Abstract: I present an overview of our current observational knowledge of the six known accretion-driven millisecond X-ray pulsars. A prominent place in this review is given to SAX J1808.4–3658; it was the first such system discovered and currently four outbursts have been observed from this source, three of which have been studied in detail using the Rossi X-ray Timing Explorer satellite. This makes SAX J1808.4–3658 the best studied example of an accretion-driven millisecond pulsar. Its most recent outburst in October 2002 is of particular interest because of the discovery of two simultaneous kilohertz quasi-periodic oscillations and nearly coherent oscillations during type-I X-ray bursts. This is the first (and so far only) time that such phenomena are observed in a system for which the neutron star spin frequency is exactly known. The other five systems were discovered within the last three years (with IGR J00291+5934 only discovered in December 2004) and only limited results have been published.

1 Introduction

Ordinary pulsars are born as highly-magnetized \( (B \sim 10^{12} \text{ G}) \), rapidly rotating \( (P \sim 10 \text{ ms}) \) neutron stars which spin down on timescales of 10 to 100 million years due to magnetic dipole radiation. However, a number of millisecond \( (P < 10 \text{ ms}) \) radio pulsars is known with ages of billions of years and weak \( (B \sim 10^{8–9} \text{ G}) \) surface magnetic fields. Since many of these millisecond pulsars are in binaries, it has long been suspected (see, e.g., Bhattacharya & van den Heuvel 1991 for an extended review) that the neutron stars were spun up by mass transfer from a stellar companion in a low-mass X-ray binary (LMXB), but years of searching for coherent millisecond pulsations in LMXBs failed to yield a detection (Vaughan et al. 1994 and references therein). The launch of the NASA Rossi X-ray Timing Explorer (RXTE) brought the discovery of kilohertz quasi-periodic oscillations (kHz QPOs; Strohmayer et al. 1996; Van der Klis et al. 1996) as well as nearly coherent oscillations ('burst oscillations') during type-I X-ray bursts in a number of LMXBs (e.g., Strohmayer et al. 1996), providing tantalizingly suggestive evidence for weakly magnetic neutron stars with millisecond spin periods (see Van der Klis 2000, 2004 and Strohmayer & Bildsten 2003 for more details about kHz QPOs and burst oscillations in LMXBs).
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Figure 1: The RXTE/ASM light curves of SAX J1808.4–3658 during the September 1996 outburst (left), the April 1998 outburst (middle) and the October 2002 outburst (right). These light curves were made using the public ASM data available at http://xte.mit.edu/ASM_lc.html. The count rates are for the 2–12 keV energy range and are daily averages.

In April 1998 the first accretion-driven millisecond X-ray pulsar (SAX J1808.4–3658) was discovered (Wijnands & van der Klis 1998a) proving that indeed neutron stars in LMXBs can spin very rapidly. This conclusion was further strengthened by the discovery of four additional systems in 2002 and 2003 (Markwardt et al. 2002a, 2003a, 2003b, Galloway et al. 2002), and recently, in December 2004, with the discovery of IGR J00291+5934 as a millisecond X-ray pulsar (Markwardt et al. 2004a). Here, I will give a brief summary of our current observational knowledge of those accretion-driven millisecond X-ray pulsars. Preliminary versions of this review were published by Wijnands (2004a, 2004b).

2 SAX J1808.4–3658

2.1 The September 1996 Outburst

In September 1996, a new X-ray transient and LMXB was discovered with the Wide Field Cameras (WFCs) aboard the Dutch-Italian BeppoSAX satellite and the source was designated SAX J1808.4–3658 (In ’t Zand et al. 1998). Three type-I X-ray bursts were detected, demonstrating that the compact object in this system is a neutron star. From those bursts, a distance estimate of 2.5 kpc was determined (In ’t Zand et al. 1998, 2001). The maximum luminosity during this outburst was $\sim 10^{36}$ erg s$^{-1}$, significantly lower than the peak outburst luminosity of ’classical’ neutron star transients (which typically can reach a luminosity of $10^{37}$ to $10^{38}$ ergs s$^{-1}$). This low peak luminosity showed that the source was part of the growing group of faint neutron-star X-ray transients (Heise et al. 1999). The outburst continued for about three weeks (see Fig. 1) after which the source was thought to have returned to quiescence. However, it was found (Revnivtsev 2003) that the source was detected
Figure 2: Examples of power spectra for each of the six currently known millisecond X-ray pulsars showing the pulsar spikes.

on October 29, 1996 (using slew data obtained with the proportional counter array [PCA] aboard RXTE) with a luminosity of about a tenth of the outburst peak luminosity. This demonstrates that six weeks after the main outburst the source was still active (possibly only sporadically), which might indicate that at the end of this outburst the source behaved in a manner very similar to what was seen during its 2000 and 2002 outbursts (see § 2.3 and § 2.4).

