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SMALL-AMPLITUDE COHERENT SIGNALS IN THE X-RAY EMISSION OF NGC 4151

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ABSTRACT

We present the results of the temporal analysis performed on four *EXOSAT* medium-energy observations of the Seyfert galaxy NGC 4151, selected for their long duration and background stability. The light curves can be adequately described in terms of regular trends (representing variations on time scales ≥ 1 day) to which small-amplitude fluctuations are superposed. The harmonic analysis, applied separately to each one of the observations, provides evidence that a substantial fraction of the power in these fluctuations is contained in coherent signals occurring at either one or both of the frequencies 7.9×10^{-5} and 1.7×10^{-4} Hz, which, within the frequency resolution achieved, are in a ratio compatible with 2 and can be therefore assumed to be harmonically related. The amplitude (peak-to-peak) of these signals varies from one observation to the other and reaches at most 7%. If the period corresponding to the lower frequency is interpreted as the signature of the orbital time of matter near the innermost stable orbit around a collapsed object, its mass can be estimated to be close to $2.5 \times 10^7 M_\odot$ for the Schwarzschild metric.

Subject headings: galaxies: individual (NGC 4151) — galaxies: nuclei — galaxies: Seyfert — galaxies: X-rays

I. INTRODUCTION

The Seyfert galaxy NGC 4151 was observed with the medium-energy (ME) experiment (Turner, Smith, and Zimmerman 1981) on board the *EXOSAT* satellite 26 times between 1983 July and 1986 March (Pounds *et al.* 1986, Perola *et al.* 1986; Yaqoob, Warwick, and Pounds 1989). The source flux, in the energy band 2–10 keV, varied by about one order of magnitude. In the course of the single observations the light curve of the source counts was often characterized by a fairly regular trend, upward or downward, with superposed small-amplitude rapid fluctuations.

The unique capabilities of *EXOSAT* to perform long uninterrupted observations, up to 2×10^5 s and to monitor simultaneously the source and the background, allow one to study the short time variability of active galactic nuclei by performing an appropriate harmonic analysis. The results reported so far for Seyfert galaxies indicate that, in general, their observed power distribution can be reasonably well described by smooth spectra with slopes between -1 and -2 in the interval 10^{-5}–10^{-3} Hz (see Pounds and McHardy 1988 for a review), with the notable exception of NGC 6814, where most of the power appears confined at a few priviledged frequencies (Mittaz and Branduardi-Raymont 1989).

In this paper we describe the results of the harmonic analysis performed on four selected observations of NGC 4151, two of which are $\sim 8 \times 10^4$ s long. We shall show that the corresponding power density spectra, in addition to a continuum largely associated with the trends, appear to contain features which can be interpreted as evidence of coherent signals in the small-amplitude rapid fluctuations.

II. OBSERVATIONS AND DATA ANALYSIS

The ME experiment comprises eight detectors arranged in two halves, one of which was pointed at the target and the other about 2° away from it to monitor the background. In the course of each observation the two halves were swapped typically every 10,000–15,000 s, in order to compensate for their different response to the particle induced background (PIB). The counts were telemetered in 10 s bins. Each detector is a proportional counter with an upper cell filled with argon (1–20 keV) and a lower cell filled with xenon (6–50 keV); we concentrated our analysis on the 2–10 keV argon counter data, the only data with a source signal statistically good for the purpose of this paper.

In order to avoid as much as possible the presence of spurious effects in the harmonic analysis of the light curves, we selected among the 26 observations those which satisfy the following criteria: long exposure time ($\geq 2.5 \times 10^4$ s) and stability of the simultaneously acquired background. There are four such observations, and they are listed in Table 1; the only other observation with a long exposure (1985/027 $\sim 10^5$ s) was excluded because the background was affected by a conspicuous increasing trend all the way through. Macroscopic instabilities in the background led us to exclude from the harmonic analysis also the first 16,000 s and the last 28,000 s of the observation 1986/060 and the last 3500 s of the observation 1985/135, thus reducing the useful duration T to the values given in Table 1. The observation 1983/193, which was performed during calibration operations, differs from the others in that the two halves were interchanged only once, after the first 40,000 s, and it is affected by several interruptions lasting from a few hundred to a few thousand seconds. In all observations temporal gaps lasting from several hundred to a few thousand seconds are present in connection with the swaps, in addition to rather frequent but fortunately short (typically 10–20 s) gaps due to telemetry dropouts.

To make sure that any variation in the count rate measured by the instrument as a whole was not the consequence of events confined to a single detector, we examined separately

TABLE 1

THE FOUR OBSERVATIONS

Date	Duration (s)	C_{av} (2–10 keV) (counts s^{-1})	B_{av} (2–10 keV)[a] (counts s^{-1})	A (% hr^{-1})	D (% hr^{-2})	α[b]	β[b]
1983/193......	8.3×10^4	8.2	11.7	3.01	−0.04	0.8%	2.1%
1985/002......	3.1×10^4	19.6	14.3	1.32	−0.05	0.4	1.5
1985/135......	3.5×10^4	9.3	13.7	−9.16	0.7	0.7	1.1
1986/060......	7.6×10^4	2.8[c]	6.7[c]	−0.41	0.04	0.8	2.6

[a] The background rate is a weighted mean between the two halves of the instrument.
[b] The quantities α and β are defined in the text.
[c] This count rate refers only to the external counters; see text.

the data from each one of them. For the observation 1986/060 we found that only the data from the external counters could be safely used, because the inner counters had been affected by repeated failures.

