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 $\sim 100$ from the peak value of $\sim 9 \times 10^{36}$ 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 $\sim 2$ 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 $\sim$ few $\times 10^{35}$ 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 $B \lesssim$ few $\times 10^7$ Gauss.

Key words: stars:neutron – stars:binaries:general – pulsars:general – pulsars:indivdual (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 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 $6 \cdot 10^{36}$ erg/s. According to ASM/RXTE data the 1996 outburst lasted for $\sim 20$ 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 $\approx 2$ (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.
The bright band spectral properties at different luminosity was detected in all observations between April 11 – 29 and the 3–100 keV spectrum maintained an approximate power law shape \( \nu \propto \nu^{-2} \). The results of the RXTE observations of SAX J1808.4–3658 can be summarized as follows:

1. The 3–100 keV spectrum maintained an approximate power law shape \( L_{\nu} \propto \nu^{-2} \) as luminosity decreased by a factor of \( \sim 100 \) (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 \( E_{\nu} \approx 0.3 \text{ keV} \). The hydrogen column density was fixed at the Galactic value \( NH = 1.3 \cdot 10^{21} \text{ cm}^{-2} \). A variation of the reflection scaling factor and the inclination angle does not qualitatively change \( \alpha \) and \( E_{\nu} \approx 0.3 \text{ keV} \). The results of the RXTE observations of SAX J1808.4–3658 can be summarized as follows:

2. The decaying part of the X–ray light curve has a sharp cut off below \( \sim 10^{36} \text{ erg/s} \) (4 kpc distance is assumed throughout the paper unless mentioned otherwise) – the luminosity has dropped by a factor of \( \sim 20 \) within \( \lesssim 3 \text{ days} \). The rise time was also short: \( \lesssim 3 \text{ days} \).
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 $L_X \propto e^{-t/10^4}$ and $L_X \propto e^{-t/1.3^4}$.

3. The total energy released in the 3–150 keV band was $\approx 8 \times 10^{32}$ 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 $L_\nu \propto \nu^{-2}$ power law spectrum does not continue to the IR band $-\frac{L_{\nu IR}}{L_X} \sim 10^{-2}$ (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 $L_X \sim$ 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 $\sim 100$. 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 $B \sim 2.2 \cdot 10^8 D_{kpc} R_6^{-3} P_{2.5}^{1/2} \left( \frac{\beta}{10} \right)^{-1/2} \left( \frac{F_X}{6 \times 10^{-8}} \right)^{1/2}$ Gauss, where $D_{kpc}$ 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, $\beta$ – 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 $\dot{M} \gtrsim 5 \cdot 10^{17} B_8^2 R_6^{16/3} M_1^{-5/3} P_2^{-7/3}$ g/s i.e. $\dot{M} \gtrsim 2.5 \cdot 10^{18} D_{kpc}^2$ for $B \sim 2.2 \cdot 10^9 D_{kpc}$ 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 to $\sim 10^{-4}$ of $\dot{M}^2$. 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 $R_{co} \approx 31 M_1^{1/3} P_{2.5}^{2/3}$ km and the source enters the “propeller” regime (Illarionov & Sunyaev 1975). The cut-off luminosity provides an estimate of the magnetic field as: $B \sim 3 \cdot 10^7 M_1^{1/3} R_6^{-8/3} P_{2.5}^{-7/6} \left( \frac{\alpha}{0.1} \right)^{-1/2}$ 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 $\tau_d \sim 1.3 \left( \frac{d}{2 kpc} \right)$ days, $\alpha$ – 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 $\sim 2$ 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 $\sim$free fall velocity. If the radiation energy flux $q$ exceeds the critical value $q_c \sim$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 $L_c \sim \text{few} \times 10^{36} - 10^{37}$ 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 $\sim 2$ up to $\sim 100$ 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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