After it was found that SAX J1808.4–3658 harbors a millisecond pulsar (§ 2.2), the three observed X-ray bursts seen with BeppoSAX/WFC were scrutinized for potential burst oscillations (In ‘t Zand et al. 2001). A marginal detection of a 401 Hz oscillation was made in the third burst. This result suggested that the burst oscillations observed in the other, non-pulsating, neutron-star LMXBs occur indeed at their neutron-star spin frequencies. This result has been confirmed by the recent detection of burst oscillations during the 2002 outburst of SAX J1808.4–3658 (§ 2.4.2).
2.2 The April 1998 outburst

On April 9, 1998, RXTE/PCA slew observations indicated that SAX J1808.4–3658 was active again (Marshall 1998; see Fig. 1 for the RXTE/ASM light curve during this outburst). Using public TOO observations of this source from April 11, it was discovered (Wijnands & Van der Klis 1998a) that coherent 401 Hz pulsations (Fig. 2) were present in the persistent X-ray flux of the source, making it the first accretion-driven millisecond X-ray pulsar discovered. After this discovery, several more public RXTE observations were made (using the PCA) which were used by several groups to study different aspects of the source. I will briefly mention those results and I point to references for the details.

A detailed analysis of the coherent timing behavior (Chakrabarty & Morgan 1998) showed that the neutron star was in a tight binary with a very low-mass companion star in a ∼2-hr orbital period. Due to the limited amount of data obtained during this outburst, only an upper limit of < 7 × 10^{-13} Hz s^{-1} could be obtained on the pulse-frequency derivative (Chakrabarty & Morgan 1998). Studies of the X-ray spectrum (Gilfanov et al. 1998; Heindl & Smith 1998; see also Gierlinski et al. 2002 and Poutanen & Gierlinski 2003) and the aperiodic rapid X-ray variability (Wijnands & van der Klis 1998b; see also Van Straaten et al. 2005) showed an object that, apart from its pulsations, is remarkably similar to other LMXBs with comparable luminosities (the atoll sources). There is apparent modulation of the X-ray intensity at the orbital period, with a broad minimum when the pulsar is behind the companion (Chakrabarty & Morgan 1998; Heindl & Smith 1998). Cui et al. (1998) and Ford (2000) reported on the harmonic content, energy dependency, and soft phase lag of the pulsations. The main result of those studies is that the low-energy pulsations lag the high-energy ones by as much as ∼200 µs (∼8% of the pulsation period; see Cui et al. [1998], Ford [2000], and Poutanen & Gierlinski [2003] for possible explanations for these soft lags).

Another interesting aspect is that the source first showed a steady decline in X-ray flux, which after 2 weeks suddenly accelerated (Gilfanov et al. 1998; Cui et al. 1998; Fig. 3). This behavior has been attributed to the fact that the source might have entered the ‘propeller regime’ in which the accretion is centrifugally inhibited (Gilfanov et al. 1998). However, after the onset of the steep decline the pulsations could still be detected (Cui et al. 1998) making this interpretation doubtful. A week after the onset of this steep decline, the X-ray flux leveled off (Cui et al. 1998; Wang et al. 2001), but as no further RXTE/PCA observations were made, the X-ray behavior of the source at the end of the outburst remained unclear. The source might have displayed a similar long-term episode of low-luminosity activity as seen at the end of its 2000 and 2002 outbursts (see § 2.3 and § 2.4).

SAX J1808.4–3658 was not only detected and studied in X-rays but also in the optical, IR, and in radio bands. The optical/IR counterpart of SAX J1808.4–3658 (later named V4580 Sgr; Kazarovets et al. 2000) was first discovered by Roche et al. (1998) and subsequently confirmed by Giles et al. (1998). A detailed study of
the optical behavior during this outburst was reported by Giles et al. (1999) and Wang et al. (2001). Both papers reported that the peak V magnitude of the source was \( \sim 16.7 \) and the source decayed in brightness as the outburst progressed. The brightness of the source leveled off at around V \( \sim 18.5 \) (I \( \sim 17.9 \)) about \( \sim 2 \) weeks after the peak of the outburst. It stayed at this level for at least several weeks before it further decreased in brightness. This behavior suggests that the source was indeed still active for a long period after the main outburst.

