X-ray variability in AGN

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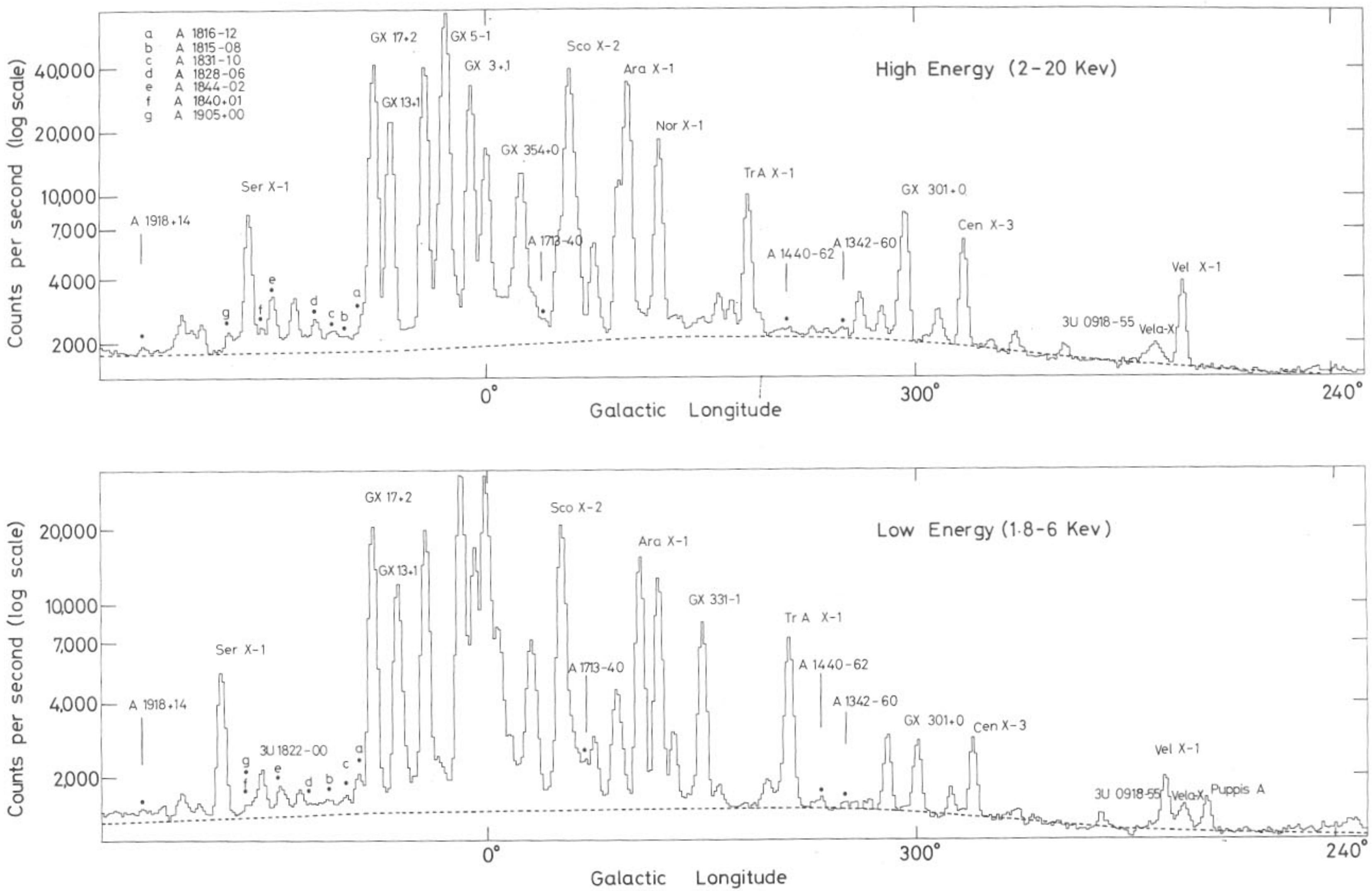
but first … some recollections on the scientific genesis of EXOSAT

- 1966/7 ESRO begins planning for 2nd generation science programme
- X-ray source identification remains a high priority in late 1960s and early 1970s
- more precise positions a key, particularly in crowded GC region



Ariel 5 Galactic plane scan shows many optically unidentified GX sources

- 1967/8 modified Oda telescope proposal submitted to ESRO to fly together with gamma ray telescope (COS-A, in LEO)
- 1969 COS-B (without x-ray telescope) in HEO recommended by Cos group
- but growing support for an x-ray mission
- Connie Dilworth suggested lunar occultation as alternative to imaging optics
- Leicester Skylark rocket flight showed that the occultation technique, viable for heavily absorbed (hard) x-ray sources, would be complementary to NASA's proposed HEAO-2 (Einstein Observatory)

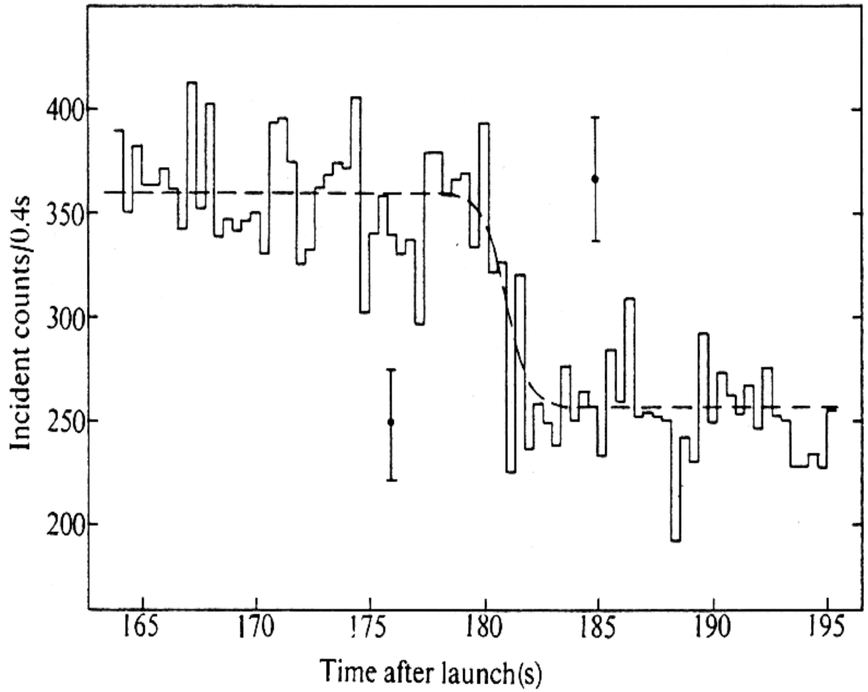
Skylark 1102 27 September 1972

objective - Lunar occultation of GX3+1

2D attitude control via Sun and Sco X-1

occultation at 02.03.26 (0.5)

position arc width 0.8 arc sec (2 sigma)



