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Letter to the Editor

The X-ray timing behavior of the X-ray burst source SLX 1735–269

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Abstract. We report for the first time on the rapid X-ray variability of the galactic bulge source and X-ray burster SLX 1735–269. The power spectrum as observed with the *Rossi X-ray Timing Explorer* is characterized by a strong band-limited noise component which is approximately flat below a 0.1–2.3 Hz break frequency; above this frequency the power spectrum declines as a power law of index 0.9. At the highest observed count rate a broad bump is superimposed on this band-limited noise. The power spectrum is very similar to that of other low-luminosity neutron-star low-mass X-ray binaries (LMXBs) and to black-hole candidates when these types of source accrete at their lowest observed mass accretion rates. However, we identify one unusual aspect of the X-ray variability of SLX 1735–269: the break frequency increases when the inferred mass accretion rate decreases. This is the opposite to what is normally observed in other sources. The only source for which the same behavior has been observed is the accretion-powered millisecond X-ray pulsar SAX J1808.4–3658. No coherent millisecond pulsations were observed from SLX 1735–269 with an upper limit on the amplitude of 2.2% rms. Observing this behavior in SLX 1735–269 increases the similarities between SAX J1808.4–3658 and the other neutron star LMXBs for which so far no coherent pulsations have been observed. We expect that other sources will show the same behavior when these sources are studied in detail at their lowest mass accretion rates.

Key words: accretion, accretion disks – stars: individual: SLX 1735-269 – stars: neutron – X-rays: stars

1. Introduction

The galactic bulge source SLX 1735–269 was discovered in 1985 by Skinner et al. (1987) during the *Spacelab 2* mission. Although observed on several occasions with other X-ray instruments (e.g., *GRANAT*/SIGMA: Goldwurm et al. 1996 and references therein; *ASCA*: David et al. 1997), little is known about this source. Goldwurm et al. 1996 detected the source up to about 150 keV with a spectral index above 30 keV of ~ -3. This is steeper than usually observed for black-hole candidates and therefore they tentatively suggested that the compact object in the system is a neutron star. *ASCA* observations of this source below 10 keV also could not uniquely identify the nature of the compact object (David et al. 1997) but they were consistent with the neutron star hypothesis. The issue of the nature of the compact object in SLX 1735–269 was finally settled by the discovery of a type I X-ray burst from this source using the Wide Field Cameras onboard *BeppoSAX* (Bazzano et al. 1997a; Bazzano et al. 1997b; Cocchi et al. 1998), demonstrating that SLX 1735–269 is a low-mass X-ray binary (LMXB) containing a neutron star.

So far, the rapid X-ray variability of this source has not been studied in detail. The neutron star nature of this system motivated us to analyze the timing behavior of this source as observed by the *Rossi X-ray Timing Explorer* (*RXTE*). We searched for quasi-periodic oscillations (QPOs) between 300 and 1200 Hz, which are often observed in neutron star LMXBs (see van der Klis 1998, 1999 for reviews), and coherent pulsations such as observed in the accretion-driven millisecond X-ray pulsar SAX J1808.4–3658 (Wijnands & van der Klis 1998a). Although those phenomena were not detected, we discovered one characteristic of the timing behavior which, so far, has only been observed for SAX J1808.4–3658, increasing the similarity between SAX J1808.4–3658 and the other neutron star LMXBs.

2. Observations, analysis, and results

SLX 1735–269 was observed using *RXTE* on several occasions (see Table 1 for a log of the observations) for a total of 11 ksec of on-source data. Data were collected simultaneously with 16 s time resolution in 129 photon energy channels (effective energy range 2–60 keV), and with 1 μs time resolution in 256 channels (2–60 keV). A light curve, an X-ray color-color diagram (CD), and an X-ray hardness-intensity diagram (HID) were created using the 16 s data, and power spectra (for the energy range 2–60 keV) were calculated from the 1 μs data using 256 s FFTs.

