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van der Klis, M.B.M.; Rappaport, S.

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X-ray observations of bright galactic bulge sources in the vicinity of GX 5−1

M. van der Klis[1,2] and S. Rappaport[3]

[1] Astronomical Institute, University of Amsterdam, Roetersstraat 15, NL-1018 WB Amsterdam, The Netherlands
[2] Cosmic Ray Working Group, Leiden, The Netherlands
[3] Department of Physics and Center for Space Research, Massachusetts, Institute of Technology, MA, USA

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Summary. Results are presented for 44 d of pointed COS-B X-ray observations of the galactic center region around GX 5−1. It is found that GX 5−1 exhibits relatively rapid ($\sim 10^3$ s) intensity transitions as well as flaring events with a typical time scale of $\sim 10^4$ s. Neither GX 5−1, GX 3+1 nor GX 9+1 shows evidence of periodic intensity modulations due to orbital motion on time scales from minutes to fractions of a day. These results are discussed in the context of proposed models for bright galactic bulge sources.

Key words: X-ray binaries – bright galactic bulge sources – Type II X-ray sources

I. Introduction

The galactic bulge contains about 15 persistent X-ray sources with an X-ray flux exceeding 100 μJy, among which are some of the brightest sources in the galaxy (see, e.g., Bradt et al., 1979). Observationally, these objects belong to the Type II X-ray sources (see, e.g., Canizares, 1975), generally characterized by the absence of pulsations and eclipses, by soft X-ray spectra and high ratios of X-ray to optical luminosity. Binary models which have been proposed for this class of objects rely on a weak magnetic field, or on one that is aligned with the rotation axis of the compact object (see, e.g., Cominsky et al., 1980), a small mass ratio $M_{\rm opt}/M_x$ (Joss and Rappaport, 1979) and the presence of a thick accretion disk (Milgrom, 1978) to explain many of the observed characteristics.

For the lower luminosity Type II sources ($L_x \lesssim 10^{36}$ erg s^{-1}) the mass transfer could be driven by gravitational radiation in a highly compact binary containing a main sequence dwarf (Rappaport et al., 1982). In the case of the higher luminosity galactic bulge sources, magnetic braking effects in a compact binary (Verbunt and Zwaan, 1981), mass transfer from a red giant (Webbink et al., 1982) and mass transfer from a helium main sequence star (Savonije, 1982) have recently been proposed to explain the high luminosity of the observed sources. The main observational differences between these models, apart from the obvious differences in appearance of the donor star (if it is visible) would be the binary period: ranging from $\gtrsim 10$ d for a red giant, to $\lesssim 1$ h for a lobe-filling helium main sequence star. However, in view of the lack of quantitative evidence, it is probably fair to say that the bright galactic bulge sources remain something of a mystery.

Previous observations of bright galactic bulge sources for durations of longer than one day (Forman et al., 1976; Mason et al., 1976; Parsignault and Grindlay, 1978) yielded X-ray light curves of typically a few tens of measurements per day. From these observations, it became clear that the sources generally have a variability factor of less than 3, and do not exhibit periodic pulsations above the level of a few percent. Ponman (1981), on the basis of Ariel V RMC observations with 100 min resolution, suggests the existence of regular variations with periods of several days in three galactic bulge sources.

In the present paper, data are presented which provide nearly continuous coverage (with 100 s resolution) over intervals of 25 h, of the X-ray flux from a field in the galactic bulge probably dominated by the brightest of the bulge sources, GX 5−1. These data were obtained during two pointed observations with a total duration of 44 d.

Send offprint requests to: M. van der Klis

II. Observations

The X-ray detector onboard the COS-B satellite (Boella et al., 1974) is a proportional counter with 80 cm^2 effective area in the energy range 2–12 keV. The collimator provides an approximately trapezoidal angular response curve with a nearly flat top of 1°.1 and a FWHM of 10°. The sensitivity is essentially zero beyond 10°.5 from the center of the field.