In the context of a harmonic analysis of the source light curve, the subtraction of the background from the sum of the "on source" detector counts is a delicate procedure, because in addition to the large difference in the PIB response of the two halves there is a small difference in the response of the same half in a different geometrical configuration: to take the latter difference into account, we corrected the background counts acquired in the offset position for the "difference spectrum" integrated in the 2–10 keV energy interval (Parmar and Izzo 1986). Since this correction may not represent exactly the circumstances in which the observations under study were obtained, the results of the harmonic analysis will have to be scrutinized also for the effects associated with the swaps because of this imperfection in our knowledge of the background.

The four light and background curves are shown in Figures 1–4 in bins of 500 s. The light curves appear to be characterized by a more or less pronounced and regular trend, to which comparatively small-amplitude and short-term variations are superposed. Quantitatively, in Table 1 we give for each observation: the average net source count rate C_{av} and background count rate B_{av}, the values of the parameter A and D obtained by fitting the light curves with a parabola:

$$\frac{C}{C_0} = 1 + A(t - t_0) + D(t - t_0)^2 , \quad (1)$$

the percentage rms of the variations in the background (α) and in the light curve residuals after subtraction of a parabolic trend (β). The quantities α and β were computed in 500 s bins and corrected for the amount expected on purely statistical grounds if the source and the background had stayed perfectly constant. We note that β was always at least ~ 2 times larger than α, thus confirming that the small-scale short-term variations in the light curves were intrinsic and not due to those present in the background.

III. THE RESULTS OF THE HARMONIC ANALYSIS

We computed the power spectral density (PSD) of the light curves by applying the Fourier transform (FT) to the data summed in bins of 50 s. Such a bin width is sufficiently long for the source to be detected at least at the 5 σ level even in the observation when it was faintest; moreover, it allows us to bridge the short gaps due to the telemetry dropouts. To take care of the other gaps previously mentioned, we used the algorithm of Deeming (1975) for unevenly spaced data. The power

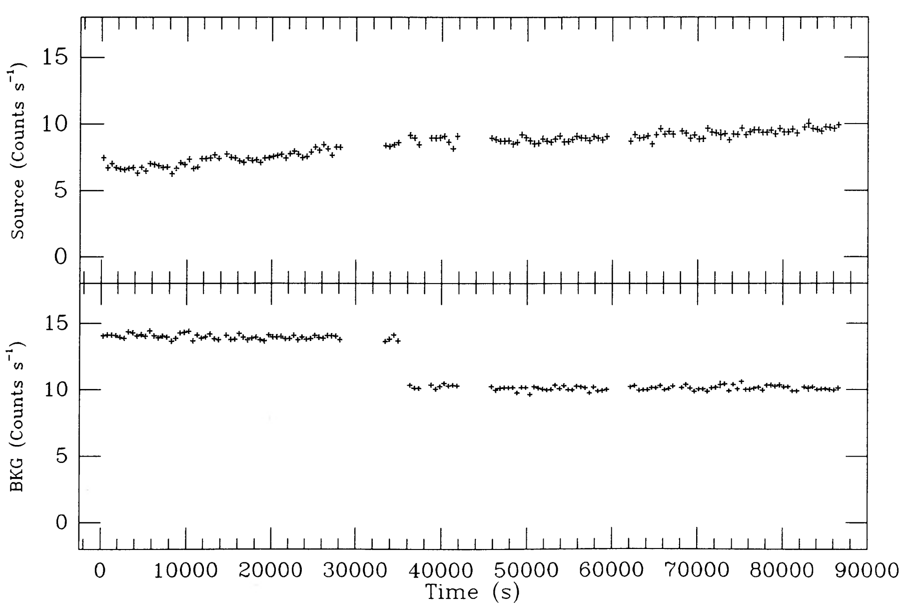


FIG. 1.—The 2–10 keV light curve of NGC 4151 and that of the simultaneous background. Observation 1983/193.