It was also reported (Giles et al. 1999) that the optical flux was modulated at the 2-hr orbital period of the system. Modeling the X-ray and optical emission from the system using an X-ray-heated accretion disk model yielded a \( A_v \) of 0.68 and an inclination of cos \( i = 0.65 \) (Wang et al. 2001), resulting in a mass of the companion star of 0.05–0.10 solar masses. During some of the IR observations, the source was too bright to be consistent with emission from the disk or the companion star, even when considering X-ray heating. This IR excess might be due to synchrotron processes, likely related to an outflow or ejection of matter (Wang et al. 2001). Such an ejection event was also confirmed by the discovery of the radio counterpart (Gaensler et al. 1999). The source was detected with a 4.8 GHz flux of \( \sim 0.8 \) mJy on 1998 April 27, but it was not detected at earlier or later epochs.

### 2.3 The January 2000 outburst

On January 21, 2000, SAX J1808.4–3658 was again detected (Wijnands et al. 2001) with the RXTE/PCA at a flux level of \( \sim 10^{10} \)–\( 15 \) mCrab (2–10 keV), i.e. about a tenth of the peak fluxes observed during the two previous outbursts. Using follow-up RXTE/PCA observations, it was found that the source exhibited low-level activity for several months (Wijnands et al. 2001). Due to solar constraints the source could not be observed before January 21 but likely a true outburst occurred before that date and we only observed the end stages of this outburst. This is supported by the very similar behavior of the source observed near the end of its 2002 October outburst (see § 2.4; Fig. 5).

During the 2000 outburst, SAX J1808.4–3658 was observed (using RXTE/PCA) on some occasions at luminosities of \( \sim 10^{35} \) ergs s\(^{-1}\), but on other occasions (a few days earlier or later) it had luminosities of \( \sim 10^{32} \) ergs s\(^{-1}\) (as seen during BeppoSAX and XMM-Newton observations; Wijnands et al. 2002, Wijnands 2003; see Fig. 3 left panel). This demonstrates that the source exhibited extreme luminosity swings (a factor of \( > 1000 \)) on timescales of days. During the RXTE observations, it was also found that on several occasions the source exhibited strong (up to 100 % r.m.s. amplitude) violent flaring behavior with a repetition frequency of about 1 Hz (Van der Klis et al. 2000; Fig. 9). During this episode of low-level activity, the pulsations at 401 Hz were also detected.

The source was again detected in optical, albeit at a lower brightness than during the 1998 outburst (Wachter & Hoard 2000). This is consistent with the lower X-ray activity seen for the source. The source was frequently observed during this outburst
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Figure 3: The XMM-Newton images of the field containing SAX J1808.4–3658 during its 2000 outburst (left panel; Wijnands 2003) and when the source was in quiescence (in 2001; right panel; see Campana et al. 2002). Clearly, SAX J1808.4–3658 (the source in the middle of the image) was brighter (albeit if only by a factor of a few) during the 2000 outburst observation than during the quiescent observation.

and preliminary results were presented by Wachter et al. (2000). The main results are presented in Figure 4 (reproduced with permission from Stefanie Wachter). The optical and X-ray brightness of the source are correlated at the end of the outburst, although one optical flare (around day 435–440 in Fig. 4) was not accompanied by an X-ray flare. However, the optical and X-ray observations were not simultaneous, which means that a brief (around a few days) X-ray flare could have been missed. During the earlier stages of the outburst, the X-ray and the optical behavior of the source were not correlated (Fig. 4 lower panel): the source is highly variable in X-rays, but quite stable in optical with only low amplitude variations. This stable period in the optical is very similar to the episode of stable optical emission in the late stages of the 1998 outburst, suggesting this is typical behavior for this source.

2.4 The October 2002 outburst

In 2002 October, the fourth outburst of SAX J1808.4–3658 was detected (Markwardt et al. 2002b), immediately launching an extensive RXTE/PCA observing campaign. The main results are summarized below.