- meanwhile HELOS approved for study by LPAC in 1971
- and selected in 1973 for start in 1975 and launch in 1979
- but growing competition from NASA
- 1978/9 NASA launch of HEAO-1 and Einstein Observatory
- HELOS re-design with addition of soft x-ray telescope - and retention of high apogee orbit

Back to my advertised topic . . . .

X-ray observations of AGN prior to the launch of EXOSAT

1960s US and UK sounding rocket campaigns detected x-ray emission from several extragalactic sources, including 3C 273, Cen A, M87 (Virgo A)

1972-4 UHURU found many more x-ray sources, including Galaxy Clusters and both radio-loud and radio-quiet AGN.
Majority of high latitude sources remained unidentified - the infamous UHGLS, suggested as a new form of galaxy in scientific case for AXAF

1974-80 Improved positions allowed Ariel 5 to identify most of the UHGLS, finding additional rich Clusters and establishing Seyfert galaxies as a class of powerful x-ray emitters.

Were Seyferts a massive analogue of BH binaries such as Cygnus X-1 ?

Rapid x-ray variability would be a key.

Is the x-ray emission in AGN powered by accretion onto a SMBH?

If so the gravitationally confined plasma might vary on timescales as short as the light crossing time across the most stable orbit.

In a Schwarzschild geometry that is:

$$\Delta\tau \sim R/c \sim 10\ GM/c^2 \sim 500 M_7\ \mathrm{s}$$

where M_7 is the mass of the central object in units of $10^7\,\mathrm{M}_\odot$

with potential x-ray variability timescales of tens of minutes to hours

A discouraging report from US colleagues as EXOSAT was being prepared for launch

- discounting NGC6814 (confusion with a CV star) finding no variability in < 12 hours

THE ASTROPHYSICAL JOURNAL, **264**:92–104, 1983 January 1

THE ABSENCE OF RAPID X-RAY VARIABILITY IN ACTIVE GALAXIES[1]

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Received 1982 April 1; accepted 1982 June 30

ABSTRACT

We have searched for variations on time scales ranging from minutes to several hours in the X-ray flux from 54 observations of 38 active galaxies. Our sample is composed mostly of Seyfert I galaxies but also includes radio galaxies, narrow emission-line galaxies, BL Lac objects, and 3C 273. Only NGC 6814 varied on time scales as short as 100 s. No other source was observed to vary with a time scale of less than 12 hr. We conclude that large-amplitude short-term variations are not a characteristic of the X-ray emission from active galaxies. Upper limits on σ_I/I ranged from 2% for Cen A, 5% for NGC 4151, to $\sim$20% for sources giving 1 count s^{-1} in our detector. Three objects, NGC 3227, NGC 4151, and MCG 5-23-16, show variability consistent with a time scale of $\sim$1 day.

then came the EXOSAT ‘long looks’ in its final few months when control gas running out

LETTERS TO NATURE 19 February 1987

Low-frequency divergent X-ray variability in the Seyfert galaxy NGC4051

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The X-ray emission from NGC4051, a nearby low luminosity Type 1 Seyfert galaxy, exhibits variations that are both rapid and apparently quasi-periodic[1,2]. Many Seyfert galaxies are variable[3] but our knowledge of the form of variability has not advanced substantially since early well-resolved observations[4] and attempts at statistical description[5]. Here we report an uninterrupted 62-h observation of NGC4051 with the EXOSAT observatory, giving an order of magnitude improvement in the quality of the time series, allowing comparison with X-ray binaries. The observed power spectral density is roughly proportional to $1/f$, similar to Cyg X-1, and characteristic of turbulent processes. No preferred timescale or luminosity gradient has been seen so far. If this behaviour holds generally for active galactic nuclei, quantities derived from short samples will be subject to selection effects.

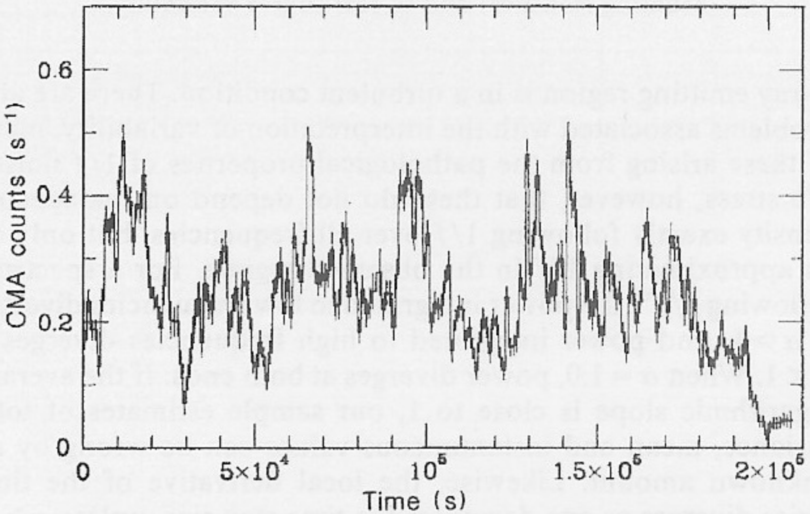


Fig. 1 X-ray light curve of NGC4051, commencing 1985 December 3 02:20 UT. Data presented here are from the EXOSAT[18] low-energy energy imaging system, the Channel Multiplier Array (CMA, ref. 19), using the thin Lexan filter, covering the energy range 0.05–2 keV. The source was also seen in the medium energy (ME, ref. 20) proportional counter array, showing variability closely similar to that seen here with the CMA. Bin size used is 1,000 s, error bars are $\pm\sigma$. Data were background-subtracted and exposure-corrected as in [2].

