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Search for neutron star spin periods in X-ray bursts

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Abstract. We report a search for pulsations in 147 Type 1 X-ray bursts observed with EXOSAT in 10 X-ray burst sources. Instead of treating each burst separately, we incoherently averaged the power spectra of all of the bursts of a given burster to improve statistics. No periodicities were detected; 99% confidence upper limits on the modulation depths of possible periodic signals with frequencies between 1 and 2048 Hz range from 2 to 20% depending on source and frequency range.

Key words: stars: neutron – stars: oscillations – X-rays: bursts

1. Introduction

Searches for the predicted millisecond pulsations in the persistent X-ray flux of low-magnetic-field neutron stars have, so far, had no success (see Vaughan et al. 1994 and references therein). Unlike the persistent X-ray emission, the result of the release of gravitational energy in the accretion process, X-ray bursts arise through nuclear combustion of accreted matter on the surface of the neutron star (see Lewin et al. 1993 for a review). The nuclear energy generation does not necessarily occur uniformly over the neutron star surface. According to theory (Fryxell and Woosley 1982, Nozakura et al. 1984, Bildsten 1995), the accumulated nuclear fuel first ignites at the point on the neutron star surface where it reaches the critical ignition column density, and then spreads by a process of convective combustion to all adjacent areas on the surface where the column density is larger than the critical propagation column density. Non-homogeneous accretion, or geometrically irregular steady burning will lead to areas with super-critical ignition column densities with adjacent areas with super-critical propagation column densities bounded by areas where the propagation column density is sub-critical (see also Chau et al. 1995). This will lead to X-ray burst emission that is non-uniform over the neutron star surface, causing periodic variability in the burst flux as the star spins. According to Bildsten (1995), the formation of isolated fuel supplies is a process that is strongly influenced by the accretion rate. At low accretion rate nuclear burning in the bursts is expected to occur uniformly over the surface, and at high accretion there are no bursts as all fuel is consumed in persistent nuclear burning. At intermediate accretion rates the above described "patchy" burning process, which would make the neutron star spin period visible, could take place.

Periodicity searches in X-ray bursts have been previously performed by Mason et al. (1980), Sadeh et al. (1982), Murakami et al. (1987), and Schoelkopf and Kelly (1991), but so far none of the reported periods has been confirmed. The most convincing detection was that by Schoelkopf and Kelly, who found a 10% half-amplitude, 4.1σ periodicity at 7.6 Hz in a burst from the soft X-ray transient Aql X-1, observed with the Einstein Monitor Proportional Counter.

In the present work, we make use of bursts observed with the EXOSAT observatory in some X-ray burst sources to perform a burst periodicity search of increased sensitivity. We calculate the power spectra of all bursts of a given burster and average them. To our knowledge this method has not been previously applied.

2. Data

We used data obtained with the 2–20 keV EXOSAT ME argon detectors (Turner et al. 1981, White and Peacock 1988). Data were recorded using a variety of high time resolution modes and at resolutions of 0.25 to 32 milliseconds. When possible, the 5–35 keV xenon detectors, which record mostly background counts, and data from detectors not pointed to the source were excluded from the analysis. The count rates during the bursts were of course strongly variable; peak count rates varied between 100 (1705-44) and 10^4 (1820-303) counts/second.

We selected a total of 147 bursts from ten sources. The number of bursts recorded in each source is given in Table 1. All bursts were of Type 1. We refer to the review of Lewin et al. (1993) for a description of the detailed burst properties of these sources, and for further references.

3. Method

In analyzing the data of a given burst source, we used the following procedure. First, we selected about 200 s of data around

Send offprint requests to: M. van der Klis, Astronomical Institute "Anton Pannekoek" each burst. We then subdivided each 200-s section into segments with a duration of 8 s, and kept only those 8-s segments that had an average count rate of more than $\sim 20\%$ above the persistent flux. On average this resulted in about four accepted 8-s segments per burst, but this number varied strongly among different bursters and between bursts. Then we calculated the power spectrum of each selected 8-s segment using an FFT. The frequency resolution was uniformly 0.125 Hz in all power spectra. Subsequently, all obtained power spectra of a given source were normalized according to Leahy et al. (1983), and summed. Finally, the average power spectrum was calculated by dividing by each summed power by the number M of summed power spectra.