2.4.1 The X-ray light curve

The RXTE/PCA light curve for this outburst is shown in Figure 5 (see Fig. 1 for the ASM light curve). During the first few weeks, the source decayed steadily, until the rate of decline suddenly increased, in a manner similar to what was observed
Figure 4: The RXTE/PCA (Wijnands et al. 2001) and the optical (I band) light curves (Wachter et al. 2000) of SAX J1808.4–3658 as observed during its 2000 outburst. The optical data were kindly provided by Stefanie Wachter.

during the 1998 outburst (see §2.2). During both the 1998 and 2002 outbursts, the moment of acceleration of the decline occurred at about two weeks after the peak of the outburst. Approximately five days later the X-ray count rate rapidly increased again until it reached a peak of about a tenth of the outburst maximum. After that the source entered a state in which the count rate rapidly fluctuated on time scales of days to hours, very similar to the 2000 low-level activity (see §2.3). The 2002 outburst light curve is the most detailed one seen for this source and it exhibits all features seen during the previous three outbursts of the source (the initial decline, the increase in the decline rate, the long-term low-level activity), demonstrating that this behavior is typical for this source.

2.4.2 The X-ray bursts and the burst oscillations

During the first five days of the outburst, four type-I X-ray bursts were detected. Burst oscillations were observed during the rise and decay of each burst, but not during the peak (Chakrabarty et al. 2003). The frequency in the burst tails was constant and identical to the spin frequency, while the oscillation in the burst rise
Figure 5: The RXTE/PCA light curves of five of the six accretion-driven millisecond X-ray pulsars. The data for SAX J1808.4-3658 was obtained during its 2002 outburst. The data were taken from van Straaten et al. (2005), except for XTE J1807–294 which were taken from Linares et al. (2005 in preparation).

showed evidence for a very rapid frequency drift of up to 5 Hz. This frequency behavior and the absence of oscillations at the peak of the bursts is similar to the burst oscillations seen in other, non-pulsating neutron star LMXBs, demonstrating that indeed the burst-oscillations occur at the neutron-star spin frequency in all sources. As a consequence, the spin frequency is now known for 18 LMXBs (12 burst-oscillations sources and 6 pulsars) with the highest spin frequency being 619 Hz. The sample of burst-oscillation sources was used to demonstrate that neutron stars in LMXBs spin well below the break-up frequency for neutron stars. This could suggest that the neutron stars are limited in their spin frequencies, possible due to the emission of gravitational radiation (Chakrabarty et al. 2003; Chakrabarty 2004).
Figure 6: The power spectrum of SAX J1808.4–3658. The top panel shows the two simultaneous kHz QPOs discovered during its 2002 outburst. The bottom panel shows the enigmatic 410 Hz QPO also seen during this outburst. The figures are adapted from Wijnands et al. (2003).

2.4.3 The kHz QPOs

Wijnands et al. (2003) reported on the discovery of two simultaneous kHz QPOs during the peak of the outburst with frequencies of $\sim 700$ and $\sim 500$ Hz (Fig. 6 top panel). This was the first detection of twin kHz QPOs in a source with a known spin-frequency. The frequency separation of those two kHz QPOs is only $\sim 200$ Hz, significantly below the 401 Hz expected in the beat-frequency models proposed to explain the kHz QPOs. Therefore, those models are falsified by the discovery of kHz QPOs in SAX J1808.4–3658. The fact that the peak separation is approximately half the spin frequency suggests that the kHz QPOs are indeed connected to the neutron-star spin frequency, albeit in a way not predicted by any existing model at the time of the discovery. The lower-frequency kHz QPO was only seen during the peak of the outburst (October 16, 2002) but the higher-frequency kHz QPO could be traced throughout the main part of the outburst (Wijnands et al. 2003). In addition to the twin kHz QPOs, a third kHz QPO was found with frequencies
Figure 7: Examples of the aperiodic timing features seen in the six millisecond pulsars. For SAX J1808.4–3658 we show a power spectrum obtained during its 1998 outburst.

(∼410 Hz) just exceeding the pulse frequency (Fig. 6 bottom panel; Wijnands et al. 2003). The nature of this QPO is unclear but it might be related to the side-band kHz QPO seen in several other sources (Jonker et al. 2000).