is smooth and divergent at low frequencies, following a form close to $1/f$, where f is frequency. The shape is not necessarily exactly $1/f$, but for our purposes the important factors are the low-frequency divergence, and the fact that no preferred time-scale stands out. We also cannot reject the possibility of modest

low mass Seyfert NGC 4051 showed large amplitude x-ray variability over 10s of minutes throughout a 62 hr on-target EXOSAT observation

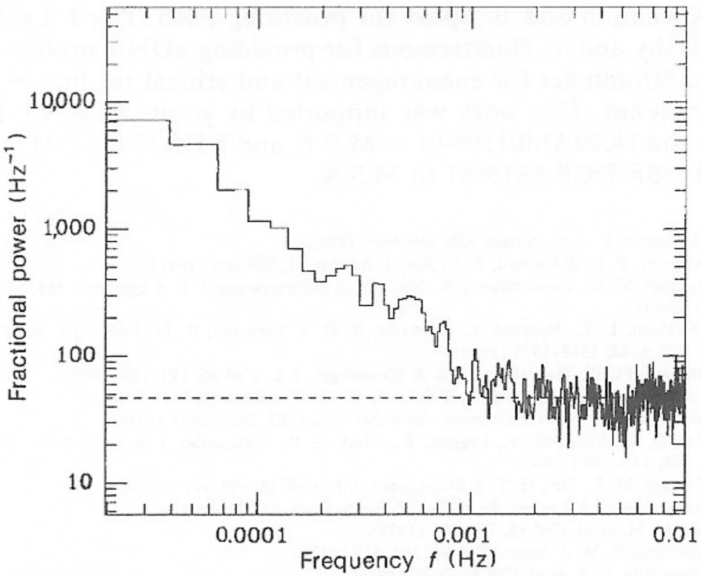


Fig. 2 Power spectral density, calculated by forming the auto-variance function (ACV), applying a Hanning roll-off, and Fourier transforming. The ACV was calculated from data summed in 50-s bins (4,531 samples), and was truncated at a lag of 512 bins, so that the lowest frequency represented in the power spectrum is sampled ~5 times. The power per Hz has been divided by the total sample variance, calculated using the same bin size, to give fractional contribution per Hz to the total observed variance. This includes contributions due to both experimental error (that is, counting statistics) and to real source variability.

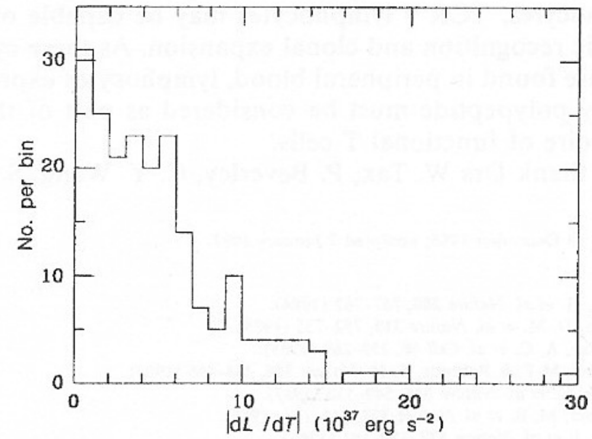


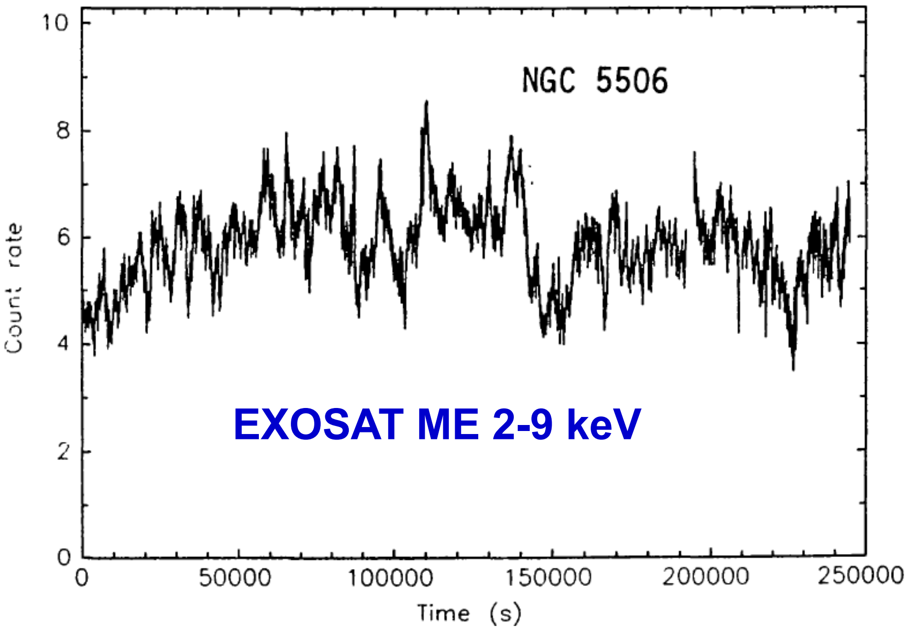
Fig. 3 Distribution of absolute values of dL/dt, in units of 10^{37} erg s^{-2}, calculated with 1,000-s bins.