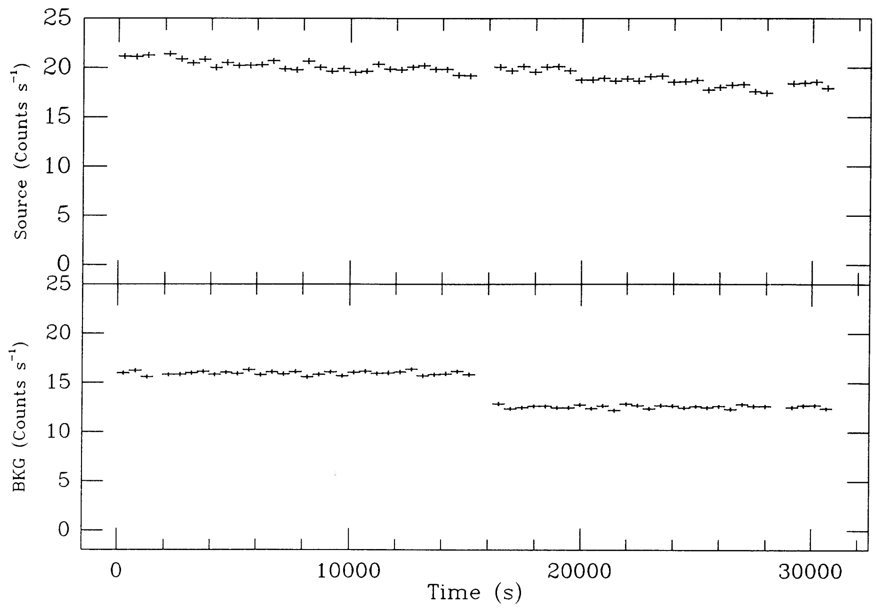


FIG. 2.—As in Fig. 1; observation 1985/002

spectra were then divided by half the total counts in the observations: with this normalization the expected value of the PSD of a Poissonian distribution of data points is equal to 2, and one can estimate the statistical significance of each spectral point with respect to the noise from the χ^2distribution with two degrees of freedom (Leahy *et al.* 1983).

The power spectra are shown in Figure 5, sampled in steps of $\Delta f = 1/T$, the frequency resolution, which differs from one observation to the other. While at frequencies higher than $\sim 3 \times 10^{-4}$ Hz the four distributions appear to be dominated by the Poissonian noise, at smaller frequencies they exhibit a significant excess on which we concentrate our attention and make the following considerations.

1. The "slope" of the distribution of the excess can be estimated by taking the ratio of the average power in the interval 0–6×10^{-5} Hz to that in the interval 6×10^{-5}–3×10^{-4} Hz: this quantity corresponds to a slope -0.7 in 1986/060, -1.9 in 1985/002, -2.1 in 1983/193 and in 1985/135. The three observations with the steeper slope are also those with the faster trend in their light curves, and it is therefore important to evaluate to what extent the power spectra of the four observations are affected by the combined effect of the trend and the windowing due to the FT algorithm (Deeter and Boynton 1982). To this purpose we computed the FT of the parabolic trends with the same sampling and duration of the original light curves. One example is illustrated in Figures 6*a* and 6*b*, which give the PSD of the trend fitted to the observation 1985/002 before and after perturbing the parabola with Poissonian fluctuations with the amplitude expected from the source plus background count rate. These figures show very clearly the

