of a test on constant flux
[d] photon index of the fitted power law spectrum
[e] intensity in 10^{-3}phot/cm^2/s/keV at 1 keV for z=0

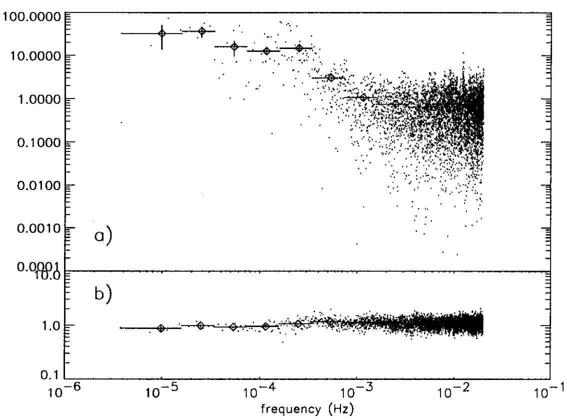

Fig. 4. a Periodogram of the ROSAT PSPC observation of October 1992 (see Fig. 3), **b** Sample periodogram of 100 simulated white noise lightcurves with the same sampling pattern as the original data.

tal observation. The complete observation consists of 16 orbits covering a time interval of about 21 days. If the first three orbits are omitted the duty cycle increases to 8.3% with a baseline of 260 ks. Due to the large gaps in the ROSAT observation of NGC 6814, Fourier techniques can only be used with great caution as the true periodogram might be strongly hampered by the convoluted Fourier transform of the sampling pattern inducing aliasing and spectral leakage (Papadakis and Lawrence 1995). In order to estimate this influence we have simulated 100 white noise lightcurves with the same mean, variance, and sampling pattern as the observed original ROSAT lightcurve. The corresponding periodograms have been compiled to a sample periodogram (Fig. 4b) which shows a nearly flat frequency distribution. The influence of the sampling pattern on the original periodogram can therefore be neglected and the increase of power towards low frequencies (see Fig. 4a) is a real temporal effect of the X-ray source.

The short term behavior is analyzed by computing the sample periodogram of the lightcurves of the 16 individual orbits (Fig. 5). At frequencies lower than 0.002 Hz the power spectrum exhibits a weak linear trend which can be interpreted as the begin of the red noise behavior. Since the background countrate of the ROSAT PSPC detector is very low (Pfeffermann et al. 1986), the flat power spectrum at high frequencies indicates the white noise behavior of the X-ray source NGC 6814 on timescales shorter than 500 sec in the observation of October 1992.

We have also applied SSM fits to the continuous lightcurves of the two longest individual orbits (Fig. 6) to examine the short term variability. The SSM is an alternative model to analyze the variability seen in the X-ray lightcurves in the frequency domain instead of the time domain. Those models are based on the theory of autoregressive processes (Scargle 1981, Honerkamp 1993), denoted as AR[p], which usually cannot be observed directly since the observational noise (i.e. detectors, particle background) overlays the process powering the AGN. An SSM-AR[p] fit applied to the time series data yields the dynamical parameters of the underlying stochastic process. The number of terms p used for the regression of the time series determines the order of the AR process. Depending on the order, the derived dynamical parameters represent damped oscillators, pure relaxators or its superpositions.

The NGC 6814 lightcurve of one orbit (Fig. 6a) can be described by an autoregressive process with a relaxator timescale of about 140 sec. This timescale corresponds to the lifetime of the exponentially decaying autocorrelation function. The other orbit (Fig. 6b) is very likely a white noise lightcurve. The Kolmogorov-Smirnov test prefers an SSM-AR[0] model and the relaxation times of higher order AR fits equal the bin time which indicates that these relaxators are negligible. Even though the statistical significance of the SSM result is limited it is interesting to note that they are in agreement with the variability timescale derived by applying the Fourier analysis.

Due to the flux contamination of the close X-ray binary RXJ1940.1-1025 the much longer EXOSAT ME or the Ginga data with a better duty cycle of NGC 6814 cannot be used for a temporal analysis of the galaxy's variability.