Fig. 1 shows the background subtracted (using PCABACKEST version 2.1b and the faint sources L7/240 background model) light curve (2.0–16.0 keV; all 5 detectors on; Fig. 1a), the CD (Fig. 1b), and the HID (Fig. 1c) (for the energy bands used to calculate the colors used in those diagrams see the caption of

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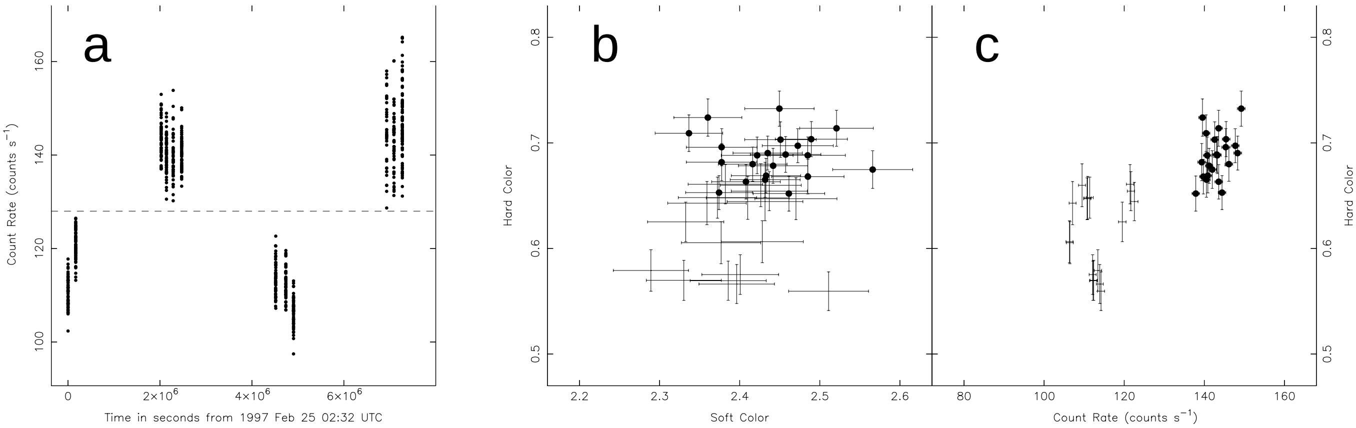

Fig. 1a–c. The 2.0–16.0 keV light curve **a**, the color-color diagram (CD) **b**, and the hardness-intensity diagram (HID) **c** of SLX 1735–269. All count rates were background subtracted. Dead-time corrections are negligible. The dashed line at 128 counts s^{-1} in **a** indicates the two different count rate ranges used to select the power spectra. In the CD, the soft color is the count rate ratio between the 3.5–6.4 and 2.0–3.5 keV bands; the hard color that between 9.7–16.0 and 6.4–9.7 keV. In the HID, the hard color is the same as in the CD and the count rate is the count rate in the photon energy range 2.0–16.0 keV. In **a** the points are 16 s averages; in **b** and **c** the points are 256 s averages. The errors on the count rate in **a** are typically 2%–4%. In **b** and **c**, the filled dots are the data above a count rate of 128 counts s^{-1} and the other points the data below this value.

Table 1. Log of the observations

Obs. ID	Date (1997)	Start – End (UTC)
20170-03-01-00	25 Feb	02:32–02:50
20170-03-02-00	27 Feb	00:58–01:16
20170-03-03-00	20 Mar	13:16–13:42
20170-03-04-00	21 Mar	21:27–21:43
20170-03-05-00	23 Mar	13:50–14:15
20170-03-06-00	25 Mar	16:57–17:13
20170-03-07-00	18 Apr	09:19–09:40
20170-03-08-00	20 Apr	22:20–22:36
20170-03-09-00	22 Apr	20:46–21:01
20170-03-10-00	16 May	07:58–08:28
20170-03-11-00	18 May	03:38–04:29
20170-03-12-00	20 May	06:06–06:48

the figure). The 2.0–16.0 keV count rate varies between ∼100 and ∼160 counts s^{-1} (Fig. 1a and c). The hard color tends to increase when the count rate increases (Fig. 1c); the soft color does not have a clear correlation with count rate.