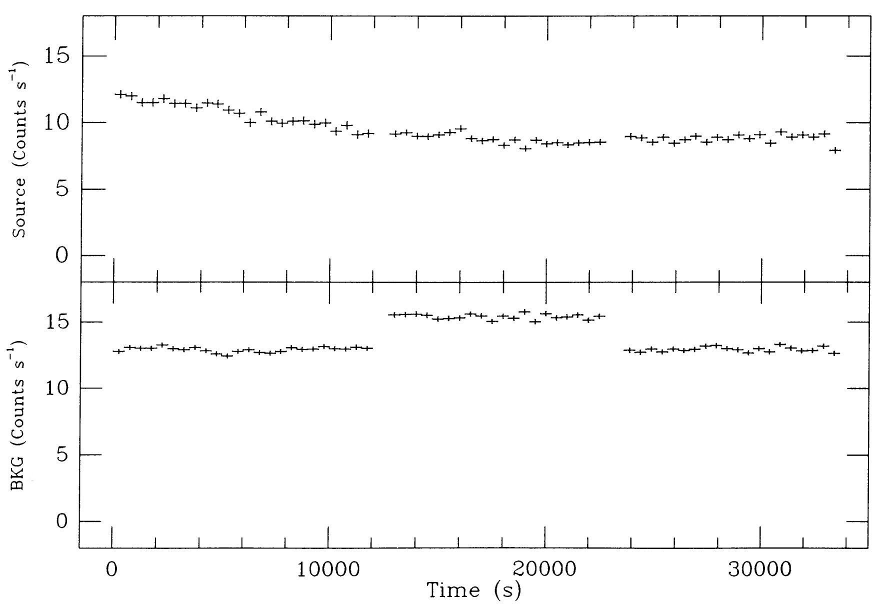


FIG. 3.—As in Fig. 1; observation 1985/135

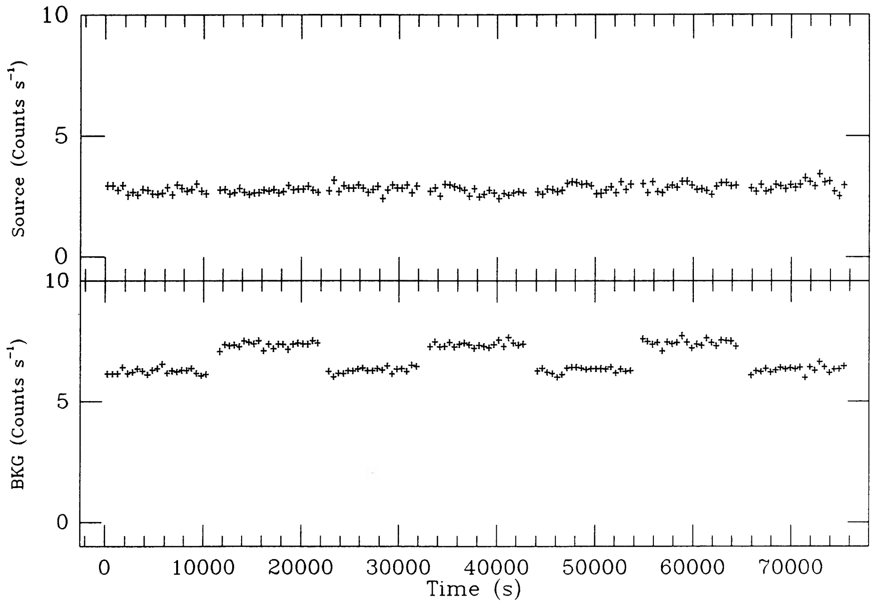


FIG. 4.—As in Fig. 1; observation 1986/060

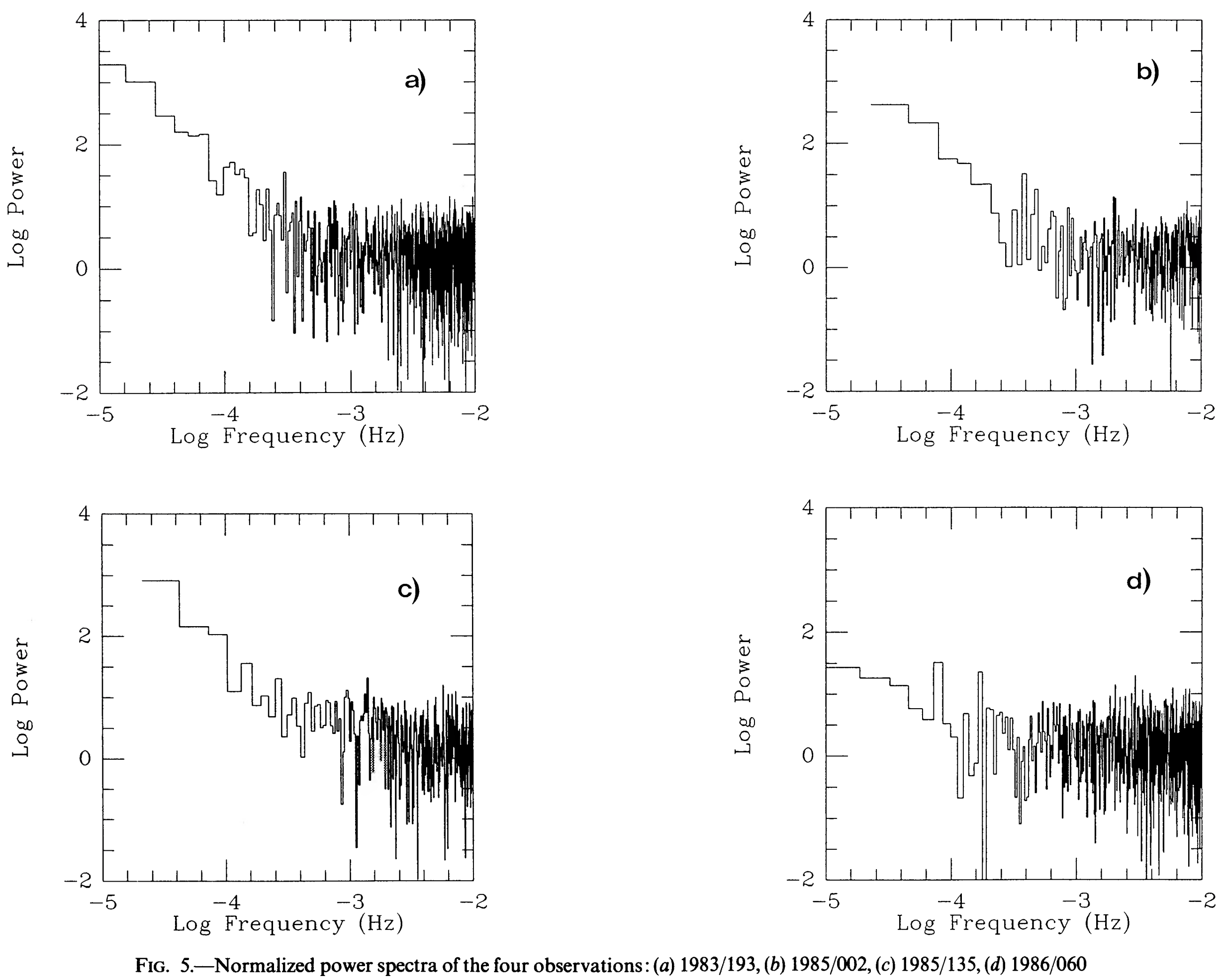
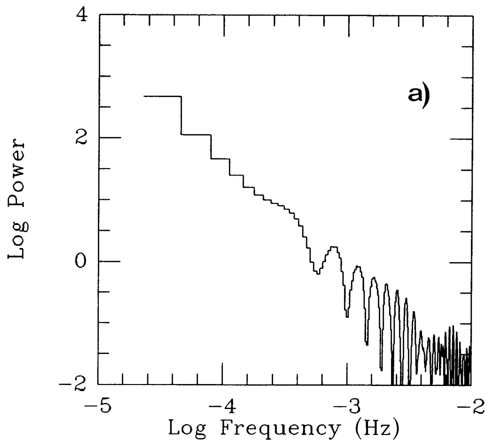


