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LETTER

Letter to the Editor

The millisecond X-ray pulsar/burster SAX J1808.4-3658: the outburst light curve and the power law spectrum

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Abstract. The X-ray light curve and broad band spectral properties of the millisecond X-ray pulsar/burster SAX J1808.4-3658 are reported. In the course of RXTE observations in April–May 1998 the 3–150 keV luminosity of the source decreased by a factor of ~ 100 from the peak value of $\sim 9\times10^{36}$ erg/s (for a 4 kpc distance). However, the spectrum was remarkably stable and maintained a roughly power law shape with a photon index of ~ 2 without a strong high energy cut-off below 100 keV, similar to that sometimes observed in the low spectral state of X-ray bursters. An approximation of the averaged spectrum with an exponentially cut-off power law with a superimposed reflected component yields the 90% lower limit on the e-folding energy $E_f \gtrsim 270$ keV. We speculate that Comptonization on the bulk motion in the radiation dominated shock might be a possible mechanism of spectral formation. The decaying part of the X-ray light curve was cut off abruptly at luminosity $\sim \mathrm{few}\times10^{35}$ erg/s. Such behavior might be due to centrifugal inhibition of accretion (transition to the "propeller" regime) as well as to disk instability. In either case an upper limit on the neutron star magnetic field strength is $B \lesssim \mathrm{few}\times10^{7}$ Gauss.

Key words: stars: neutron – stars: binaries: general – pulsars: general – pulsars: individual (SAX J1808.4-3658) – X-rays: bursts – X-rays: general

1. Introduction

The transient X-ray source SAX J1808.4–3658 was discovered in September 1996 using the Wide Field Camera (WFC) aboard BeppoSAX (in't Zand et al. 1998). The source was not detected by WFC in August and October 1996 or by MIR–KVANT/TTM (N.Alexandrovich & K.Borozdin, private communication) 7 years before in March and August–September 1989 with the upper limits of $\sim 1/50$ and $\sim 1/10$ of the September 1996 peak flux. Two Type I X-ray bursts were detected by WFC in September 1996. The analysis of the X-ray bursts gave 4 kpc source distance for which the 0.4–10 keV persistent luminosity was $6\cdot10^{36}$ erg/s. According to ASM/RXTE data the 1996 outburst lasted for ~ 20 days.

Recently the Rossi X–Ray Timing Explorer detected a new outburst from SAX J1808.4–3658 (Marshall et al. 1998). Coherent pulsations with a period of 2.49 msec (Wijnands & van der Klis 1998) and Doppler shift due to orbital motion with a period of 2^h (Chakrabarty & Morgan 1998) were discovered. The analysis of the RXTE/HEXTE data from April 11 and 13 revealed a remarkable power law spectrum of the source in the 15–120 keV band with a photon index of ≈ 2 (Heindl et al. 1998). The optical counterpart of SAX J1808.4–3658 brightened by $> 3.4^m$ and reached $m_V = 16.6$ on April 18 (Roche et al. 1998). Giles et al. 1998 detected a roughly sinusoidal modulation of 0.12^m in the V–band with a 2^h binary system period.

2. Observations and data reduction

We used the target–of–opportunity public domain data of the PCA and HEXTE instruments aboard RXTE (Bradt et al. 1993). The data were analyzed according to RXTE Cook Book recipes using FTOOLS, version 4.1, tasks. The VLE and L7 background models were used for the PCA data acquired before and after May 2 respectively. Due to the low source count rate ($\sim 5-10\%$ of the PCA background) the PCA spectra and the best fit parameters for the May 2 and 3 observations might be affected by the background subtraction errors. The May 6 data ($\sim 3-5\%$ of the background) were excluded from the spectral analysis. A systematic error of 1% of the source count rate and 2% of the PCA background count rate was added quadratically to the statistical error. The ASM light curve was retrieved from http://space.mit.edu/XTE/ASM_lc.html.

3. Results

The 3–25 keV light curve and the spectra of SAX J1808.4–3658 are shown in Figs. 1 and 2. In order to characterize the broad band spectral properties at different luminosity the power law model was used. The best fit parameters are listed in Table 1.