During the 33 d of the first observation, from September 17 to October 20, 1975, the center of the circular field of view gradually drifted from $\alpha = 269°.4$, $\delta = -25°.1$ to $\alpha = 268°.4$, $\delta = -24°.1$; during the second observation, February 24 to March 7, 1977 (11 d), the drift was from $\delta = -25°.2$ to $-24°.9$ at a constant $\alpha = 270°.0$. Short term pointing jitter was damped to better than 1′.

Figure 1 shows a map of the observed region with the detector field of view during the 1975 observation superimposed. It is clear that there were a number of sources within the field of view; however, on the basis of the luminosities quoted in the catalogues of Forman et al. (1978) and Bradt et al. (1979), and under the assumption that no transient sources were active, only three of these sources, GX 5−1, GX 3+1, and GX 9+1, are likely to have contributed appreciably (>5%) to the total counting rate (Table 1). The contribution of GX 5−1 was very likely to have been between 25 and 65% of the total.

Figure 2 shows the behaviour of the counting rate during both observations, together with an observation of the Crab nebula which was made just before the 1975 GX 5−1 observation. For these plots, the original data, consisting of ~ 25 s integrations of the X-ray flux alternated with ~ 75 s of background measurements every 102.4 s, have been averaged into 1024 s bins. A charged particle background of approximately 100 c/s has been subtracted. The typical statistical error per bin is 1 c/s (1 σ). Gaps

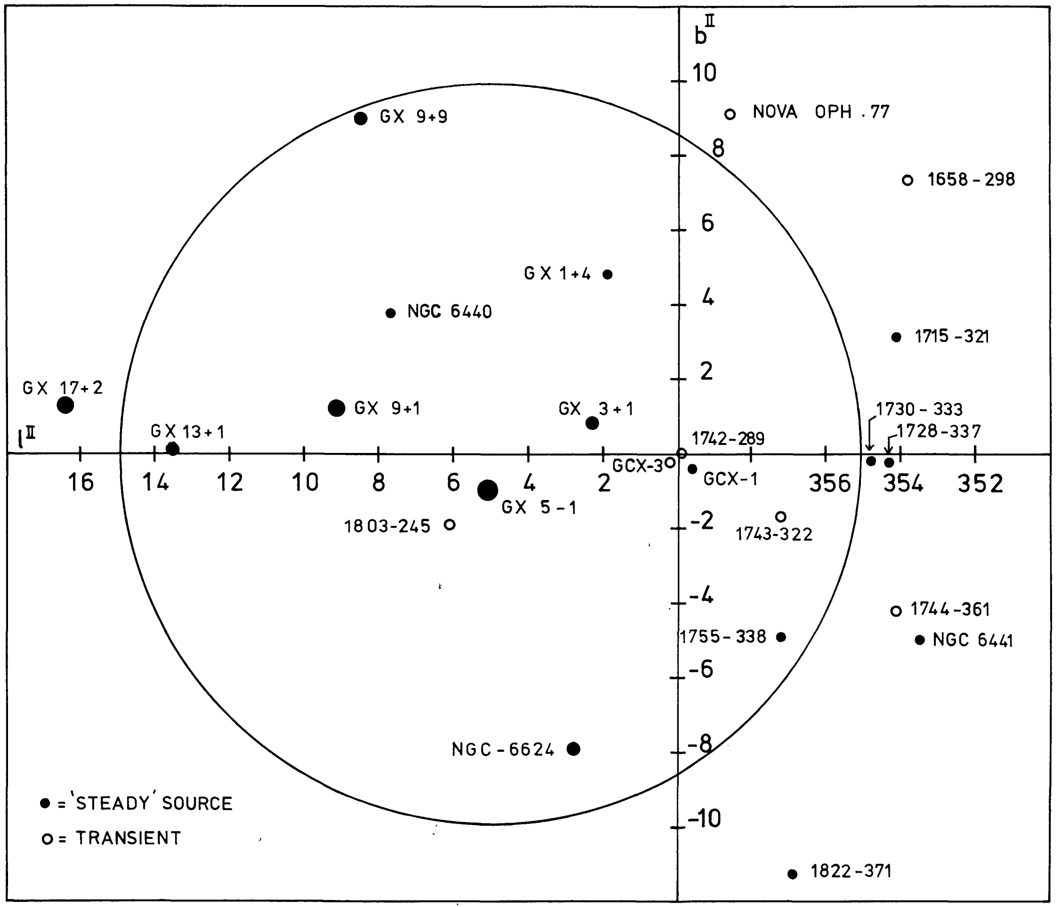

Fig. 1. Map of the observed region near the galactic center. The geometrical transmission of the detector decreases approximately linearly from the center to the edge of the field of view (large circle)

in the data are due to passage of the satellite through the radiation belts of the Earth, once per $1^{\mathrm{d}}.5$ orbit, and to occasional charged particle "storms".