FIG. 5.—Normalized power spectra of the four observations: (*a*) 1983/193, (*b*) 1985/002, (*c*) 1985/135, (*d*) 1986/060



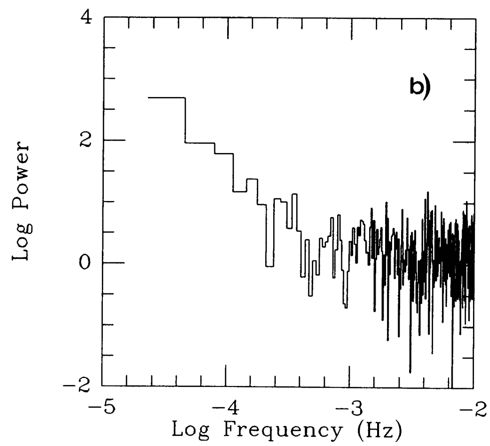


FIG. 6.—The normalized power spectra of the parabolic trend fitted to the observation 1985/002, (*a*) before and (*b*) after, perturbing the parabola with Poissonian noise.

effects of the window, in particular that of shifting a substantial fraction of the power associated with the trend toward the higher frequency part of the interval on which we are concentrating. This effect represents a limitation for the standard FT technique in evaluating slopes intrinsically steeper than -2 and should be held responsible for the fact that the slope of the PSD of the trend turns out to be approximately equal to -2 in all four observations, while the amplitude is correlated with the steepness of the trend. We would therefore conclude that the steep slope in the PSD of the observations 1983/193, 1985/002, and 1985/135 is due to the dominant contribution of the trend to their PSD, while the shallow slope in the observation 1986/060 can be interpreted as due to a contribution by the short-term variations which is comparatively large with respect to the power associated with the slow trend.

2. In the spectral region around 10^{-4} Hz of the observation 1986/060 we further note the presence of unresolved features that are particularly outstanding relative to the overall excess. This suggests the presence of "real" features, as opposed to features due to statistical fluctuations in an intrinsically continuum distribution. The former possibility looked sufficiently attractive to us to encourage further investigations on all four observations.

To this purpose we computed the PSD of the four light curves which obtain after subtracting the parabolic trend: they are given in Figures 7*a*–7*d*. We note, first, that most of the excess at the lower frequencies has disappeared, as expected; second, that an excess power is still evidently present below 3×10^{-4} Hz in the observations 1983/193, 1985/002, 1986/060, those three with the larger value of β in Table 1; third, and most important, that in these observations a substantial fraction of this power is concentrated in a few outstanding features. Here by "outstanding" we mean points with a value such that the probability of a fluctuation in the Poissonian noise is very small. By choosing for the PSD a limiting value of 20, corresponding to a probability of 4.5×10^{-5}, the points with a value larger than that are listed in Table 2, where, for further reference, they are identified with a letter. There are two such features in each one of the three spectra: they are all unresolved (in the sense that the adjacent points on each side of them have a value much lower than 20), with the exception of the feature 1983/193b which comprises two adjacent points with values 20.95 and 18, respectively. In Table 2 we give also the frequency resolution Δf, the net power P_f associated with each one of the features, and the total power P_t between 0 and 3×10^{-4} Hz, together with the number N of independent PSD points in this interval, and the ratio P_f/P_t (by "net" we mean the power corrected for the contribution expected from the Poissonian noise); note that each feature contains at least 27% of P_t.

We have carefully scrutinized the possibility that these features might be associated with the swaps or be traced in the background. With regard to the swaps, the answer is positive for the features 1983/193a and 1985/002a, and only these two, because they occur at the frequency where, in each of the two observations, one would expect to find most of the power

TABLE 2

FEATURES IN THE POWER SPECTRA

Date	Δf (Hz)	Identification	f (Hz)	P_f	$P_t(N)$	$\frac{P_f}{P_t} \times 100$
1983/193......	1.2×10^{-5}	a	2.3×10^{-5}	42[a]	112 (25)	38
		b	7.5×10^{-5}[b]	35[b]		31
1985/002......	3.2×10^{-5}	a	6.4×10^{-5}	25[a]	69 (9)	36
		b	1.6×10^{-4}	21		30
1986/060......	1.3×10^{-5}	a	7.9×10^{-5}	21	77 (22)	27
		b	1.7×10^{-4}	27		35

[a] Probably of instrumental origin.
[b] This feature comprises two adjacent points; the frequency given is the mean of the two.