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Table 1. SAX J1808.4–3658. Parameters of spectral approximation of PCA and HEXTE data by a power law model

Date 1998	Time, UT	Expos.[1],sec PCA	HEXTE[2]	PCA α	PCA $F^{3}_{3-25keV}$	HEXTE α	HEXTE $F^{3,4}_{20-150\,keV}$	PCA+HEXTE α	PCA+HEXTE $F^{3,5}_{3-150keV}$	χ^2_r
11/04	19:50–21:44	2974	2041	2.00 ± 0.01	245.4 ± 0.8	2.13 ± 0.09	138.8 ± 9.6	2.01 ± 0.01	450.0 ± 3.1	1.50
13/04	01:52–02:23	1375	949	1.97 ± 0.01	224.2 ± 0.8	2.13 ± 0.12	153.9 ± 4.2	1.97 ± 0.01	423.4 ± 3.3	1.36
16/04	17:19–23:01	9266	8620	1.95 ± 0.01	145.3 ± 0.5	2.03 ± 0.06	99.9 ± 4.8	1.96 ± 0.01	279.3 ± 1.8	1.43
17/04	01:42–04:39	5675	4018	1.95 ± 0.01	140.8 ± 0.5	2.10 ± 0.08	91.5 ± 5.7	1.96 ± 0.01	270.4 ± 1.9	1.41
18/04	03:09–09:19	13980	9179	1.96 ± 0.01	123.6 ± 0.4	2.06 ± 0.05	82.9 ± 3.7	1.96 ± 0.01	235.9 ± 1.6	1.48
18/04	12:34–01:03	25285	17056	1.96 ± 0.01	118.5 ± 0.4	2.08 ± 0.05	77.5 ± 3.1	1.97 ± 0.01	225.5 ± 1.5	1.54
20/04	21:03–23:09	5120	3557	1.98 ± 0.01	98.1 ± 0.3	2.11 ± 0.13	59.5 ± 6.4	1.99 ± 0.01	182.7 ± 1.5	1.49
23/04	15:53–23:21	16493	11135	2.01 ± 0.01	81.0 ± 0.3	2.03 ± 0.09	55.7 ± 4.0	2.01 ± 0.01	147.8 ± 1.1	1.59
24/04	16:08–23:22	8547	10426	2.03 ± 0.01	77.6 ± 0.3	2.12 ± 0.10	47.1 ± 3.8	2.04 ± 0.01	138.5 ± 1.1	1.49
25/04	14:23–21:41	15045	10120	2.04 ± 0.01	73.1 ± 0.3	2.08 ± 0.11	45.7 ± 4.0	2.05 ± 0.01	129.5 ± 1.0	1.60
26/04	16:01–23:28	15819	10748	2.05 ± 0.01	48.5 ± 0.2	2.11 ± 0.16	27.6 ± 3.6	2.05 ± 0.01	85.6 ± 0.8	1.36
27/04	14:30–19:31	8765	6006	2.11 ± 0.02	24.8 ± 0.2	2.15 ± 0.44	15.8 ± 5.1	2.11 ± 0.01	41.8 ± 0.6	1.22
29/04	14:24–18:58	8536	5735	2.10 ± 0.02	19.9 ± 0.1	2.39 ± 0.61	12.7 ± 5.2	2.10 ± 0.02	33.8 ± 0.6	1.04
02/05[6]	01:26–02:59	3259	1988	1.86 ± 0.13	1.6 ± 0.1	2.0[7]	$\lesssim 4.7$[8]	1.86 ± 0.13	3.4 ± 0.6	0.70
03/05[6]	19:10–21:01	4072	2790	2.29 ± 0.08	3.3 ± 0.1	2.0[7]	$\lesssim 4.6$[8]	2.29 ± 0.07	4.9 ± 0.4	0.70

The errors are 90% confidence; [1] – dead time corrected; [2] – on source, sum of two clusters of detectors; [3] – the energy flux in 10^{-11} erg/sec/cm^2; [4] – original HEXTE normalization [5] – the HEXTE normalization was adjusted to match the PCA data; [6] – low source count rate ($\sim 5-10\%$ of the PCA background, see text); [7] – fixed; [8] – 90% upper limit;

The pulsation with ≈ 2.5 msec period was detected in all observations between April 11–29 and on May 3 with the relative rms of $\approx$ 4–7% increasing slightly as luminosity decreased.