During the EXOSAT observations many different time resolutions were used. Therefore, power spectra obtained from different bursts of the same source generally had different Nyquist frequencies, and the averaged power spectrum had adjacent frequency ranges with different values of M. The resulting different sensitivities in these frequency ranges were properly taken into account in the analysis.

For pure Poisson noise, the powers P_i in the summed power spectrum (the "noise powers") are χ^2 distributed with $2M$ degrees of freedom. By increasing M, the sensitivity is increased. As an example, for the source 4U 1636−53, where EXOSAT recorded 60 bursts, the pulse amplitude sensitivity is increased by a factor ~3.5 as compared to searching a single burst.

The trends that are present in each 8-s data segment due to the burst envelopes produce power at low frequency in the power spectra. It is possible to reduce this power by fitting the trends with polynomials and subtracting them from the light curves before doing the transforms. However, comparisons between power spectra of raw and detrended time series showed that this correction was not necessary: the extra power was confined to frequencies $\lesssim 1$ Hz. An exception was the case of the source GX 354−0, which has very short bursts, so that the extra power extended to higher frequencies (~4 Hz). This made the sensitivity to pulsations at frequencies below 4 Hz slightly lower.

We looked for significant excesses in the averaged power spectra using our knowledge of the Poisson noise power distribution in each frequency range and taking into account the number of trials. When no significant excesses were found, we estimated upper limits on the power that could have been present due to pulsations (the "signal power"). These upper limits were estimated from the highest actually observed power in each frequency range (van der Klis 1989), and under the assumption that the distribution of powers from the combined noise and signal time series is that described by Groth (1975). We refer to Vaughan et al. (1994) for a detailed description of this method.

Finally, the upper limit on the signal power P_{UL} was converted into an upper limit on the fractional pulse amplitude A for an assumed sinusoidal pulse profile using (Leahy et al. 1983) $A = (2P_{\rm UL}/0.773N_{\rm ph})^{0.5}(\pi\nu_{\rm j}/2\nu_{\rm Nyq})(\sin(\pi\nu_{\rm j}/2\nu_{\rm Nyq}))^{-1}$, where $N_{\rm ph}$ the number of counts per transform, $\nu_{\rm Nyq}$ the Nyquist frequency, and $\nu_{\rm j}$ the frequency of the j-th bin in the power spectrum. For $N_{\rm ph}$ we used simply the average number of counts over all data segments whose power spectra were averaged. For $\nu_{\rm Nyq}$ and $\nu_{\rm j}$ we chose conservative values: the maximum frequency and the central frequency of the range involved.

Our procedure of using a straight average of the individual power spectra, and of estimating the pulse amplitude using Eq. (1) as described above ignores the fact that through a burst, and between bursts, the X-ray flux varies considerably. However, in the absence of any knowledge of how the pulse amplitude depends on the X-ray flux (or the burst phase) it is not useful to attempt to optimize the averaging procedure or improve the amplitude calculation beyond our simple approach.

In contrast to the case of persistent flux searches, which ideally use very high frequency resolutions in our case the frequency resolution is low, so that there is usually no danger that pulsation peaks will move over several frequency bins due to orbital Doppler shifts. The maximum frequency shift due to orbital motion $\Delta\nu_{\rm max}$ is (Vaughan et al. 1994):

$$\frac{\Delta\nu_{\rm max}}{\nu_{\rm pulse}} = 0.0021\frac{M_2}{M_{\rm tot}}\left(\frac{P_{\rm orb}}{1\,{\rm hr}}\right)^{-1/3}\left(\frac{M_{\rm tot}}{M_\odot}\right)^{1/3} \quad (1)$$

where $\nu_{\rm pulse}$ is the pulse frequency, M_2 the mass of the donor star, $M_{\rm tot}$ the total mass of the system and $P_{\rm orb}$ the orbital period.

For a low mass X-ray binary with a 1.4 $M_\odot$ neutron star and a Roche lobe filling 0.1–0.3 $M_\odot$ main sequence red dwarf companion we find that the critical pulse frequency above which Doppler shifts can cause the pulse peak to move over one frequency bin is between 400 and 800 Hz. For 4U 1820−30, the binary with the shortest known orbital period (685 seconds) this critical frequency is 173 Hz (using $M_2 = 0.28$; van der Klis et al. 1993). Only in a few cases do the Nyquist frequencies in our search (Table 1) exceed the relevant critical frequency; in these cases, depending on the true orbital parameters, the orbital inclination and the orbital phases during the observations, the pulse amplitude sensitivity may have been lowered by a factor $\sim (\nu_{\rm pulse}/\nu_{\rm crit})^{0.5}$.