The first frame of Fig. 2, containing the Crab data, shows a nearly steady flux. A small downward trend in the counting rate is due to the pointing drift. From this observation it is deduced that 1 COS-B c/s corresponds to 12.6 μJy (2–11 keV mean) for a Crab-type spectrum. This observation also clearly demonstrates the stability of the detector as well as the constancy of the non-X-ray background.

The change in counting rate behaviour on day 16, after slewing to the GX 5−1 field, is readily evident. The total counting rate increases by a factor of about two over that of the field containing the Crab nebula. The appearance of the count rate plot is dominated by flaring behaviour and relatively abrupt changes in intensity with an amplitude of ~40 c/s; these have a characteristic time scale of a few thousand seconds. Together with some slower transitions of similar amplitude, these combine to yield an erratic temporal behaviour which shows no apparent periodicities.

The same type of behaviour is visible in the second observation (last frame of Fig. 2), more than a year later.

III. Analysis

In a search for periodicities with small amplitude which might underlie the irregular variability of the signal, the data have been subjected to a Fourier analysis. A 2^{15}-point fast Fourier transform yielded a power spectrum with a frequency resolution of 0.3 μHz and a Nyquist limit corresponding to 200 s (Fig. 3). None of the peaks in the power spectrum corresponding to periods shorter than about 1 d is significant. For periods longer than one day, the power spectrum is much enhanced by the effect of the $1^{\mathrm{d}}.5$ satellite period and the intrinsic source variability that is apparent in the data. Accordingly, many of the low frequency amplitudes exceed the 99% confidence upper limit for statistical fluctuations due to photon noise. The same is also true for the transform of the "window"-function and for transforms of data obtained during other observations. The significance of any peak in this region is therefore difficult to evaluate from our data alone.

Taking into account the excess variability in the signal at low frequencies, we quote upper limits (99% confidence) on periodic variability for the various sources within the field of view. The upper limits for the individual sources in Table 2 are given for the (worst case) assumption, that they were at their lowest luminosity thus far observed. Apart from the DC component, the highest peak in the power spectrum (of marginal significance), corresponds to a period of $6^{\mathrm{d}}.5 \pm 1^{\mathrm{d}}.0$ and a full amplitude of 13 c/s (see Fig. 3). This peak is probably caused by recurring 1–2 d episodes of lower average flux visible in the data around days 21, 27, 32, 39, and 47.

IV. Discussion

The observed irregular intensity transitions occur on a short time scale (a few 10^3 s). This makes it highly probable that each