We selected power spectra based on the background corrected count rates in the 2.0–16.0 keV band and averaged them. We obtained two average power spectra: the first one corresponds to a count rate <128 counts s^{-1}; the second one to >128 counts s^{-1} (see also Fig 1a). These two power spectra are shown in Fig. 2. Although the count rate differs only slightly between the two selections (10%–20%) the difference in the power spectra is remarkable. Both power spectra show a broad band-limited noise component. They were fitted (after subtraction of the Poisson level) with a broken power law. For the high count rate power spectrum also a Lorentzian was added in order to fit the bump superimposed on the band-limited noise near 0.9 Hz.

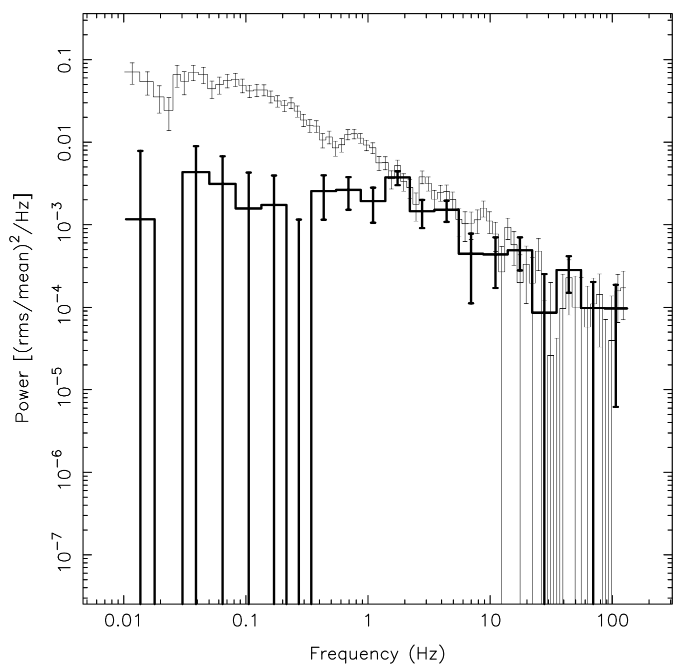

Fig. 2. The power spectra (2–60 keV) obtained for SLX 1735–269. The thin line is the power spectrum corresponding to a count rate of > 128 counts s^{-1} (2.0–16.0 keV; background subtracted) and the thick line is the power spectrum corresponding to a count rates of < 128 counts s^{-1} (see also Fig. 1a). The spectra were logarithmically rebinned and the Poisson level was subtracted. Due to lower count rates, less data, and weaker band-limited noise (see Table 2), the signal-to-noise ratio of the power spectrum corresponding to the low count rate selection was much less than that of the other power spectrum. For display purposes, different frequency bin sizes were used for the two power spectra.

The fit parameters are presented in Table 2. The break frequency was higher (2.3 Hz) when the count rate was low than when it was higher, probably by an order of magnitude (see

Table 2. Power spectral fit parameters

Count rate[a] (counts s^{-1})	#[b]	Band limited noise: Break frequency (Hz)	Rms[c] (%)	α^{d}_{below}	α^{d}_{above}	Bump: Rms[e] (%)	FWHM (Hz)	Frequency (Hz)	χ^2	d.o.f.
113±6	15	$2.3^{+1.0}_{-0.7}$	16.7±1.7	0[f]	0.9±0.2	<7[g]			45	36
141±5	21	0.11±0.02	23.6±0.6	$-0.04^{+0.13}_{-0.15}$	0.91±0.03	$4.7^{+0.9}_{-0.7}$	0.3±0.1	0.87±0.05	151	162

[a] 2.0–16.0 keV; errors are the standard deviation of each selection
[b] Number of power spectra averaged
[c] 2–60 keV; integrated over 0.01–100 Hz
[d] α_{below} and α_{above} are the power law index below and above the break frequency, respectively
[e] 2–60 kev
[f] Parameter fixed
[g] Assuming a FWHM between 5 and 10 Hz and a frequency between 10 and 15 Hz

also Fig. 2). The index below the break during the highest count rates is ~ 0; during the lowest count rates this parameter had to be fixed to 0 due to the low statistics. The indices above the break in both count rate regimes are consistent with each other at ∼0.9. The strength of the noise is ∼24% rms in the high count rate selection, and ∼17% in the low count rate selection. The bump present on top of the broad-band noise at high count rate had an amplitude of 4.7% rms (3.3σ), a FWHM of 0.3 Hz, and a frequency of 0.87 Hz.