Wijnands et al. (2003) pointed out that there appear to exist two classes of neutron-star LMXBs: the 'fast' and the 'slow' rotators. The fast rotators have spin frequencies >∼400 Hz and the frequency separation between the kHz QPOs is roughly equal to half the spin frequency. In contrast, the slow rotators have spin frequencies below <∼400 Hz and a frequency separation roughly equal to the spin frequency. These latest kHz QPO results have spurred new theoretical investigations into the nature of kHz QPO, involving spin induced resonance in the disk (e.g., Wijnands et al. 2003; Kluzniak et al. 2004; Lee et al. 2004; Lamb & Miller 2004; Kato 2004).
2.4.4 The low-frequency QPOs

During the peak of the outburst and in its subsequent decay, broad-noise and QPOs with frequencies between 10 and 80 Hz were detected in the power spectra (Fig. 7). Similar phenomena have been observed in other non-pulsating systems and are likely to be related to the noise components seen in SAX J1808.4–3658. Van Straaten et al. (2004, 2005) have studied the broad-band power spectra (including the noise components, the low-frequency QPOs, and the kHz QPOs) of SAX J1808.4–3658 in detail as well as the frequency correlations between the different power-spectral components. Interestingly, using those frequency correlations, van Straaten et al. (2004, 2005) suggested that the higher-frequency kHz QPO could also be identified during the 1998 outburst but at the lowest frequencies found so far in any kHz QPO source (down to \(\sim 150\) Hz). Previous work (Wijnands & van der Klis 1998b) on the aperiodic timing features of SAX J1808.4–3658 during its 1998 outburst had already found these features but they could not be identified as the higher-frequency kHz QPO due to their low frequency and broad character.

Van Straaten et al. (2004, 2005) also compared the results of SAX J1808.4–3658 with those obtained for other non-pulsating neutron-star LMXBs. In those other sources, the frequencies of the variability components follow an universal scheme of correlations. The correlations observed for SAX J1808.4–3658 are similar but they show a shift in the frequencies of the kHz QPOs. It is unclear what physical mechanism(s) underlies this difference among sources (van Straaten et al. 2004, 2005).

During the 1998 and 2002 outbursts of SAX J1808.4–3658, the source exhibited similar X-ray fluxes. However, at similar flux levels, the characteristic frequencies observed during the 1998 outburst are much lower (by a factor of \(\sim 10\)) than during the 2002 outburst (van Straaten et al. 2005; see Fig. 8). Again it is unclear what causes this huge difference between the two outbursts but it might be related to the 'parallel track' phenomena observed for the kHz QPOs in the non-pulsating neutron-star LMXBs (e.g., van der Klis 2000).

2.4.5 The violent 1 Hz flaring

Violent flaring was observed on many occasions at a \(\sim 1\) Hz repetition frequency during the late stages of the 2002 outburst (Fig. 9), similar to what had been observed during the 2000 outburst. This proves that also this violent flaring is a recurrent phenomenon and can likely be observed every time the source is in this prolonged low-level activity state. Preliminary results presented in Figure 9 (right panels) show examples of power spectra obtained during the end stages of the 2002 outburst. During certain observations the 1 Hz QPO is rather narrow and its first overtone can be seen clearly (Fig. 9 top right panel). During other observations, the 1 Hz QPO is much broader and its wings blend with the first overtone (Fig. 9 middle two right panels). In addition to the 1 Hz QPO, other QPOs around 30–40
2.4.6 The pulsations

The pulsations could be detected at all flux levels with an amplitude of 3% – 10%. There was no evidence for a 200.5 Hz subharmonic in the data (upper limit of 0.38% of the signal at 401 Hz; Wijnands et al. 2003) confirming the interpretation of 401 Hz as the pulsar spin frequency. A detailed analysis and discussion of the coherent timing analysis will be presented by Morgan et al. (2005, in preparation).

2.4.7 Observations at other wavelengths

Rupen et al. (2002b) reported the detection of SAX J1808.4–3658 at radio wavelengths. On October 16, 2002, they found a 0.44-mJy source at 8.5 GHz and a day later, the source was detected at 0.3 mJy. Monard (2002) reported that on October 16, 2002, the optical counterpart was detectable again at magnitudes similar to those observed at the peak of the 1998 outburst.
2.5 SAX J1808.4–3658 in quiescence