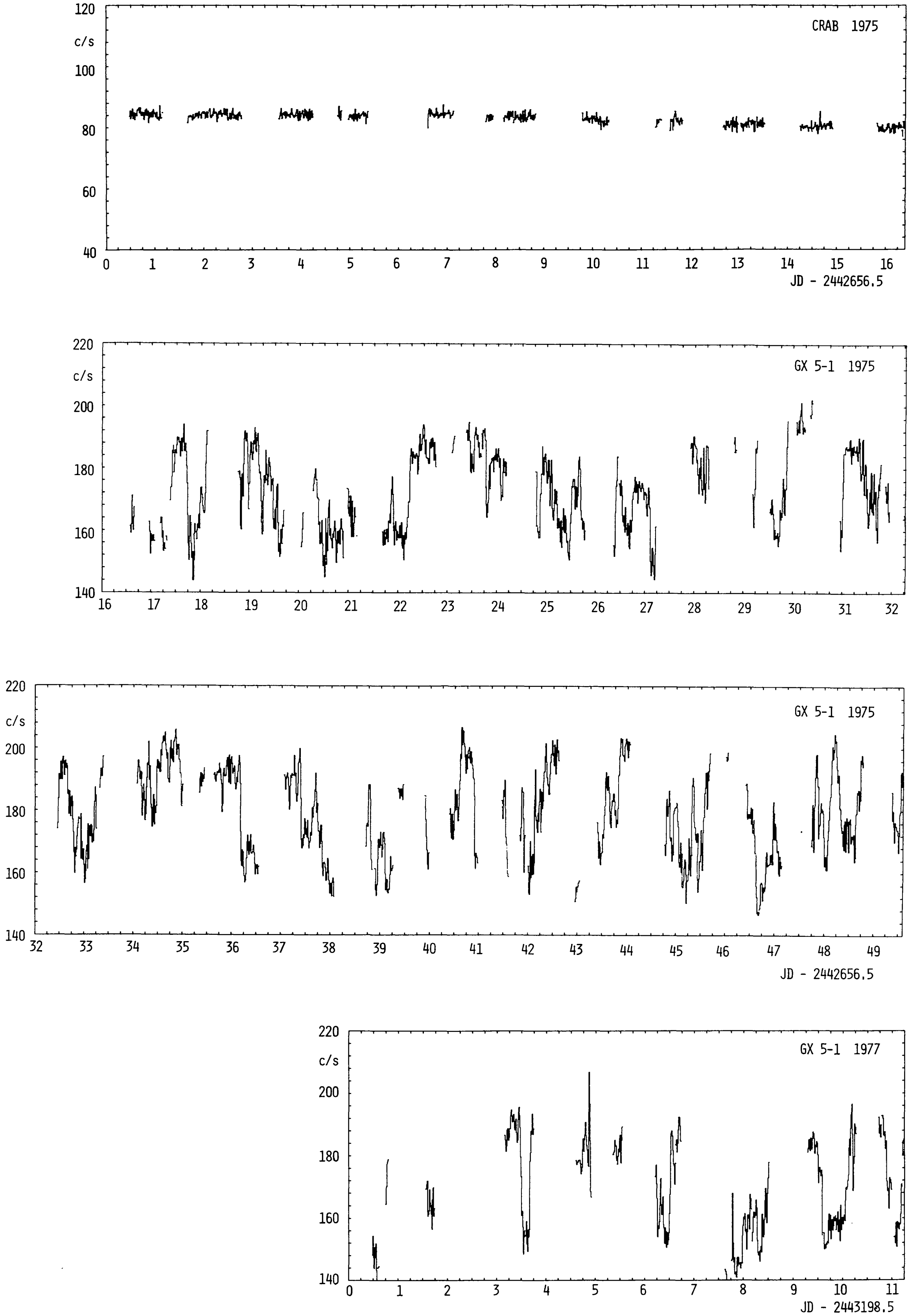

Fig. 2. The counting rate from the GX 5−1 field and, for comparison, from the Crab at 1024 s resolution. A charged particle background of about 100 c/s has been substracted from the signal; statistical error per bin is about 1 c/s. Note that the first three frames are consecutive in time

Table 1. Observed steady sources

Source	Offset (°)	Collimator Transmission	Expected Counting Rate (c/s) Max	Min	Expected Percentage Of Total Max	Min
GX 5-1 (1758-250)	0.2	1.00	111	42	65	25
GX 3+1 (1744-265)	2.9	0.76	40	13	24	8
GX 9+1 (1758-205)	4.1	0.62	33	11	19	6
NGC 6440 (1745-203)	4.5	0.58	8.3	0.8	4.9	0.5
GCX-3 (1743-288)	4.9	0.54	3.8	0	2.3	0
GCX-1 (1742-294)	5.5	0.47	4.5	1.9	2.6	1.1
GX 1+4 (1728-247)	5.7	0.45	7.8	1.2	4.6	0.7
NGC 6624 (1820-303)	8.3	0.20	6.5	1.0	3.8	0.6
GX 13+1 (1811-171)	8.4	0.19	6.8	2.3	4.0	1.3
1755-338	9.3	0.12	0.9	0.3	0.5	0.2
GX 9+9 (1728-169)	9.5	0.11	2.8	1.5	1.7	0.9
FIELD TOTAL			225.4	75.0		
OBSERVED			~ 175			