The bursts whose power spectra we averaged were collected over a 3-year period. Therefore we also consider accretion induced spin-up or spin-down as a cause of pulse frequency shifts. Using standard formulae (Rappaport & Joss 1977) and assuming a neutron star magnetic field strength of $\lesssim 10^9$ G and accretion rates at or below the Eddington critical rate, we estimate that pulse frequency shifts would amount to the width of one frequency bin after several thousand years, and are therefore negligible.

4. Results and discussion

We found no significant excesses in the average power spectra. The 99% confidence upper limits on the sinusoidal pulse amplitudes are listed in Table 1. These upper limits are given as a fraction of the average *burst* flux; they have been corrected for the persistent flux and background. For most of our sources we obtained upper limits that are below previously reported detections in other, but similar, sources (Aql X-1, Schoelkopf and Kelley 1991, 10%; 4U 1608−52, Murakami et al. 1991, 8–20%).

Table 1. Upper limits on sinusoidal amplitude (99% confidence)

Source	Frequency range (Hz)	Number of bursts	Upper limit (%)
4U 1636−53 [1]	1–16	60	1.9
	16–64	45	2.7
	64–256	12	4.5
Ser X-1	1–16	3	11
	16–64	1	13
EXO 1747−214	1–16	2	11
GC X-1	1–16	2	8.8 [2]
4U 1705−44	1–64	24	3.9
	64–256	16	5.9
	256–512	14	7.3
	512–2048	6	7.0
EXO 0748−676	1–16	33	4.5
	16–128	12	6.6
	128–256	2	18
4U 1820−30 [3]	1–64	7	3.4
	64–256	3	4.8
GX 354−0	4–16	8	6.3
	16–64	5	6.7
	64–73	3	6.2
	73–256	1	8.3
Rapid Burster	1–64	2	8.2
4U 1735−44	1–32	6	9.6
	32–64	5	11
	64–256	1	15

[1] The upper limits for 4U 1636−53 were calculated from the average power spectra of all bursts, radius expansion bursts included. The average power spectra with these bursts omitted have also been checked. In addition the average power spectra of all radius expansion bursts have also been investigated for possible oscilations of the expanding atmosphere (Murakami & Inoue 1987).

[2] Only the two bigger bursts observed were used to determine the upper limit. The two smaller bursts were also checked, but we suspect that these came from another source.

[3] All bursts show radius expansion; see also note 1.

The negative result of our search has two possible interpretations: either coherent pulsations are present in bursts, but in the sources we studied their frequencies are higher than a few 10^2 Hz or their average amplitudes are smaller than a few percent, or *no* coherent pulsations are normally present in bursts. This latter possibility might apply if the nuclear burning does not lead to anisotropic emission after all. Another possibility is that the anisotropy is changing on time scales similar to the spin period. If the pulse profile changes that rapidly, the signature of the rotation in the power spectra will not be a sharp peak.

There is a number of ways in which one might improve the sensitivity of searches such as ours. By correcting for binary orbital acceleration during the burst, sensitivity to particularly $\gg$100 Hz pulsations could be improved, especially in long ($\gtrsim$10 s) bursts occurring in systems with tight binary orbits. However, as the binary orbits are not known one would need to perform a search in acceleration space (see, e.g., Vaughan et al. 1994), and because the reconstructed pulse frequencies would still be Doppler-shifted by different amounts in different bursts, the pulsation peaks would end up in different frequency bins in the power spectra. *Coherent* transformation of the bursts is possible in principle, but with standard methods in practice computationally prohibitive. Collecting more bursts and applying the method of incoherent addition that we used here will improve pulse amplitude sensitivity as roughly the fourth root of the number of bursts. The most likely way to success, however, is to increase detector area, as pulse amplitude sensitivity scales as the square root of the count rate. Searches using archival Ginga data, and with NASA's X-ray Timing Explorer seem most promising.

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