A power law fit to the 3–150 keV spectrum averaged over April 11–25 gives a value of reduced $\chi^2_r = 2.0$ for 297 dof. The deviations are mostly due to PCA data: $\chi^2_r = 4.4$ (50 dof) and $\chi^2_r = 1.3$ (246 dof) for PCA and HEXTE respectively. Heindl & Smith 1998 noted that the addition of an emission line at ~ 6.8 keV with an equivalent width ≈ 50 eV, a black body component at lower energy and a high energy cut off above $\approx$ 30 keV with an e–folding energy of $E_f \approx 127$ keV significantly improved the quality of the fit in terms of the χ^2 statistics.

The significant brightening of the source in the optical band (Roche et al. 1998) plus an iron K$-\alpha$ line and a broad hump near $\sim$ 30 keV in X-ray band (Fig. 2) indicate the presence of a reflected component which might result in some apparent steepening of the spectrum above 30 keV. An accurate account for the effect of reflection requires knowledge of the geometry and ionization state of the reflecting material and accurate cross-calibration of the PCA and HEXTE instruments. In order to estimate the shape of the intrinsic source spectrum we fit the April 11–25 averaged 3–150 keV data with an exponentially cut-off power law reflected from neutral material (pexrav model in XSPEC). The equivalent width of the line, ~ 50 eV, suggests that the solid angle subtended by the reflecting media is $\Omega/2\pi \sim 0.4$ (Basko, Sunyaev, & Titarchuk 1974, George & Fabian 1991), assuming a solar abundance of iron and a fiducial value of the disk inclination angle of $\theta = 60°$. The reflection scaling factor, fixed at this value, the best fit parameters for the intrinsic spectrum are: photon index $\alpha \approx 2.00 \pm 0.02$ and e-folding energy $E_f \approx 365^{+175}_{-95}$ keV (90% errors) with $\chi^2_r = 1.11$ (292 dof). The hydrogen column density was fixed at the Galactic value $NH = 1.3 \cdot 10^{21}$ cm^{-2}. A variation of the the reflection scaling factor and the inclination angle does not qualitatively change α and E_f: $\alpha \approx 1.96 \pm 0.02$, $E_f \approx 255^{+80}_{-50}$ keV for $\Omega/2\pi \sim 0.3$, $\theta = 60°$ and $\alpha \approx 2.03 \pm 0.02$, $E_f \approx 395^{+90}_{-100}$ keV for $\Omega/2\pi \sim 0.3$, $\theta = 30°$.