In quiescence, SAX J1808.4–3658 has been observed on several occasions with the BeppoSAX and ASCA satellites (Stella et al. 2000; Dontani et al. 2000; Wijnands et al. 2002). The source was very dim in quiescence, with a luminosity close to or lower than $10^{32}$ ergs s$^{-1}$. Due to the low number of source photons detected, these luminosities had large errors and no information could be obtained on the spectral shape or possible variability in quiescence. Due to the limited angular resolution of BeppoSAX, doubts were raised as to whether the source detected by this satellite was truly SAX J1808.4–3658 or an unrelated field source (Wijnands et al. 2002). Campana et al. (2002) reported on a quiescent observation of the source performed with XMM-Newton which resolved this issue. They detected the source at a luminosity of $5 \times 10^{31}$ ergs s$^{-1}$ and found that the field around SAX J1808.4–3658 is rather crowded with weak sources. Two such sources are relatively close to SAX J1808.4–3658 and might have conceivably caused a systematic positional offset during the BeppoSAX observations. Despite this fact it is very likely that SAX J1808.4–3658 was indeed detected during those BeppoSAX observations.
Using *XMM-Newton*, Campana et al. (2002) obtained enough photons to extract a quiescent X-ray spectrum, which was not dominated by the same thermal component seen in other quiescent neutron star transients; such a thermal component is thought to be due to the cooling of the neutron star in-between outbursts. However, the spectrum of SAX J1808.4–3658 was dominated by a power-law shaped component. The non-detection of the thermal component was used to argue that the neutron star was anomalously cool, possibly due to enhanced core cooling processes (Campana et al. 2002). It has been argued (Stella et al. 2000; Campana et al. 2002) that the propeller mechanism, which might explain (some of) the hard X-ray emission in quiescence, is not likely to be active since this mechanism is expected to stop operating at luminosities $<10^{33}$ ergs s$^{-1}$, because at those luminosities the source should turn on as a radio pulsar. Instead, it was proposed that the quiescent X-rays originate in the shock between the wind of a turned-on radio pulsar and the matter flowing out from the companion star (Stella et al. 2000; Campana et al. 2002). Di Salvo & Burderi (2003) suggested that the quiescent X-rays could also be due to direct dipole radiation from the radio pulsar. Using simple accretion disk physics and the quiescent luminosity found by Campana et al. (2002), they determined that the magnetic field strength of the neutron star in SAX J1808.4–3658 should be in a quite narrow range of $(1 - 5) \times 10^8$ Gauss.

The quiescent optical counterpart of SAX J1808.4–3658 was studied by Homer et al. (2001). They reported that on August 10, 1999, the orbital modulation was still present in white light observations (estimated V magnitude of $\sim 20$), with a semi-amplitude of $\sim 6\%$. It has the same phasing and approximately sinusoidal modulation as seen during outburst, and with photometric minimum when the pulsar is behind the companion star. During observations taken in July 2000 the quiescent counterpart was even fainter and no significant orbital modulation could be detected. Using these results, it has been suggested that the optical properties of SAX J1808.4–3658 in quiescence are evidence of an active radio pulsar (Burderi et al. 2003). Campana et al. (2004) reported on the first optical spectrum of this source during its quiescent state. They concluded that a very high irradiating luminosity, a factor of $\sim 100$ larger than directly observed from the X-rays, must be present in the systems, which was suggested to be derived from a rotation-powered neutron star. If true, a pulsating radio source might be expected, but a search at 1.4 GHz could not detected the source (Burgay et al. 2003). This could be due to the effects of free-free absorption and searches at higher frequencies to limit these effects might still yield a pulsating radio source during the quiescent state of SAX J1808.4-3658.
3 XTE J1751–305

3.1 The 2002 outburst

The second accretion-driven millisecond pulsar (XTE J1751–305) was discovered on April 3, 2002 (Markwardt et al. 2002a). Its spin frequency is 435 Hz (Fig. 2) and the neutron star is in a very small binary with an orbital period of only 42 minutes. The timing analysis of the pulsations gave a minimum mass for the companion star of 0.013 solar mass and a pulse-frequency derivative of $<3 \times 10^{-13} \text{ Hz s}^{-1}$. Assuming that the mass transfer in this binary system was driven by gravitational radiation, the distance toward the source could be constrained to at least 7 kpc and the orbital inclination to $30^\circ–85^\circ$, resulting in a companion mass of 0.013–0.035 solar masses, suggesting a heated helium dwarf (Markwardt et al. 2002a). 