The non-transient X-ray sources in the field of view of the COS-B X-ray detector. The flux from non-transient, unresolved sources in the galactic center region is estimated to have contributed less than 2 c/s to the total counting rate (Forman et al. 1978). Second column gives the distance of the source from the center of the detector field, third the collimator transmission efficiency at which the source was observed. Maximum and minimum expected counting rates were calculated according to the flux ranges given in Bradt et al. (1979).

Table 2. Upper limits to modulation

Source	1.0-0.38 d	0.38-0.16 d	0.16-0.06 d	0.06-0.01 d	0.01 d-200 s
Total Count Rate	3.4%	1.9%	1.1%	0.5%	0.2%
GX 5-1	14%	7.5%	4.2%	2.1%	0.9%
GX 3+1	43%	24%	13%	6.6%	2.9%
GX 9+1	57%	31%	18%	8.8%	3.9%
GX 13+1	-	-	81%	41%	18%

99% confidence upper limits to periodic modulations. The upper limits were derived from the local mean power for an assumed exponential distribution of power amplitudes. Note that the upper limits for an individual source were calculated from the (worst case) assumption that the source was at its lowest previously observed level.

individual transition is the result of an event in one particular source, rather than the accidental superposition of smaller flux changes from several of the sources in the field of view, all taking place within $\sim 10^3$ s. The amplitude of the flares and transitions, ~ 40 c/s, then pinpoints GX 5−1 as the only remaining source with a previously observed flux range large enough to have caused them (Table 1). As they are visible in both observations, separated by 1.5 yr, they probably do not originate from a transient source. It should be noted, however, that an origin of this variability in an unknown recurrent transient or in one of the observed "steady" sources at an unusually high level of variability can not strictly be excluded.

If the rapid irregular variability arises in GX 5−1, this implies that this source frequently changes its intensity with a factor of at least 2 within less than an hour. Within the framework of a binary model with mass accretion, one might attempt to explain the variability in terms of changes in the intrinsic X-ray flux, i.e., in the accretion rate, or as the result of variable extinction or obscuration of the X-rays.

First, consider variable partial obscuration of an extended X-ray source by an accretion disk whose thickness varies with azimuth angle (White and Holt, 1982). If the thickness of the disk is some fixed function of the position angle with respect to the symmetry axis of the binary system, (e.g., depends on the angular distance from the impact point of the accretion stream), it would be difficult to understand how such a disk could effectively hide the orbital motion of the system, while causing rapid intensity changes of a factor of >2.

Changes in the distribution of absorbing gas structures on the scale of the binary system, moving under the influence of gravitational forces, would occur on time scales similar to the orbital period, and consequently this could only serve to explain the observed flux changes in highly compact systems with periods of the order of 1 h. In larger systems, small absorbing structures would have to be invoked.

The present data do not contain spectral information, but in previous observations (Mason et al., 1976; Parsignault and Grindlay, 1978), on somewhat longer time scales than discussed here, a positive correlation between intensity and spectral hardness was observed for GX 5−1 and several similar sources. This is opposite to the inverse correlation that is expected for intensity variations due to changing absorption, and rather points to variations in the accretion rate itself as an explanation for the observed variability. A higher accretion rate could cause spectral hardening by, for example, an increase in absorption close to the compact object (Kylafis et al., 1979 and references therein), or by higher temperatures in the X-ray producing region.

It is possible that the degree of variability in the accretion rate required to explain the luminosity variations is caused by instabilities in the inner region of the accretion disk (Lightman, 1974; Pringle, 1976). These might be more pronounced in Type II X-ray binaries because of the probable absence of a strong magnetic field, which could allow the disk to extend very much closer to the compact object than in Type I sources.