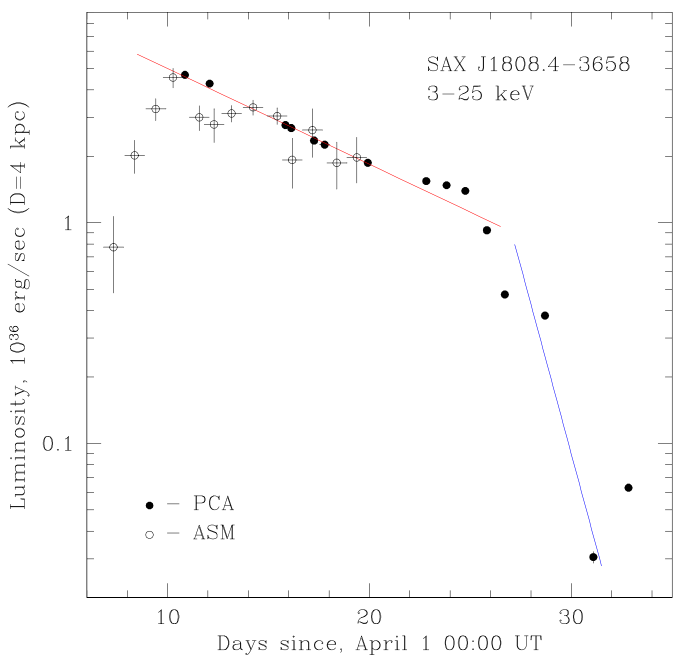

Fig. 1. The 3–25 keV light curve of SAX J1808.4–3658. The PCA fluxes are those from Table 1, the ASM count rate was converted to 3–25 keV energy flux assuming a Crab like spectrum. The solid lines are $L_X \propto e^{-t/10^d}$ and $L_X \propto e^{-t/1.3^d}$.

The results of the RXTE observations of SAX J1808.4–3658 can be summarized as follows:

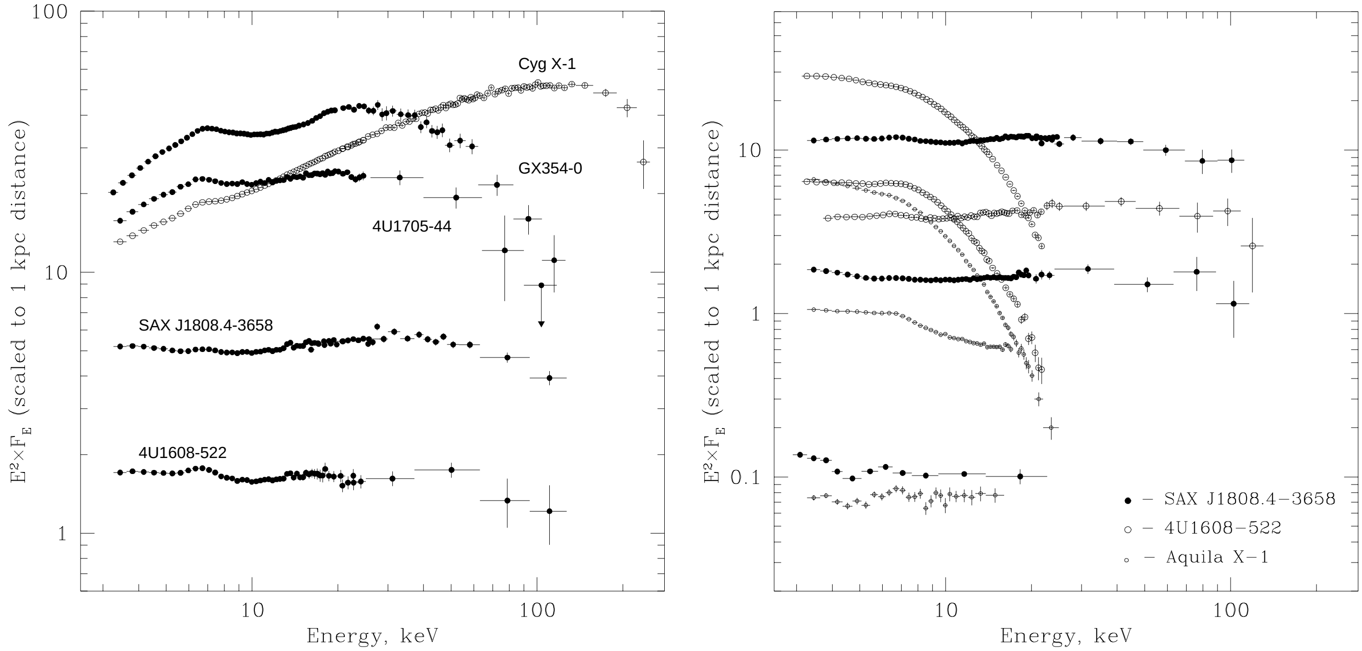

Fig. 2. *Left:* The averaged (April 11–25) spectrum of SAX J1808.4–3658 and the spectra of several X-ray bursters and black hole Cyg X–1 in the low spectral state. *Right:* The spectra of SAX J1808.4–3658 obtained on April 11–13, 26–29 and May 2-3 in comparison with the spectra of other X-ray bursters at different luminosity: 4U1608–522 (Spring 1996 outburst) and Aquila X–1 (Spring 1997). All spectra were obtained using RXTE public data.