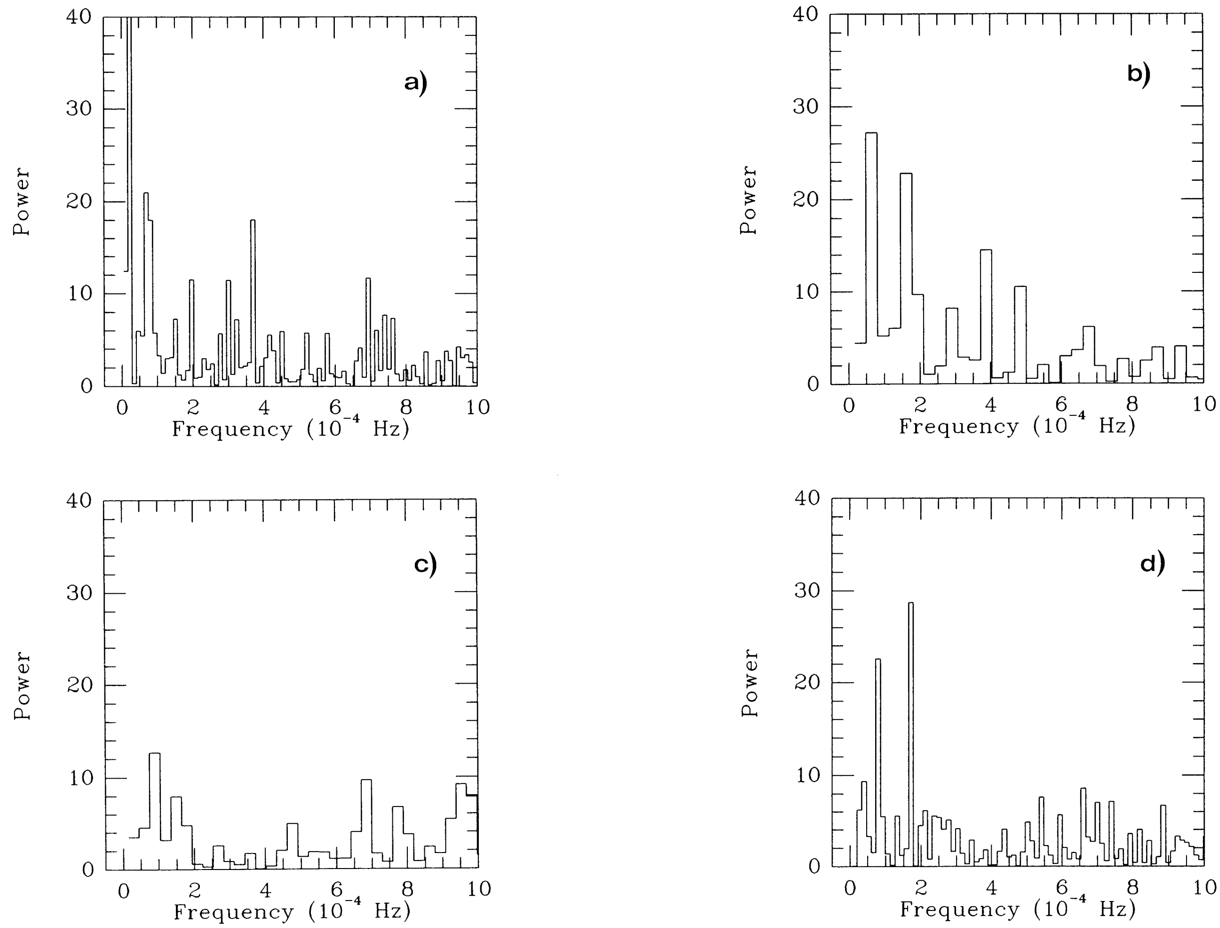


FIG. 7.—The normalized power spectra of each observation computed after the subtraction of a parabolic trend: (*a*) 1983/193, (*b*) 1985/002, (*c*) 1985/135, (*d*) 1986/060.

caused by imperfect corrections for the difference between the two instrument halves: we shall therefore disregard them from now on and concentrate on the remaining four. With regard to the background, we studied separately the counts in the 2–10 keV interval collected by the counters pointed away from the source and those in the 12–20 keV interval recorded by the counters pointed at the source. The overall distribution in the PSD of the two background measurements turned out to be consistent with Poissonian noise, and in particular nothing suspect was found at the frequencies of the four features of interest.

After this scrutiny both features in the observation 1986/060 have remained bona fide. The probability of a chance occurrence of each one of these features due to the Poissonian noise can be obtained from the χ^2 distribution with two degrees of freedom multiplied by the total number of independent frequency bins and turns out to be 9×10^{-3} (feature a) and 4×10^{-4} (feature b). A more conservative estimate should take into account the possibility that the two features might be fluctuations in an intrinsically smooth distribution of power, and therefore evaluate the probability that 62% of P_t (see Table 2) be concentrated by chance in only two out of 22 "channels." To this purpose we assumed for simplicity a model where intrinsically the power P_t is distributed evenly among the 22 channels (that is a flat distribution) and produced several thousands of random data sets with the same variance of the 1986/060 light curve. We then used the results of these simulations to estimate that probability which turned out to be 7×10^{-4} (corresponding to a 3.4 σ result).

By comparison with simulations properly accounting for the noise, we found that the narrow structures of the features 1985/002b, 1986/060a, and 1986/060b are compatible with those expected in the case of coherent undamped signals of amplitude proportional to $(P_f)^{1/2}$ with a peak frequency falling within about $\pm\frac{1}{4}\Delta f$ of the "sampling" values given in Table 2. The feature 1983/193b, on the other hand, could also have a structure intrinsically similar to that of the other three, if its peak frequency were very close to the value given in the same table, which is the middle between two adjacent sampling points. If, accordingly, we take $\pm 0.25\Delta f$ as the uncertainty to be associated with the values given in Table 2, we note that the frequencies of 1986/060a (7.9×10^{-5} Hz) and 1986/060b (1.7×10^{-4} Hz) are in a ratio consistent with 2, as if they were harmonically related; furthermore, the frequencies of 1983/193b and 1985/002b are consistent with those of 1986/060a and 1986/060b, respectively. These coincidences, along with the previous considerations, give a rather convincing support to the hypothesis that the four features in question are real and represent evidence for the existence of small-amplitude coherent signals in three out of the four light curves that we have analyzed. In particular, the condition that the two peaks in 1986/060 are harmonically related reduces the previous esti-

