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# Timing the accretion flow around accreting millisecond pulsars

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## **Abstract.**

At present, ten years after they were first discovered, ten accreting millisecond pulsars are known. I present a study of the aperiodic X-ray variability in three of these systems, which led to the discovery of simultaneous kHz quasi periodic oscillations in XTE J1807–294 and extremely strong broadband noise at unusually low variability frequencies in IGR J00291+5934. Furthermore, we classified SWIFT J1756.9–2508 as an atoll source and measured in its 2007 outburst spectral and variability properties typical of the extreme island state. I also give detailed estimates of the total fluence during the studied outbursts.

**Keywords:** Neutron stars - X-ray binaries - Pulsars

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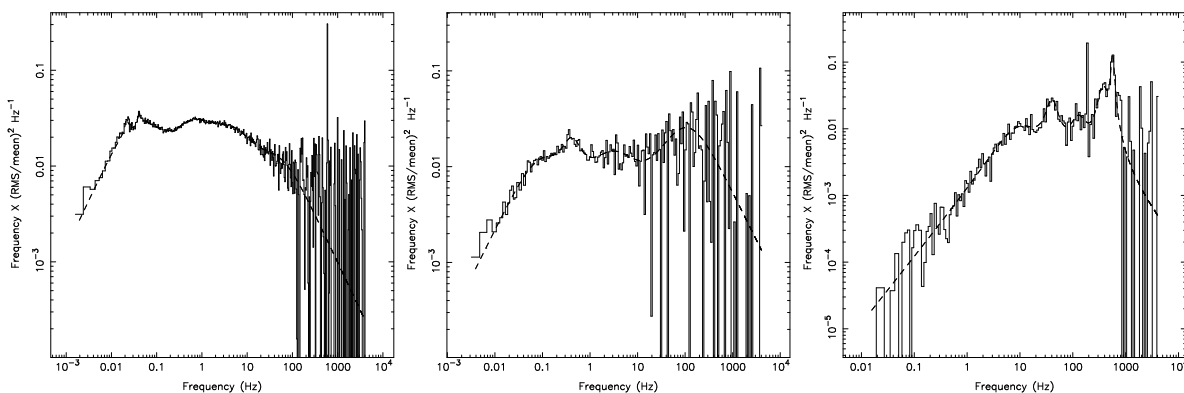
## **INTRODUCTION**

During the last decade accreting millisecond pulsars (AMPs) have revealed a number of interesting phenomena and have opened a new window to the physics of accretion onto neutron stars (NSs). The first of such systems was discovered by Wijnands and van der Klis [1, SAX J1808.4–3658], presenting the first prove of an accreting neutron star having both millisecond spin period and dynamically important magnetic field. Ten AMPs have been discovered to date, and in three of them millisecond X-ray pulsations have been seen to appear in and disappear from the persistent emission, producing predominant [HETE J1900.1-2455; 2] intermittent [SAX J1748.9-2021; 3] or very rare [Aql X-1; 4] episodes of pulsations. This implies that the AMP within them is only active or visible during a relatively small fraction of the time, which may provide a link with the much more numerous class of non-pulsating neutron star low-mass X-ray binaries (NS-LMXBs).

One way to study accretion onto compact objects is to analyze the aperiodic variability in the X-ray flux coming from these sources, which tells us about processes occurring in the inner accretion flow [5, 6]. Such timing of the accretion flow, combined with a study of the X-ray spectrum, reveals different “accretion states”. We show in this paper three different AMPs in three different accretion states, we describe their aperiodic variability and quantify their outburst fluence.

## IGR J00291+5934

The sixth AMP was discovered on December 2<sup>nd</sup>, 2004: IGR J00291+5934 [7]. Coherent pulsations were found at a frequency of 598.9 Hz, modulated by the  $\sim 2.5$  hr orbital motion [8, 9]. Follow up observations of the outburst, which lasted about two weeks, were performed by *RXTE* (see Fig. 2). Our study of IGR J00291+5934 showed what still constitutes the strongest X-ray variability seen in a NS-LMXB, namely the fractional rms was  $\sim 50\%$ . We also measured the lowest characteristic frequencies ever seen in a NS-LMXB, with a break in the flat-topped power spectrum at  $\sim 0.04$  Hz [see Figure 1 and ref. 10, for more details and discussion]. This AMP is therefore an extreme example of what is often called “extreme island” state of atoll sources [a low-luminosity class of NS-LMXB, see 11].