1. The 3–100 keV spectrum maintained an approximate power law shape $I_\nu \propto \nu^{-2}$ as luminosity decreased by a factor of ~ 100 (Table 1, Fig. 2). Under the abovementioned assumptions about the reflected component, the lower limit on the exponential cut-off in the intrinsic spectrum averaged over April 11–25 is $E_f \gtrsim 270$ keV.
   The spectrum differs substantially from the low state spectra of the X-ray bursters often observed at $L_X \sim 10^{37}$ erg/s (3–150 keV; e.g. GX354–0, 4U1705–44, Fig. 2). It is similar to the spectra of some X-ray bursters at sufficiently low luminosity $L_X \lesssim (1-2)\cdot 10^{36}$ erg/s (e.g. 4U1608–522 and Aql X–1, Fig. 2).
2. The decaying part of the X-ray light curve has a sharp cut off below $\sim 10^{36}$ erg/s (4 kpc distance is assumed throughout the paper unless mentioned otherwise) – the luminosity has dropped by a factor of ~ 20 within $\lesssim 3$ days. The rise time was also short: $\lesssim 3$ days.
3. The total energy released in the 3–150 keV band was $\sim 8 \times 10^{42}$ erg, corresponding to an accreted mass of $\sim 2 \times 10^{-11} M_\odot$. The peak value of the mass accretion rate was $\dot{M} \sim 7 \times 10^{-10} M_\odot/yr$. These estimates however do not take into account the energy radiated below 3 keV and above 150 keV which could be non negligible.
4. The $I_\nu \propto \nu^{-2}$ power law spectrum does not continue to the IR band – $\frac{L_{IR}}{L_X} \sim 10^{-2}$ (IR data – from Roche et al. 1998).

4. Discussion

Theories of the spectral formation in accreting pulsars with a strong magnetic field predict a change of the physical conditions near the surface of the neutron star at $L_X \sim \mathrm{few} \times 10^{36}$ erg/sec. In the case of X-ray bursters strong spectral changes are associated with the transition from the soft to the hard spectral state at $L_X \sim 10^{36} - 10^{37}$ erg/sec (Fig. 2). We therefore expected to observe spectral evolution as luminosity decreased by a factor of ~ 100. Remarkably no significant spectral changes were detected (Table 1, Fig. 2). This, together with the detection of X-ray pulsations of roughly the same relative amplitude, implies that essentially the same mechanism is responsible for the spectral formation in a broad luminosity range.

4.1. A rotation powered pulsar?

Stability and shape of the spectrum of SAX J1808.4–3658 suggests considering a possibility, that the 1998 outburst was powered by the standard pulsar emission mechanism. For magnetic dipole emission the field strength required to generate X-ray flux F_X [erg/s/cm^2] is $B \sim 2.2 \cdot 10^9 D_{\rm kpc} R_6^{-3} P_{2.5}^4 \left(\frac{\beta}{0.1}\right)^{-1/2} \left(\frac{F_X}{4\cdot 10^{-9}}\right)^{1/2}$ Gauss, where $D_{\rm kpc}$ is the distance in kpc, R_6 – the neutron star radius in 10^6 cm, $P_{2.5}$ – rotation period divided by 2.5 msec, β – the efficiency of the production of X-ray photons. On the other hand the 1996 outburst was accretion powered as the Type I X-ray bursts were detected. For the accretion to proceed uninhibited by the centrifugal force due to the rotating magnetosphere of the neutron star the accretion rate would be $\dot{M} \gtrsim 5\cdot 10^{17} B_9^2 R_6^{16/3} M_{1.4}^{-5/3} P_{2.5}^{-7/3}$ g/s i.e. $\dot{M} \gtrsim 2.5 \cdot 10^{18} D_{\rm kpc}^2$ for $B \sim 2.2 \cdot 10^9\ D_{\rm kpc}$ Gauss. Therefore, independent of the source distance, the 2–10 keV flux observed in 1996 ($2 \cdot 10^{-9}$ erg/s/cm^2) would correspond

