Phase-resolved X-ray spectroscopy of the millisecond pulsar SAX J1808.4–3658

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ABSTRACT

We present new results based on RXTE observations of the millisecond pulsar SAX J1808.4–3658 carried out during the decay of the April 1998 outburst. The X-ray spectrum can be fitted by a two-component model. We interpret the soft component as blackbody emission from a heated spot on the neutron star, and the hard component as coming from Comptonization in plasma heated by the accretion shock as the material collimated by the magnetic field impacts onto the neutron star surface. The hotspot is probably the source of seed photons for Comptonization. The hard component illuminates the disc, giving rise to a reflected spectrum. The amount of reflection indicates that the disc is truncated at fairly large radii (20–40 $R_g$), consistent with the lack of relativistic smearing of the spectral features. The inferred evolution of the inner radius is not consistent with the magnetic field truncating the disc. Instead it seems more likely that the inner disc radius is set by some much longer time-scale process, most probably connected to the overall evolution of the accretion disc. This disc truncation mechanism would then have to be generic in all low mass accretion rate flows both in disc accreting neutron stars and black hole systems.

The phase resolved spectra show clearly that the blackbody and hard Comptonized spectra pulse independently. This obviously gives an energy dependent phase lag. Full general relativistic effects are not required to explain this. The soft blackbody component is optically thick, so its variability is dominated by its changing projected area, while the Doppler shifts (which are maximized 90° before the maximum in projected area) are somewhat stronger for the translucent column.

We do not detect Compton reflection from the neutron star surface, though we predict that it should be present in the X-ray spectrum. This would give an unambiguous observational measure of $M/R$ if there is any iron on the neutron star surface which is not completely ionized.

Key words: accretion, accretion discs – pulsars: individual (SAX J1808.4–3658) – X-rays: binaries

1 INTRODUCTION

Neutron stars and Galactic black holes have very similar gravitational potentials, so the accretion flow in these systems might also be expected to be similar. The key difference is that neutron stars have a solid surface. Therefore, they can have a boundary layer and thermal emission from the surface. Additionally, where there is a strong magnetic field the accretion flow is collimated along the field lines. When the spin and magnetic axes are misaligned the surface emission should be coherently pulsed at the spin period. This is seen in the X-ray pulsars – high mass X-ray binary systems where young, rapidly rotating neutron stars with a high magnetic field ($\geq 10^{12}$ G) collimate the accreting material onto the magnetic poles. However, up till 1998 no millisecond pulses were seen from the low mass X-ray binaries (LMXBs), so there was no direct measure of the spin and magnetic field in such systems. This would be an important test of models of the formation of the millisecond pulsars. Currently the most probable scenario for these rapidly rotating, low magnetic field ($\sim 10^8$ G) neutron stars is that their progenitors are the LMXBs, where the neutron star is spun up through accretion torques, which also might dissipate the magnetic field (e.g. the review by Bhattacharya & Srinivasan 1995).
This situation changed dramatically with the discovery of the coherent X-ray pulsations with 2.5 ms period from the transient X-ray source SAX J1808.4–3658 (Wijnands & van der Klis 1998a). Its rapid rotation and inferred magnetic field of a few ∼10^8 G is in excellent agreement with the predictions of the millisecond pulsar progenitor models (Psaltis & Chakrabarty 1999). The key question is then what makes SAX J1808.4–3658 so different from the rest of the LMXBs? Are there only a rather limited number of fundamental parameters which determine the accretion flow – the mass of the neutron star, mass accretion rate, magnetic field, spin of the neutron star and angle between the spin and magnetic axes. These could be coupled with the age and/or evolutionary state of the system, and a further variable which could alter the appearance of the system is its inclination angle to the line of sight.

One way in which to look for differences is to do a detailed comparison of the spectrum and variability of SAX J1808.4–3658 with other neutron star LMXBs. These fall into two main categories, atolls and Z sources, named after their different behaviours on a colour–colour diagram (Hasinger & van der Klis 1989). Atolls can show rather hard spectra dominated by a power law component, similar to that seen in the galactic black holes (e.g. Mitsuda et al. 1989; Yoshida et al. 1993; Barret et al. 2000). This hard or island state is generally seen only at mass accretion rates below a few per cent of Eddington (Ford et al. 2000). Above this the source spectrum makes a rapid transition to a much softer spectrum, termed the banana branch, so tracing out a C (or atoll) shape on a colour–colour diagram. Conversely the Z sources move from a horizontal branch, through a normal branch to the flaring branch as their mass accretion rate increases, tracing out a Z shape on a colour–colour diagram. The power spectral properties also correlate with atoll or Z source classification, and with position on the colour–colour diagram (see e.g. the review by van der Klis 1995).