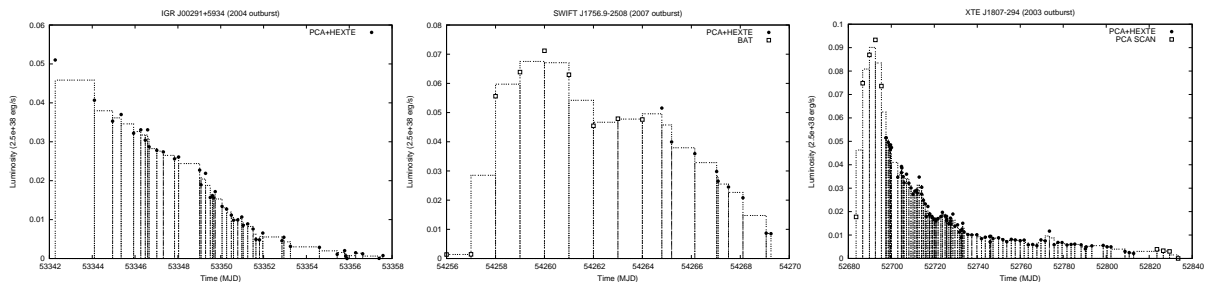
**FIGURE 1.** Power spectra (in power times frequency representation and rms normalized) of three AMPs in outburst: IGR J00291+5934 (*left*), SWIFT J1756.9–2508 (*center*) and XTE J1807–294 (*right*). The break frequency in IGR J00291+5934 is more than two orders of magnitude lower than that of XTE J1807–294, which shows instead simultaneous kHz QPOs.

## SWIFT J1756.9–2508

On June 7<sup>th</sup>, 2007, a new X-ray transient was discovered [12] with the burst alert telescope (BAT) onboard *Swift*. Follow up *RXTE* observations revealed that this was the eighth discovered AMP and showed a pulse frequency of  $\sim 182$  Hz and an orbital period of  $\sim 54$  minutes [13, 14, 15]. The outburst lasted about two weeks (see Fig. 2). We analyzed the aperiodic variability of the source, comparing it with other AMPs and with atoll sources. We thereby classified SWIFT J1756.9-2508 as an atoll source in the extreme island state. Using both PCA and HEXTE data we detected a hard tail in its energy spectrum extending up to 100 keV, fully consistent with such source and state classification [16]. It is interesting to note that so far all AMPs show spectral and timing [except for the shifts in the frequency-frequency correlations, see 17, 18] properties identical to those of atoll sources, which suggests that low mass accretion rate is a necessary (even though seemingly not sufficient) ingredient to make an AMP.

## XTE J1807–294

A new transient X-ray source was discovered in the Galactic bulge region on February 13<sup>th</sup>, 2003. Subsequently, coherent pulsations were detected at a frequency of 190.6 Hz turning the new system, XTE J1807–294, into the fourth discovered AMP [19]. An orbital period of  $\sim 40$  minutes was determined [20], still the shortest among AMPs. The outburst was followed by *RXTE* during five months (see Fig.2). We discovered seven pairs of twin kHz quasi-periodic oscillations in XTE J1807–294 [18], with a frequency separation approximately equal to the spin frequency (see M. van der Klis contribution in these proceedings for further details).



**FIGURE 2.** Light curves of the three AMP outbursts studied herein. Filled circles show the *RXTE*-PCA&HEXTE measurements and empty squares those of *Swift*-BAT or PCA scans.

## OUTBURST FLUENCES

An important question that still remains open is why AMPs show pulsations whereas most of NS-LMXBs do not. The solution proposed by Cumming et al. [21] invokes screening of the magnetic field in “classical” NS-LMXBs by a time-averaged mass accretion rate higher than that of AMPs. In order to test this and other theories (NS crust cooling, binary evolution) a careful estimate of how much mass falls onto the neutron star surface is of capital importance [22]. For this purpose we measure the unabsorbed 2-200 keV flux during the three AMP outbursts mentioned above, using data from both PCA and HEXTE onboard *RXTE*. We fit the broadband, background and deadtime corrected, energy spectra with an absorbed disk blackbody plus power law model (fixing the column density to the Galactic value in the source direction). For XTE J1807–294 we use data from the PCA scans of the Galactic bulge [23] to cover the rise and the final decay, as there are no pointed *RXTE* observations during those parts of the outburst. In the case of SWIFT J1756.9–2508 we use data from the *Swift*-BAT transient monitor<sup>1</sup>, as most of the outburst had no *RXTE* pointings. We calibrate the conversion between PCA-scan/BAT and PCA&HEXTE fluxes in those parts of the outbursts where both fluxes are available, thus implicitly assuming that the spectral shape does not vary drastically. The resulting lightcurves, translated to luminosities in units of  $2.5 \times 10^{38}$  erg/s, are shown in Figure 2. Table 1 shows our measurements of the fluence, radiated energy and peak

<sup>1</sup> <http://swift.gsfc.nasa.gov/docs/swift/results/transients/>

luminosity for the three outbursts studied (see note on distances used therein). We also show in Table 1 the range spanned by the break frequency in the power spectrum, which indicates the relative change in X-ray variability frequencies, as well as the orbital period of each system.

**TABLE 1.** Parameters of the AMP outbursts studied in this work.

	Outburst fluence ( $10^{-3}$ erg/cm $^2$ )	Outburst energy* ( $10^{43}$ erg)	Peak luminosity* (% Eddington)	Break frequency (Hz)	Orbital period (min)
XTE J1807–294	7.2	5.5 [8]	9.5 [8]	5.3–10.2	40
IGR J00291+5934	1.4	0.6 [6]	5 [6]	0.03–0.05	150
SWIFT J1756.9–2508	1.5	1.2 [8]	7 [8]	0.09–0.12	54

\* The fiducial distance used is indicated, in kiloparsecs and between brackets. These three AMPs have not shown X-ray bursts and their distances are therefore uncertain [see, however, 24, 25].

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