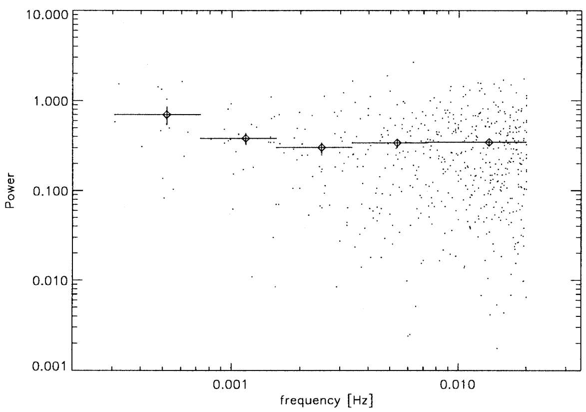

Fig. 5. Sample periodogram of the ROSAT PSPC observation of October 1992 (see Fig. 3, compilation of the 16 individual orbit periodograms).

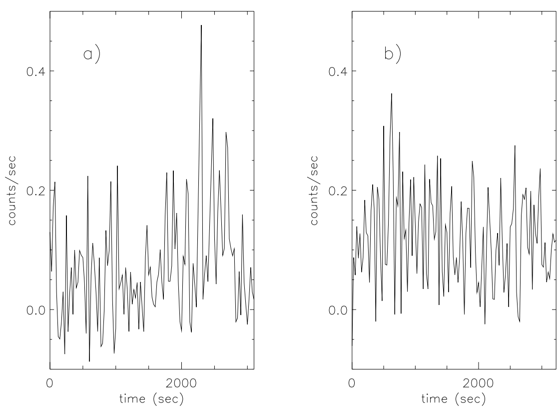

Fig. 6a and b. Orbit lightcurves (orbit 1/16 and 3/16, 25 sec bins).

5. Discussion

Despite the fact that the Seyfert galaxy NGC 6814 has lost its periodicity it still remains one of the the most variable AGN with short term variability on timescales of a few hundred seconds. If a homogeneous X-ray emission region is assumed, this variability timescale is of the same order as the light travel time across the innermost region of the AGN accretion disk. The characterization of AGN variability by this single timescale is misleading as this timescale strongly depends on the observed realization of the lightcurve and therefore varies from one observation to the next. Furthermore the AGN periodograms indicate that the variability is not dominated by a single variability timescale but by a distribution of timescales. The goal is to describe this distribution of all occuring timescales in a more general way (McHardy 1988).

An alternative approach to the short term variability is to interpret the observed X-ray variability as the superposition of single X-ray shots generated in the emission process. This scenario starts with UV photons which are generated by the inflow of accretion inhomogeneities. These UV photon peaks trigger X-ray flares with a specific pulse profile by thermal Comptonisation (Payne 1980, Liang and Nolan 1983). The relaxation time of the exponentially decaying shots corresponds to the obtained relaxator timescale. This relaxation time determines the distribution of frequencies in the periodogram with the typical 'red noise' behavior and the flattening at low frequencies.

Table 2. SSM Fit to orbit lightcurve (Fig. 6a)

Model SSM AP[p]	R^a	P^b (sec)	τ^c (sec)	KS-test^d
0	1	-	-	74.2%
1	0.859	0	137.4	96.7%
2	0.822	0	136.2	95.0%
		0	5.1	

[a] Variance of the observational noise
[b] Damped oscillator and [c] relaxator timescales
[d] Kolmogorov-Smirnov test on white noise residuals

Table 3. SSM fit to orbit lightcurve (Fig. 6b)

Model	R^a SSM AR[p]	P^b (sec)	τ^c (sec)	KS-test^d
0	1	-	-	95.4%
1	0.857	0	25.1	77.4%
2	0.814	154.4	21.5	99.3%

[a] Variance of the observational noise
[b] Damped oscillator and [c] relaxator timescales
[d] Kolmogorov-Smirnov test for white noise residuals

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