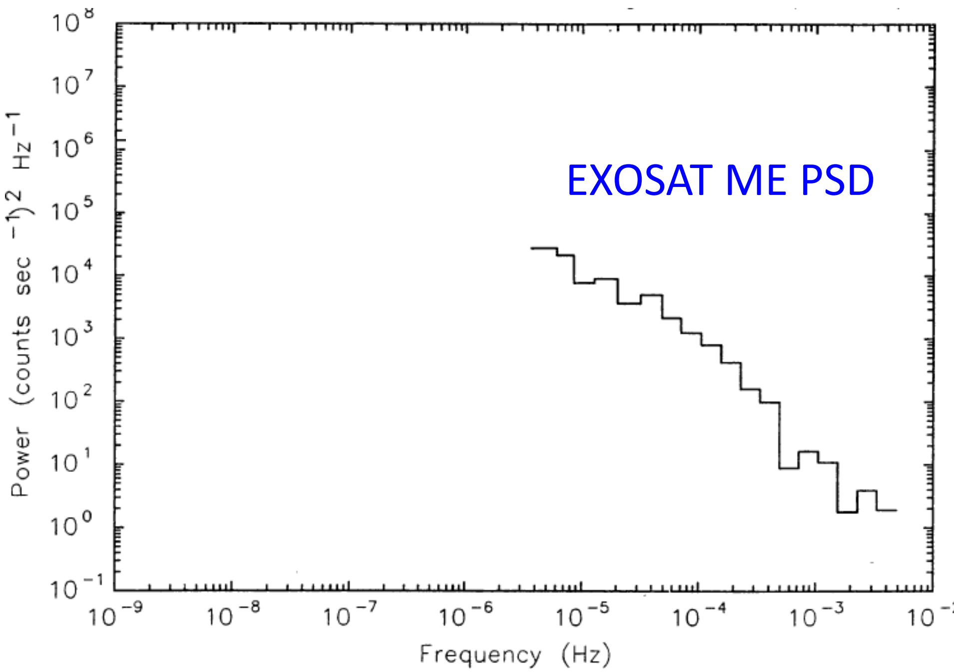
scale' as used by Barr and Mushotzky[3] thus depends on data quality and coverage. (Given an instrumental time resolution limit, one only has to wait long enough before seeing a factor of two change.) Furthermore, only for exponential events will the doubling timescale deduced from large and small amplitude changes be identical.

The shape of the power spectrum also implies problems for another quantity of interest, dL/dt, the rate of change of luminosity, which can be used in model-independent formulae to derive the efficiency of energy generation, and the compactness parameter[13]. The arguments used are weak if applied to

high amplitude fast variability – but no characteristic timescales

more luck with a more massive Seyfert NGC 5506



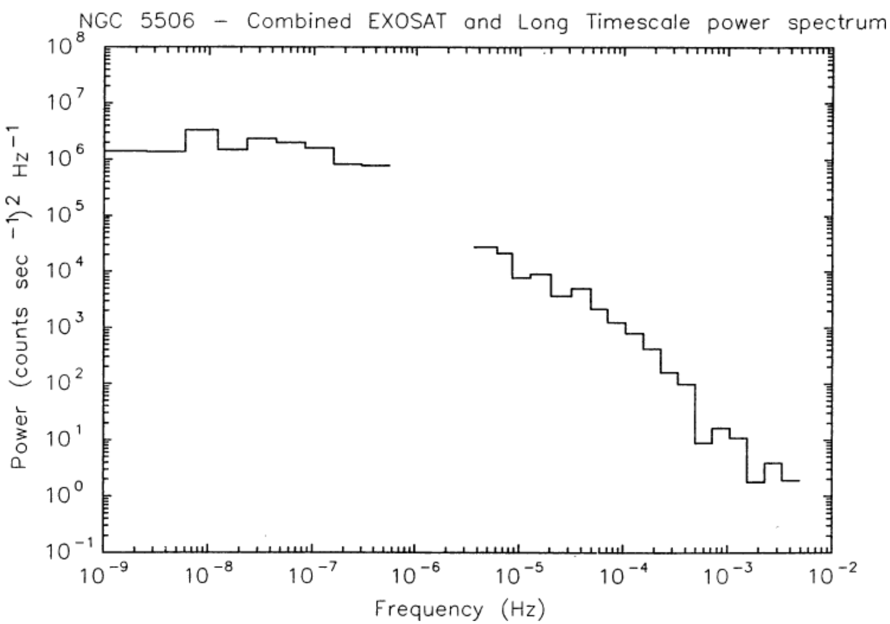


(McHardy and Czerny 1987)

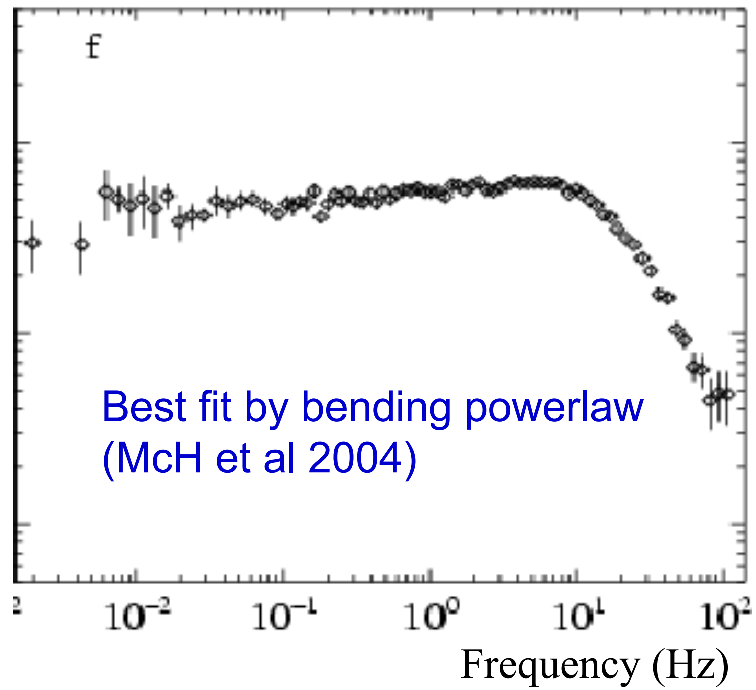
(McHardy 1988)

again no strong characteristic timescale in the high frequency (EXOSAT) power spectrum

However, adding long timescale data, eg from Ariel 5 reveals a bend in the PSD, similar to that in the black hole binary system, Cygnus X-1, from which we can scale to get a BH mass.