The apparent lack of variability on time scales of hours for GX 5−1, GX 3+1, and GX 9+1 tends to rule against highly compact binary models. It should be noted, however, that the X-ray flux of the 41 min X-ray binary 4U 1626−67 (Middleditch et al., 1981) is not observed to modulate with the orbital period. Furthermore, the 50 min X-ray binary 4U 1915−05 (Walter et al., 1982; White and Swank, 1982), which exhibits partial and erratic X-ray eclipses, would exhibit only a small amount of power at 50 min in a Fourier spectrum, and such modulations would have been difficult to detect in any of the sources except for GX 5−1.

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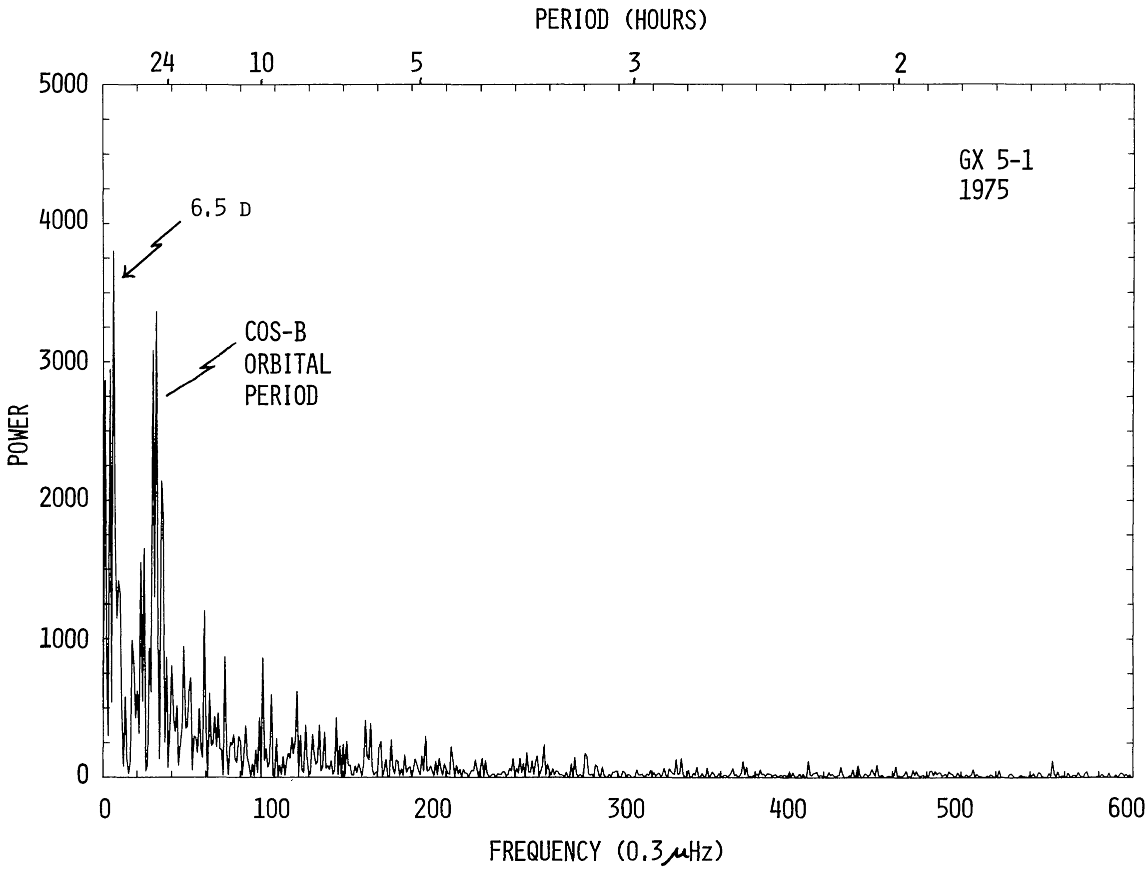

Fig. 3. The low-frequency part of the power spectrum of the GX 5 − 1 1975 observation. The power was normalized to a mean value of 1 at high frequencies. The complex appearance of the spectrum around 7.7 μHz (1ᵈ.5) is due to the satellite orbital period. Notice the high power in the 1.8 μHz (6ᵈ.5) bin, marked by an arrow

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