We searched for kHz QPOs but none were found, with upper limits (95% confidence levels) between 13 to 26% rms (depending on count rate selection, frequency range, and assumed FWHM of the kHz QPO). These upper limits are higher than the strengths of kHz QPOs detected in other low-luminosity neutron star LMXBs. Therefore, we cannot exclude the presence of QPOs with frequencies between 100 and 1500 Hz. Upper limits (95% confidence level) on coherent pulsations in the frequency range 100–1000 Hz were 2.2% rms, which is significantly lower than the 4%–6% rms detected for the accretion-driven millisecond X-ray pulsar SAX J1808.4–3658 (Wijnands & van der Klis 1998a; Cui, Morgan, & Titarchuk 1998). However, it is possible that SAX J1808.4–3658 has a low system inclination (see Chakrabarty & Morgan 1998) and that SLX 1735–269 has a much larger inclination. The pulsations in SLX 1735–269 will then be smeared out over many frequency bins, making a 4%–6% rms amplitude pulsation undetectable in our analysis.

We fitted the X-ray spectra corresponding to the two power spectral selections. The X-ray spectrum corresponding to a count rate of >128 counts s^{-1} could be adequately fitted with an absorbed power law with a power law index of ∼2.2 (using an N_H of 1.47×10^{22} atoms cm^{-2}; David et al. 1997). The 3–25 keV flux was 3.8×10^{-10} ergs cm^{-2} s^{-1}, corresponding to an intrinsic luminosity of 3.3×10^{36} ergs s^{-1} (assuming a distance of 8.5 kpc). The X-ray spectrum corresponding to a count rate of <128 counts s^{-1} was fitted with an absorbed power law with index 2.4. The fit was considerably improved when a gaussian line, near 6.7 keV with a width of 0.8 keV, was added. The 3–25 keV flux was 2.8×10^{-10} ergs cm^{-2} s^{-1}, corresponding to an intrinsic luminosity of 2.4×10^{36} ergs s^{-1}. These fluxes are in the range previously observed for SLX 1735–269. The steeper power law for the low count rate selection is consistent with the smaller hard color in the CD (Fig. 1 *left*), compared to that of the high count rate selection.

3. Discussion

We presented for the first time an analysis of the rapid X-ray variability properties of the X-ray burst source SLX 1735-269. The timing properties are very similar to those of other low luminosity low magnetic field strength neutron star LMXBs and black hole candidates during their lowest observed mass accretion rates (Wijnands & van der Klis 1999 and references therein). The power spectrum is dominated by a broad band-limited noise component which follows roughly a power law at high frequency, but breaks at a certain frequency below which the power spectrum is approximately flat. When the statistics are sufficient, a broad bump can be detected super imposed on top of this band-limited noise, which is also often observed in other X-ray binaries (see Wijnands & van der Klis 1999 and references therein). The power spectra resemble those obtained for the low-luminosity neutron star LMXBs called the atoll sources, when they accrete at their lowest observed mass accretion rates (i.e., when they are in their so-called island state). We therefore suggest that SLX 1735–269 was during the *RXTE* observations in the island state, assuming it is an atoll source. Also similar to other X-ray binaries is that when the break frequency changes the high frequency part above the break remains approximately the same (see, e.g., Belloni & Hasinger 1990).

However, we observe one uncommon feature of the broad-band noise component: the break frequency increased when the X-ray flux, and therefore possibly the mass accretion rate, decreased. In atoll sources the break frequency decreases when the inferred mass accretion rate decreases (e.g., Prins & van der Klis 1998; Méndez et al. 1997; Ford & van der Klis 1998). So far, only one other source is known for which the break frequency has been observed to increase with decreasing inferred mass accretion rate: the accretion-driven millisecond X-ray pulsar SAX J1808.4–3658 (see Wijnands & van der Klis 1998b). During the beginning of the decay of the 1998 April outburst of this transient source, the break frequency decreased with decreasing