Cyg X-1 SOFT state PSD



>>>>> SMBH mass in NGC5506 a few times $10^7 M_\odot$

Four other contrasting EXOSAT long looks – two rapidly variable and two not

logX ~ 42.3

~ 43.2

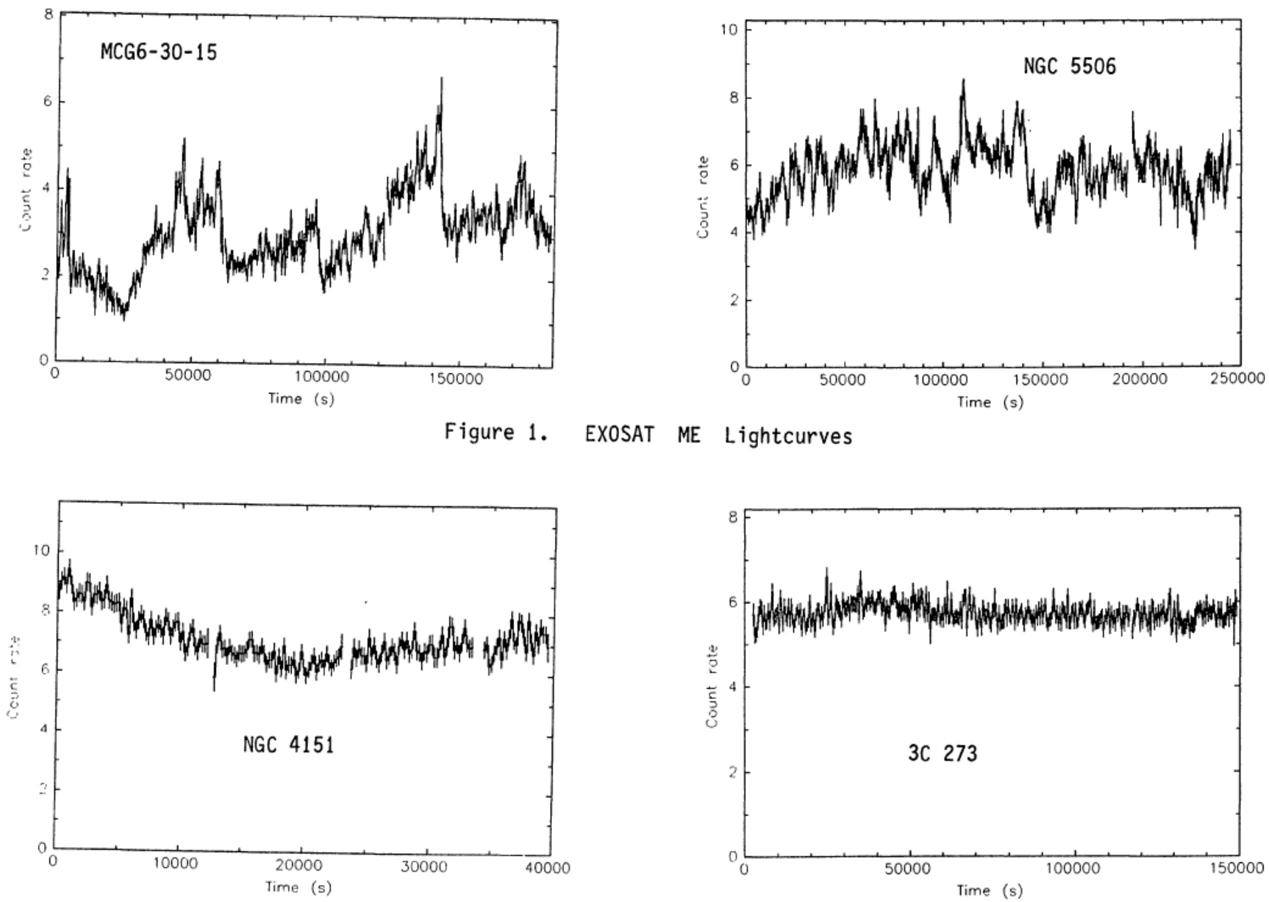


Figure 1. EXOSAT ME Lightcurves

~ 42.5 but obscured

~ 45 massive

McHardy (1988) Mem.della.Soc.Ast.Italiana vol 59 pp 239-259

Looking back – why was EXOSAT so much more successful in finding rapid variability than the large A2 detector on HEAO-1 ?

- less optimum choice of objects: including heavily obscured Seyfert 2 and extreme luminosity (massive BH) AGN, eg 3C 273
- higher detector background
- use of xenon detector (3 – 15 keV) when (as we now know) strongest variability at lower energies
- but the most important difference was probably much worse sampling as a result of LEO for HEAO spacecraft

In summary –from a user perspective:

EXOSAT 1983-86 - a pioneering first European X-ray astronomy mission

- deep space orbit
- uniquely broad spectral cover
- operated as a true international observatory

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EXOSAT-2 (a.k.a. XMM-Newton) 1999 -