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to $\sim 10^{-4}$ of $\dot{M}c^2$. Such a low efficiency of production of X-ray photons is unlikely for an accreting neutron star. Moreover, such a high $\dot{M}$ would lead to a steady nuclear burning of the accreting matter, which contradicts the detection of the Type I X-ray bursts. Thus, the standard pulsar emission mechanism can be ruled out.

4.2. The X-ray light curve

The X-ray light curve is similar to the outburst profiles of two very different types of accreting sources – the neutron star soft X-ray transients (e.g. Zhang et al. 1998, Campana et al. 1998) and Type B outbursts in dwarf Novae (Warner 1995). An abrupt cut-off of the light curve is also common for the black hole X-ray transients (Tanaka & Shibazaki 1996). Two different interpretations of the abrupt decline of luminosity at the end of the outburst are possible in the case of SAX J1808.4–3658:

1. Closure of the centrifugal barrier at low accretion rate when the magnetosphere reaches the corotation radius $R_{co} \approx 31 M_{1.4}^{1/3} P_{2.5}^{2/3}$ km and the source enters the "propeller" regime (Illarionov & Sunyaev 1975). The cut-off luminosity provides an estimate of the magnetic field as: $B \sim 3 \cdot 10^7 M_{1.4}^{1/3} R_6^{-8/3} P_{2.5}^{7/6} \left(\frac{L_X}{10^{35}}\right)^{1/2}$ Gauss.
2. Disk instability. The decay time scale is defined by the propagation of the cooling wave. A rough estimate for the SAX J1808.4–3658 binary system parameters is $\tau_d \sim 1.3 \left(\frac{0.1}{\alpha}\right)$ days, α – viscosity parameter (Warner 1995) which approximately accounts for the observed decay time scale (Fig. 1). The above expression for B is an upper limit in this case.

4.3. Spectral formation

A possible mechanism resulting in the formation of a power law spectrum with a slope ~ 2 might be Comptonization on the bulk motion in a radiation dominated shock (Blandford & Payne 1981, Lyubarskii & Sunyaev 1982). If, as indicated by the X-ray pulsation, there is non negligible disk–magnetosphere interaction, the accreting matter is funneled onto the polar caps with ~free fall velocity. If the radiation energy flux q exceeds the critical value q_c ~local Eddington flux, the radiation dominated shock is formed near the surface of the neutron star at the polar regions (Davidson 1973, Basko & Sunyaev 1976), where $\gtrsim 2/3$ of the accretion energy is released. A naive estimate – assuming that the magnetosphere is close to corotation, the magnetic field inside the magnetosphere is not distorted and the in-falling matter fills the magnetic funnel – gives the value of the critical luminosity $L_c \sim \mathrm{few} \times 10^{36} - 10^{37}$ erg/sec, which exceeds by more than an order of magnitude the minimum luminosity observed for SAX J1808.4–3658. However, an accurate calculation of q/q_c requires detailed knowledge of the disk–magnetosphere interaction and the accretion flow pattern inside the magnetosphere. It is important to note that in order for this mechanism to be responsible for the spectral formation in SAX J1808.4–3658, self adjustment of the accretion funnel to maintain $q/q_c \sim 1$ in a broad range of the accretion rates is required.

Comptonization on the bulk motion in the radiation dominated shock near the stellar surface in the equatorial area might also occur in the case of the "classical" X-ray bursters if the neutron star is smaller than the last marginally stable orbit (Kluzniak & Wagoner 1985, Sunyaev & Shakura 1986). The power law spectra with a slope ~ 2 up to ~ 100 keV are indeed observed for some of the "classical" X-ray bursters at low luminosity, $L_X \lesssim 10^{36}$ erg/sec (Fig. 2).

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