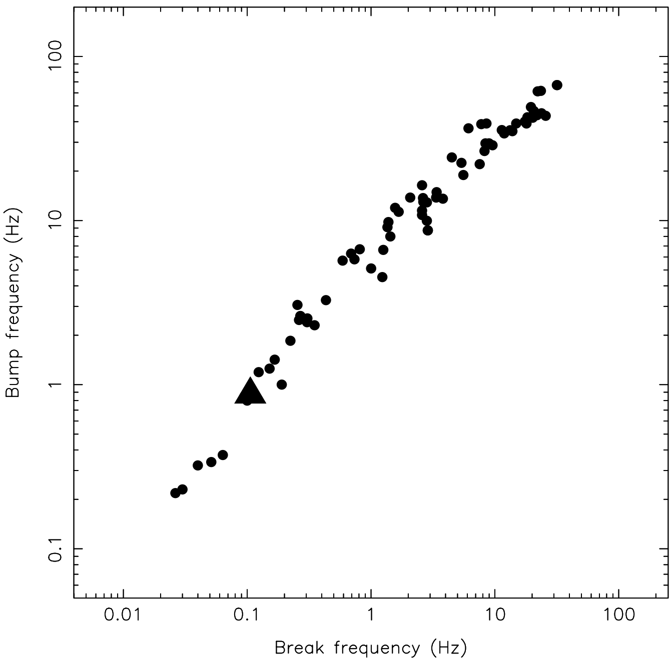

Fig. 3. The frequency of the bump versus the break frequency of the band-limited noise for several sources. The filled bullets are taken from Fig. 2*a* of Wijnands & van der Klis (1999) and represent the neutron star LMXBs (including the accretion-driven millisecond X-ray pulsar SAX J1808.4–3658) and the black-hole candidates analyzed by them. The filled large triangle is SLX 1735–269. The error bars are smaller than the size of the data points.

X-ray flux. However, half-way the decay the break frequency suddenly increased again while the X-ray flux kept on decreasing. Wijnands & van der Klis (1998b) tentatively proposed that this unexpected behavior of the break frequency could be due to the unique pulsating nature of SAX J1808.4–3658 compared to the non-pulsating neutron star LMXBs and black holes candidates, or it could be due to the first ever detailed study of the timing properties of a neutron star LMXB at such low mass accretion rates. With our analysis of SLX 1735–269, which is a persistent LMXB and for which no coherent millisecond pulsations could be detected, it has been shown that the latter is most likely the case. Thus, the unexpected behavior of the accretion-driven millisecond X-ray pulsar is not a unique feature of this system, increasing the similarities of that source with the other, non-pulsating neutron star LMXBs.

During the highest count rates a bump is present on top of the band-limited noise. Wijnands & van der Klis (1999) showed that the frequency of this bump correlates well to the frequency of the break in low-luminosity neutron star LMXBs (including the accretion-driven millisecond X-ray pulsar) and black hole candidates. Fig. 3 shows the same data plotted in Fig. 2a of Wijnands & van der Klis (1999), but now including the data point of SLX 1735–269 (triangle). SLX 1735–269 is right on the relation defined by the other sources. Again, SLX 1735–269 is very similar to other low-luminosity LMXBs. The point obtained for SLX 1735–269 is at the low end of the neutron star points (the lower-frequency points are mostly for black-hole candidates) and very similar to the data of the X-ray bursters 4U 1812–12 and 1E 1724–3045 (see Wijnands & van der Klis 1999). The latter two sources are, therefore, good candidates to display the same increase of the break frequency with decreasing mass accretion rate.

It is also interesting to note that the 3–25 keV luminosity of SLX 1735–269 ($\sim$2–3 $\times 10^{36}$ ergs s^{-1}) is very close to the 3–25 keV luminosity of SAX J1808.4–3658 when in this source the break-frequency and the mass accretion rate became anti-correlated ($\sim 2 \times 10^{36}$ ergs s^{-1}; Wijnands & van der Klis 1999). It is possible that this anti-correlation occurs at a specific X-ray luminosity, which might be similar in all neutron star LMXBs. This can easily be checked by studying neutron star LMXBs in detail at such low luminosities.

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