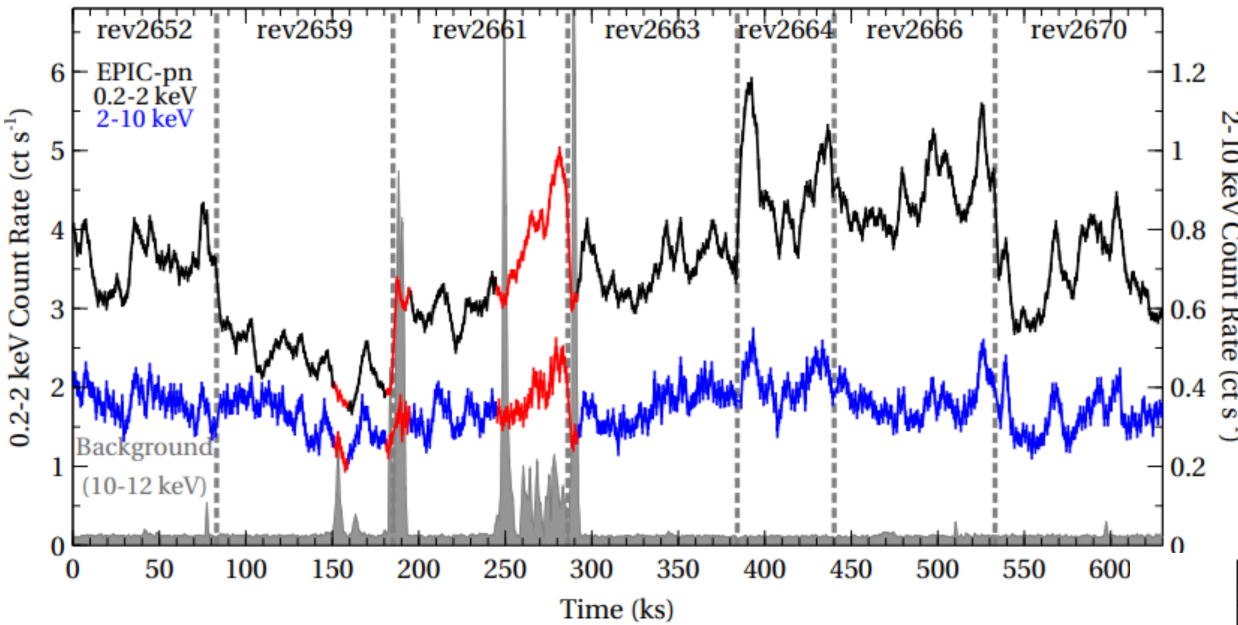
the highest photon grasp of any current x-ray observatory

- best for timing
- and for spectroscopy
- new fields of study, eg powerful AGN winds

My final slides show related XMM-Newton data from a 2014 XMM study of the luminous Seyfert galaxy and archetypal UFO, PG1211+143 (a source originally chosen as of interest by the EPIC PI, Martin Turner, and originally passed to me for study as Martin was too busy with EPIC support !).

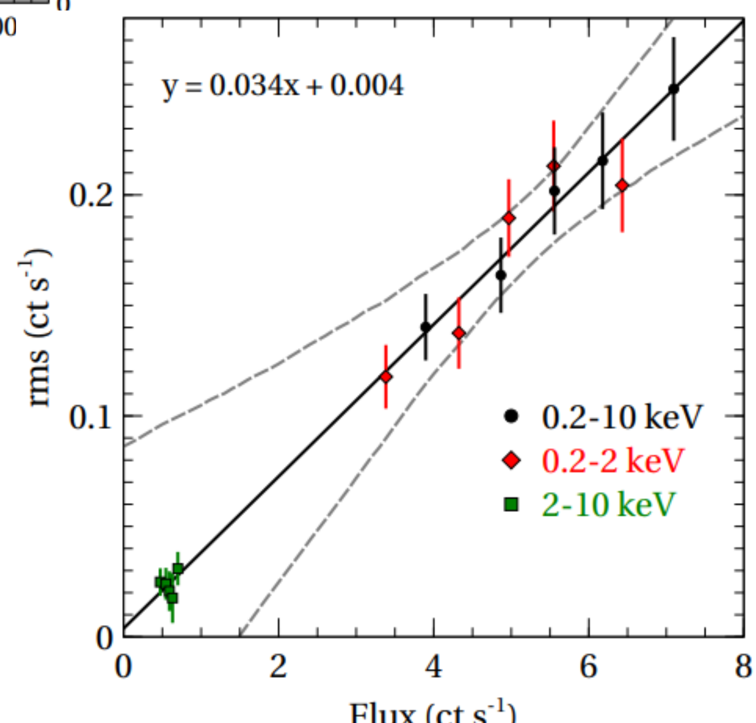
Slides courtesy Andrew Lobban and from Lobban et al 2016,2018.