The broad band spectrum of SAX J1808.4–3658 is entirely typical of an atoll system in the island state, with a power law hard X-ray spectrum (Heindl & Smith 1998; Gilfanov et al. 1998). The variability power spectrum of SAX J1808.4–3658 is also very similar to island state atoll systems (apart from the coherent signal at the spin period): the broad band noise properties (Wijnands & van der Klis 1998b) and even the correlation between the noise break frequency and the QPO frequency matches onto that from other LMXBs (Wijnands & van der Klis 1999).

Thus it seems highly unlikely that there is any large scale difference between the properties of the accretion flow in SAX J1808.4–3658 compared with other neutron star LMXB systems. Yet there is a coherent spin pulse in SAX J1808.4–3658 which is definitely not present in the other atoll systems (Vaughan et al. 1994; Chandler & Rutledge 2000).

There were three observed outbursts of SAX J1808.4–3658: in September 1996 (in ’t Zand et al. 1998), in April 1998 (Wijnands & van der Klis 1998a) and in January 2001 (Wijnands et al. 2001). Here we examine the RXTE spectra of SAX J1808.4–3658 from 1998 outburst in detail, looking at both the phase averaged and phase resolved spectra at differing mass accretion rates as the outburst declines. We derive a source geometry which is consistent with the observational constraints, and finally speculate that evolutionary effects are responsible for visibility of the spin pulse.

2 OBSERVATIONS

We analyse RXTE observations of 11–29 April 1998 (HEASARC archival number P’30411) of the millisecond pulsar SAX J1808.4–3658 using FTOOLS 5.0. We extract the PCA energy spectra from the top layer of detectors 0 and 1 from the Standard-2 data files. A comparison with the Crab spectra shows that a 0.5 per cent systematic error is appropriate in RXTE epoch 3 PCA observations for this restricted data selection between energies of 3–20 keV (Wilson & Done 2001). These PCA spectra are combined with the 20–150 keV data from HEXTE cluster 0. The relative normalization of the PCA and HEXTE instruments is still uncertain, so we allow this to be an addition free parameter in all spectral fits. Table 1 contains the log of observations. Observation 1 has a ∼12° pointing offset, therefore the count rates are lower than in the second observation, though the actual X-ray flux is higher.

We also extract phase-resolved energy spectra from the PCA Event mode data files with timing resolution of 122 µs (except for the April 13 observation where we used GoodXenon mode files, with resolution of 1 µs). We have generated folded light-curves in 16 phase bins, for each PCA channel, all layers, detectors 0 and 1. We have chosen beginning of the phase (φ = 0) at the bin with lowest 3–20 keV count rate. Photon arrival times were corrected for orbital movements of the pulsar and the spacecraft. Background files were made from Standard-2 data for exactly the same periods when our phase-resolved spectra were extracted. Power density spectra (PDS) were extracted from the same data files as the phase-resolved spectra, in the 3–20 keV energy range, though we have used all detectors this time. We calculate power density spectra in the 1/128–2048 Hz frequency range from averaging fast Fourier transforms over 128 s data intervals.

All spectral analysis (both phase-resolved and phase-averaged) is done using the XSPEC 11 spectral package (Arnaud 1996). The error of each model parameter is given for a 90 per cent confidence interval. We fix the absorption to a 90 per cent confidence interval. We fix the absorption to a 90 per cent confidence interval. We fix the absorption to a 90 per cent confidence interval. We fix the absorption to a 90 per cent confidence interval. We fix the absorption to a 90 per cent confidence interval. We fix the absorption to a 90 per cent confidence interval. We fix the absorption to a 90 per cent confidence interval. We fix the absorption to a 90 per cent confidence interval. We fix the absorption to a 90 per cent confidence interval. We fix the absorption to a 90 per cent confidence interval. We fix the absorption to a 90 per cent confidence interval. We fix the absorption to a 90 per cent confidence interval. We fix the absorption to a 90 per cent confidence interval. We fix the absorption to a 90 per cent confidence interval. We fix the absorption to a 90 per cent confidence interval. We fix the absorption to a 90 per cent confidence interval. We fix the absorption to a 90 per cent confidence interval. We fix the absorption to a 90 per cent confidence interval. We fix the absorption to a 90 per cent confidence interval. We fix the absorption to a 90 per cent confidence interval. We fix the absorption to a 90 per cent confidence interval. We fix the absorption to a 90 per cent confidence interval. We fix the absorption to a 90 per cent confidence interval. We fix the absorption to a 90 per cent confidence interval. We fix the absorption to a 90 per cent confidence interval. We fix the absorption to a 90 per cent confidence interval. We fix the absorption to a 90 per cent confidence interval.