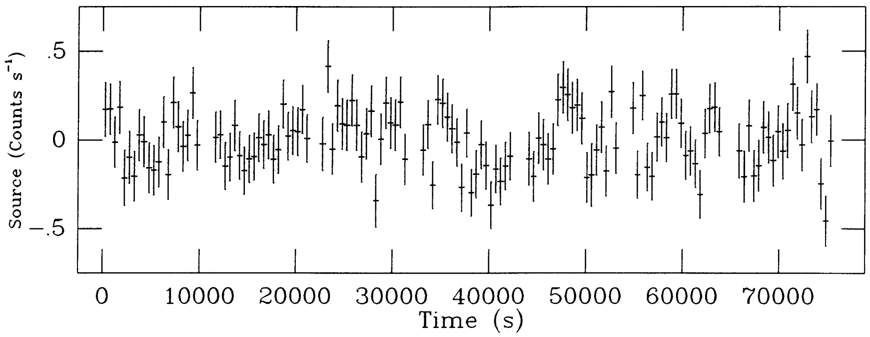


FIG. 8.—The light curve of observation 1986/060 after the subtraction of the parabolic trend

mate of the probability of their chance occurrence in an intrinsically flat distribution to 3.5×10^{-5}, corresponding to a 4.1 σ result.

To estimate the amplitude of these signals, we folded the light curves (after subtraction of the parabolic trend) in 10 phase bins with the periods corresponding to the frequencies given in Table 2. As an example we present in Figure 8 the detrended light curve of observation 1986/060 and in Figure 9 the same curve folded with the period of the two features. The results are collected in Table 3, where we give the amplitude peak-to-peak A_{pp} both in counts s^{-1} and in percentage relative to the average count rate C_{av} (Table 1), the reduced χ^2 (nine degrees of freedom) and the corresponding probability for the absence of a modulated signal, which is, except in one case, much smaller than 10^{-3}.

To exclude, to the best of our knowledge, yet another possibility, we investigated also whether these signals could be produced by another object in the field of view (FWHM = 45′) of the *EXOSAT* ME. Another relatively faint X-ray source is indeed located only 5′ away from the target, the BL Lac object 1E 1207.9+3945, the only source other than NGC 4151 detected in the field (~ 1 deg^2) covered by the CMA in the focal plane of the *EXOSAT* low-energy (LE) experiment (this instrument is described in de Korte *et al.* 1981). The observations carried out over ~ 3 yr have shown that the LE flux of this object, through the 3000 Lexan filter, was always lower than $\sim 10 \times 10^{-3}$ counts s^{-1} (Giommi *et al.* 1987). In particular, during the 1985/002 observation its count rates through the aluminum-parylene (0.1–2 keV) and the 3000 Lexan (0.05–2 keV) filters were $(2.6 \pm 1.1) \times 10^{-3}$ counts s^{-1}, and $(5.7 \pm 1.6) \times 10^{-3}$ counts s^{-1}, respectively. If the modulated signal revealed during this observation were due to the BL Lac object, then, to justify an amplitude of ~ 1 counts s^{-1} in the 2–10 keV band of the ME experiment, its spectrum, estimated assuming a galactic absorbing column density $N_H = 2.1 \times 10^{20}$ cm^{-2} (Giommi *et al.* 1987), should have had an energy spectral index equal to about zero. Since this value of the spectral index is very unusual for this class of objects, it seems very unlikely that the modulation could be associated with the X-ray emission from this object.

IV. DISCUSSION

The short (≤ 1 day) time scale variability in the X-ray flux of Seyfert galaxies has been extensively studied with *EXOSAT*, and its amplitude appears, in a statistical sense, to be inversely correlated with the luminosity (Pounds and McHardy 1988). The harmonic analysis of observations with long (up to $\sim 10^5$ s) duration shows that, among those with the more pronounced variability, the majority, represented by NGC 4051 (Lawrence *et al.* 1987), NGC 5506 (McHardy and Czerny 1987), MCG 6-30-15 and Mkn 335 (Pounds and Turner 1986; Pounds and McHardy 1988) displays a PSD distribution in the interval 10^{-5}–10^{-3} Hz which can be reasonably well represented by a smooth spectrum with a slope between -1.2 and -1.5, with no evidence of preferred time scales, while NGC 6814 represents as yet a unique case where most of the power is concentrated in a few frequencies within the interval 5×10^{-5}–5×10^{-4} Hz which appear to obey a harmonic relationship (8.2×10^{-5} Hz being the frequency of the fundamental), and the rest is distributed with a slope close to -2 (Mittaz and Branduardi-Raymont 1989).