PG 1211+143: Variability Analysis

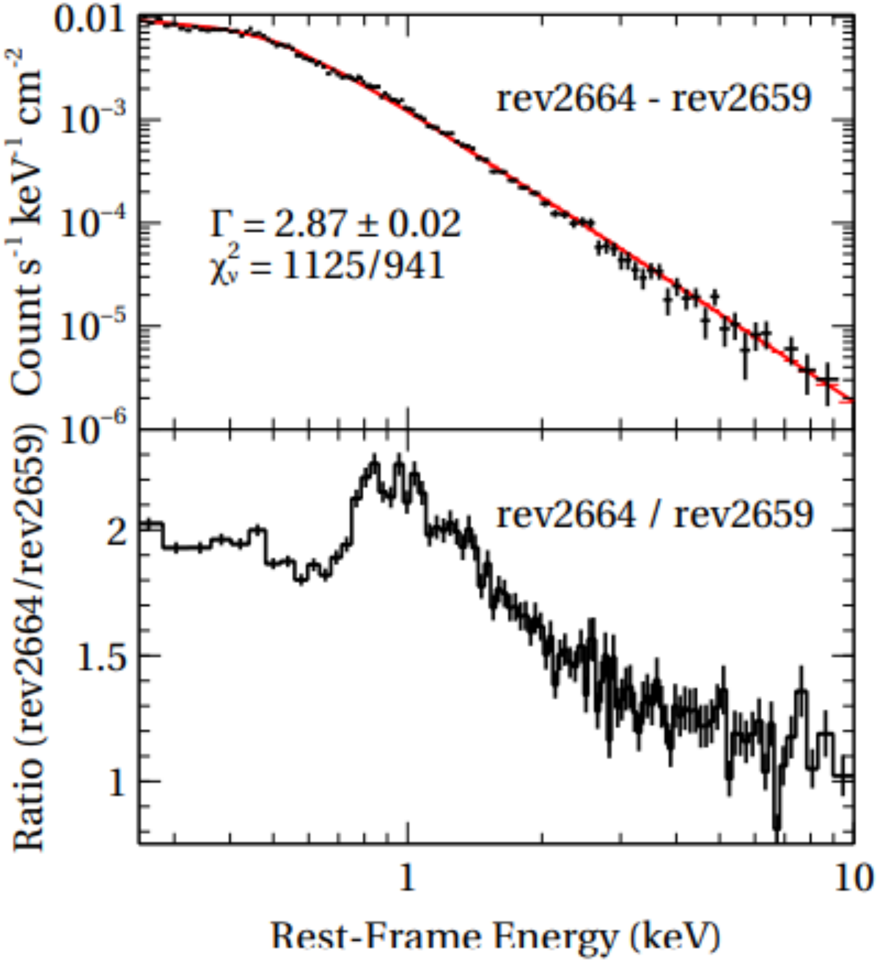


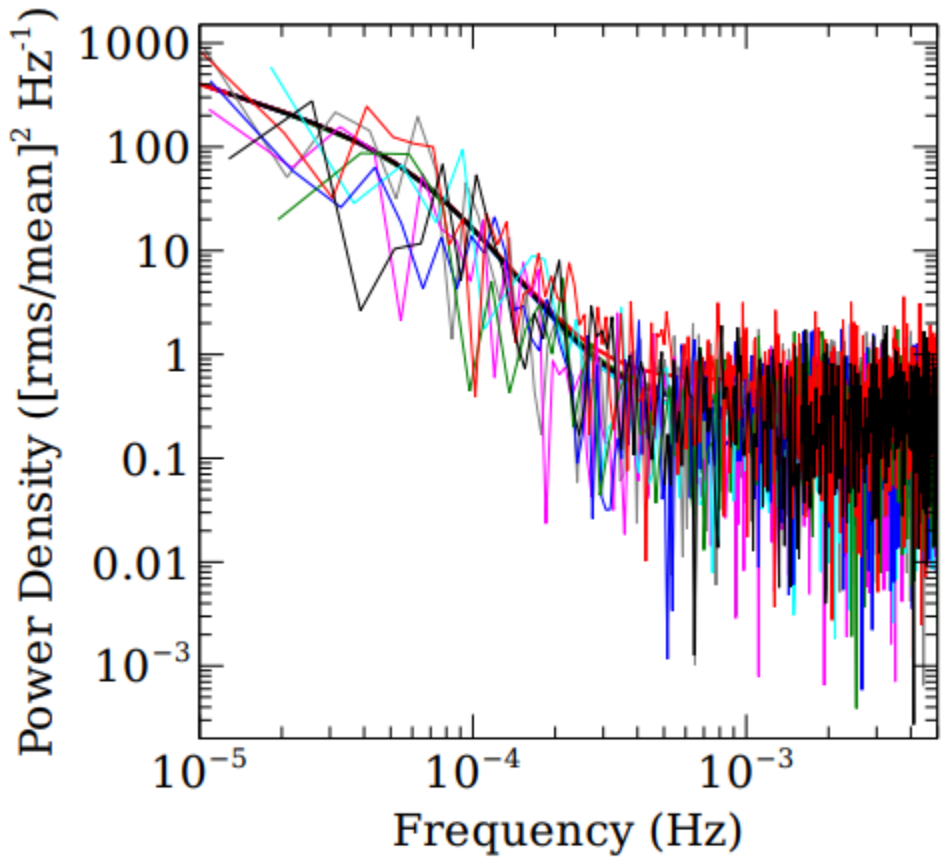
- EPIC-pn lightcurve (soft and hard bands); dt = 1ks
- Varies by ~50% on inter-orbit (~10ks) timescales
- Soft band brighter and more variable

- rms-flux relation across three energy bands
- Absolute rms amplitude of variability scales linearly with source flux (dashed lines show 95% uncertainty bands)
- Similar to behaviour observed in other AGN, XRBs and ULX sources (Uttley & McHardy 2001; Gleissner et al. 2004; Heil & Vaughan 2010)
- Suggests similar intrinsic accretion processes, scaling with black-hole mass



PG 1211+143: Variability Analysis

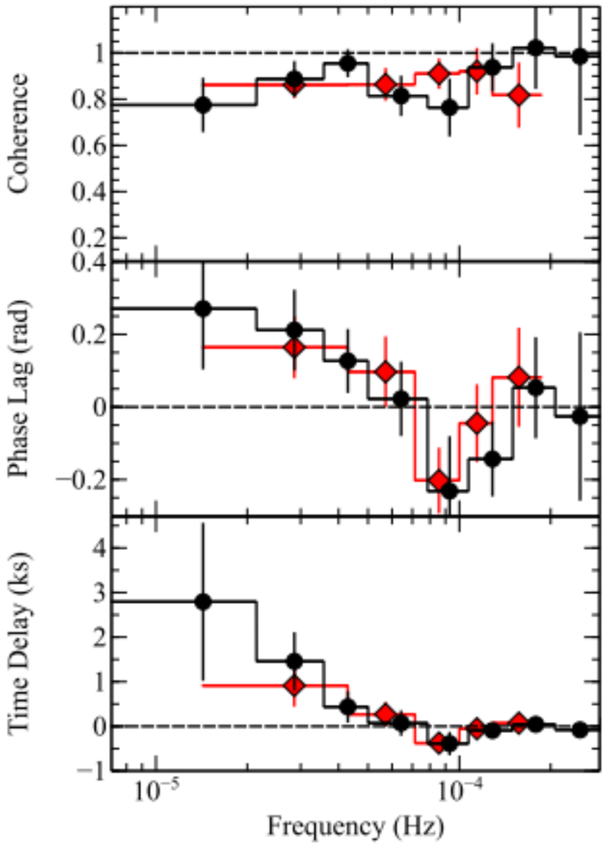




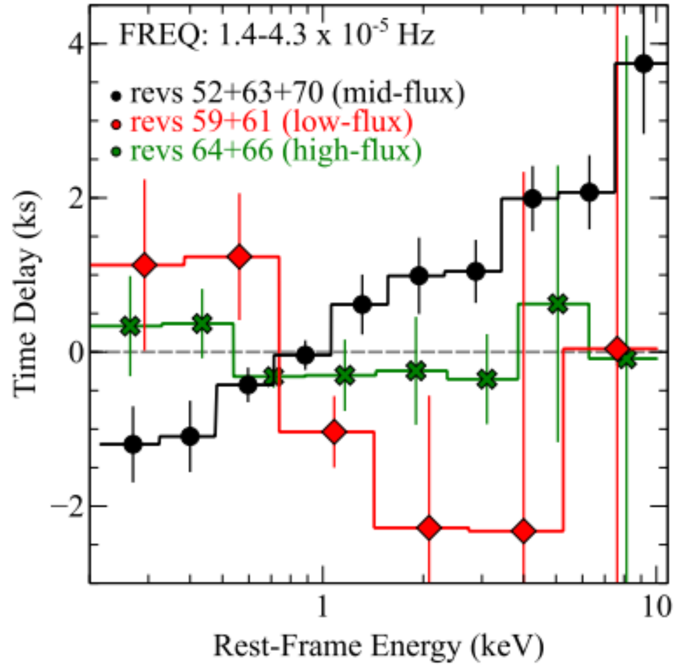
- Difference and ratio spectra
- Steep component dominates variability
- Significant residual structure at ~0.8-1 keV – warm absorber

- PSD: raw periodograms
- Bending power-law model detects PSD break at ~7e-5 Hz
- Long XMM campaign detects break for first time in this source
- Consistent with BH-mass scaling relations (González-Martin & Vaughan 2012)

PG 1211+143: hard and soft lags

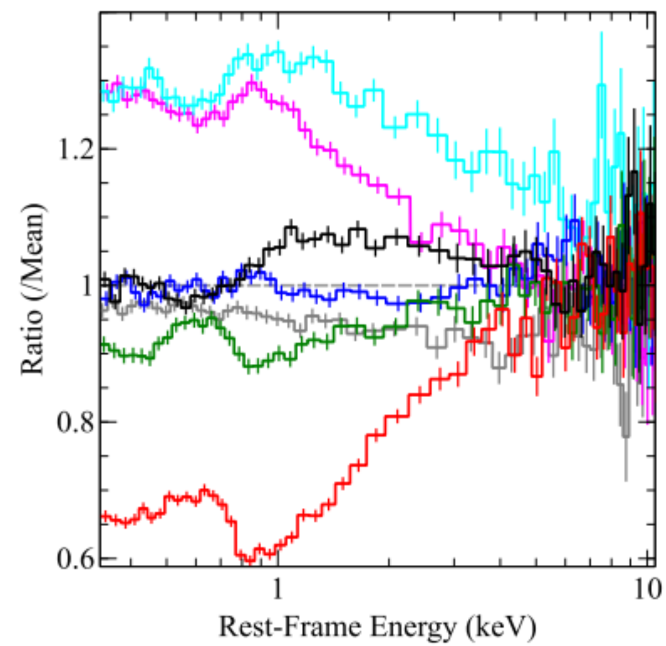


•Fourier time lags: 0.7-1.5 vs 2-10 keV
•Low frequencies: hard lag
•High frequencies: soft lag emerges
•Black: 70ks segments; red: 35ks segments

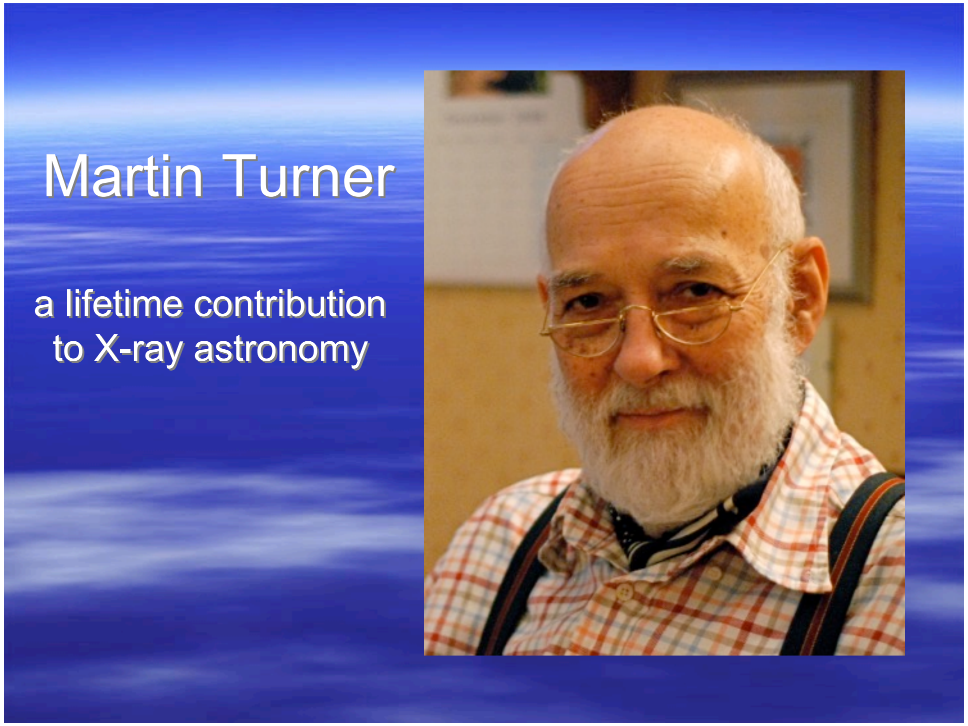


•All seven EPIC-pn observations as ratio to mean spectrum
•Red = rev2659: significant absorption event – linked to changing lag behaviour?

•Energy-dependence of low-frequency lags against broad reference band
•On-average: log-linear shape
•But: dependence changes with flux and/or time
•Linked to 'absorption event' in rev2659?



In celebrating the success of EXOSAT perhaps it is also timely to recall some heroic colleagues no longer with us.
One such is of course Martin Turner:



EXOSAT	MEDA
GINGA	LAC
XMM	EPIC

a much missed friend and colleague with truly the golden touch !