NGC 4151 has still a somewhat different behavior, in partic-

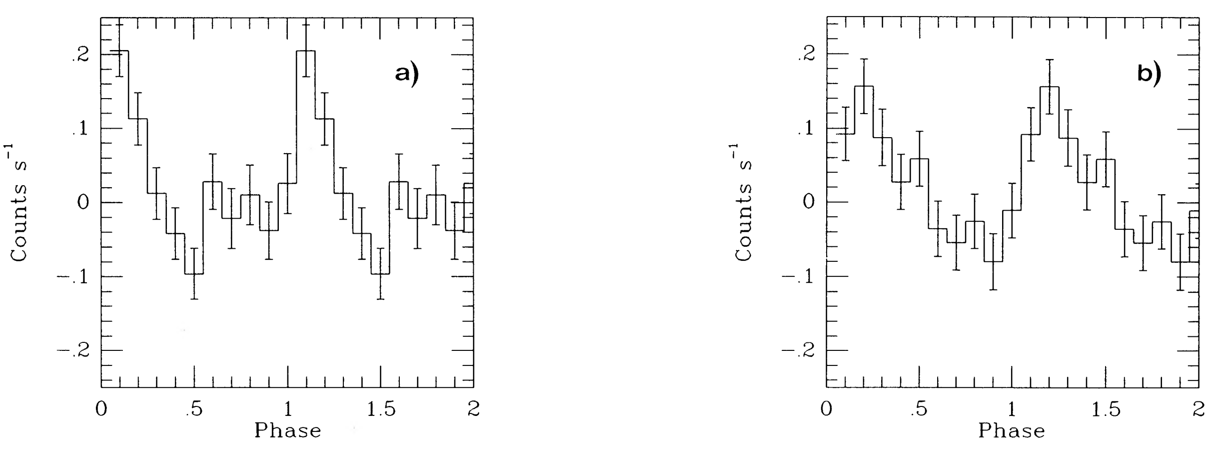


FIG. 9.—The light curve given in Fig. 8 folded with (*a*) $P = 12{,}614$ s; (*b*) $P = 5824$ s

TABLE 3

RESULTS OF THE FOLDING

Date	Identification	Period (10^3 s)	A_{pp} (counts s^{-1})	A_{pp}	χ_r^2	Probability (10^{-3})
1983/193......	b	13, 3	0.28 ± 0.08	3.4%	5.2	0.0003
1985/002......	b	6, 2	0.57 ± 0.15	2.9	4.0	0.04
1986/060......	a	12, 6	0.21 ± 0.05	7.5	3.1	1.0
	b	5, 8	0.20 ± 0.05	7.1	4.2	0.02

ular because the amplitude of its variations on time scales much smaller than 1 day is far less pronounced than in other objects of comparable luminosity, such as NGC 5506. We can tentatively recognize the existence of two modes:

1. Large-amplitude variations occurring with typical time scales ≥ 1 day, as previously reported by Mushotzky, Holt, and Serlemitsos (1978), Lawrence (1980), and Perola *et al.* (1986), which are responsible for the trends found in observations lasting 1 day or less, and for the power found at the very low frequencies. When applying the standard FT algorithm, however, the presence of a trend can yield a slope in the PSD approximately equal to -2, which is essentially caused by a redistribution of power from low to high frequencies due to effects of the window: we would therefore conclude that the intrinsic slope of the PSD at low frequencies may be steeper than -2.

2. Small-amplitude variations with time scales much shorter than 1 day. Our harmonic analysis of four observations lead us to conclude that the power associated with these variations tends to be concentrated in two features at about 7.9×10^{-5} Hz and 1.7×10^{-4} Hz, which may or may not be simultaneously present, and which correspond to coherent signals of amplitude (peak-to-peak) at most equal to 7%. Within the uncertainties associated with the frequency resolution, it appears that the features occur at the same frequency in different observations and the ratio of the frequencies is compatible with 2, as it they were harmonically related.

With respect to NGC 6814, it is interesting to note the similarities in the slope of the continuum and in the frequency of the coherent signals, despite the outstanding difference in their relative strengths.

The two modes in the variations of the X-ray flux of NGC 4151 could be associated with different physical mechanisms occurring in the innermost region of an accretion disk surrounding the central object, but it goes beyond the scope of this paper to attempt their interpretation in terms of the complex models which are currently discussed in the literature. We limit ourselves to pointing out that the periodic modulation in the X-ray flux of NGC 4151 could be associated with the orbital motion of matter near the innermost stable orbit around a collapsed object (Sunyaev 1973): if this were the case and if the frequency 7.9×10^{-5} Hz (period 12,600 s) were interpreted as the fundamental, then the resulting value of the mass of the object would be close to $2.5 \times 10^7\ M_\odot$ for the Schwarzschild metric, and to $2 \times 10^8\ M_\odot$ for the extreme Kerr metric.

We find it encouraging that this mass estimate agrees well with those obtained from an analysis of the variations of the ultraviolet emission lines in NGC 4151 ($M = 3.7 \pm 0.5 \times 10^7\ M_\odot$, Clavel *et al.* 1987; $M = 5 \times 10^7\ M_\odot$, Gaskell 1988), suggesting that privileged time scales can be found in the X-ray emission of Seyfert galaxies which are immediately related to the mass of the central object.

Finally, we note that the case of NGC 4151, together with that of NGC 6814 despite the differences mentioned, seems to indicate that preferred time scales can be more easily found in objects where the type of short-term variability, which converts into a PSD slope much shallower than -2, is, at least temporarily, absent.

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