Chandra briefly observed the source, resulting in an arcsecond position (Markwardt et al. 2002a). The source reached a peak luminosity of $>2 \times 10^{37} \text{ ergs s}^{-1}$, an order of magnitude brighter than the peak luminosity of SAX J1808.4–3658. However, the outburst was very short with an e-folding time of only $\sim7$ days (compared to $\sim14$ days for SAX J1808.4–3658; Fig. 3) resulting in a low outburst fluence of only $\sim2.5 \times 10^{-3} \text{ ergs cm}^{-2}$ (Markwardt et al. 2002a). A potential re-flare was seen two weeks after the end of the outburst during which also a type-I X-ray burst was seen. Preliminary analysis of the burst indicated that the burst did not come from XTE J1751–305 but from another source in the field of view. This was later confirmed (In ’t Zand et al. 2003) and the burst likely originated from the bright X-ray transient in Terzan 6. It was also determined that the transient in Terzan 6 could not have produced the re-flare (In ’t Zand et al. 2003) suggesting that this re-flare could still have come from XTE J1751–305. However, van Straaten et al. (2005) suggested (based on a X-ray color study using RXTE/PCA observations) that this re-flare was emitted by one of the background sources and not by XTE J1751–305. Van Straaten et al. (2005) also investigated the aperiodic timing properties of the source (an example power spectrum is shown in Fig. 7) and the correlations between the characteristic frequencies of the observed power-spectral components. The frequency correlations were similar to those of the non-pulsating neutron-star LMXBs. In contrast with the results obtained for SAX J1808.4–3658 (§24.4), no frequency shift was required for XTE J1751–305 to make the frequency correlations consistent with those of the non-pulsating sources. Using these correlations, van Straaten et al. (2005) suggested that the highest-frequency noise components in XTE J1751–305 are likely due to the same physical mechanisms as the kHz QPOs. They also investigated the correlations between the characteristic frequencies and the X-ray colors of the source and concluded that it did not behave like an atoll source.

A previous outburst in June 1998 was discovered using archival RXTE/ASM data (Markwardt et al. 2002a), suggesting a tentative recurrence time of $\sim3.8$ years. Miller et al. (2003) reported on high spectral resolution data of the source obtained with XMM-Newton to search for line features in the X-ray spectrum. However,
they only detected a continuum spectrum dominated by a hard power-law shaped component (power-law index of $\sim 1.44$) but with a 17% contribution to the 0.5–10 keV flux from a soft thermal (black-body) component with temperature of $\sim 1$ keV. Gierlinski & Poutanen (2004) studied in detail the X-ray spectrum of the source during its 2002 outburst using the archival \textit{RXTE} and \textit{XMM-Newton} observations. They find that XTE J1751–305 exhibited very similar behavior as SAX J1808.4–3658 during its 1998 outbursts. They also find that the pulse profile cannot be described by a simple sinusoid, but that a second harmonic is needed (the peak-to-peak amplitude of the fundamental was found to be 4.5% but of the second harmonic only 0.15%). Gierlinski & Poutanen (2004) also report that a clear energy dependency of the pulse profile was observed and that the higher energy photons arrive earlier than the softer (this ‘soft lag’ reached $\sim 100$ $\mu$s at about 10 keV, where it saturated). Searches for the optical and near-infrared counterparts were performed but no counterparts were found (Jonker et al. 2003), likely due to the high reddening toward the source. These non-detections did not constrain any models for the accretion disk or possible donor stars.

3.2 XTE J1751–305 in quiescence

Recently, XTE J1751–305 was observed in quiescence using \textit{Chandra} (Wijnands et al. 2005). Sadly, they could not detect the source in their $\sim 43$ ksec observation, with 0.5–10 keV flux upper limits between 0.2 and $2.7 \times 10^{-14}$ ergs s$^{-1}$ cm$^{-2}$ depending on assumed spectral shape, resulting in 0.5–10 keV luminosity upper limits of $0.2 - 2 \times 10^{32} (d/8\text{ kpc})^2$ ergs s$^{-1}$, with $d$ the distance toward the source in kpc. Using simple accretion disk physics in combination with these luminosity upper limits, Wijnands et al. (2005) could constrain the magnetic field of the neutron star in this system to be less than $3 - 7 \times 10^8 \frac{d}{8\text{ kpc}}$ Gauss (depending on assumed spectral shape of the quiescent spectrum).

4 XTE J0929–314

4.1 The 2002 outburst

The third accretion-driven millisecond X-ray pulsar XTE J0929–314 had already been detected with the \textit{RXTE}/ASM on April 13, 2002 (Remillard 2002) but was only found to be harboring a millisecond pulsar with a pulsations frequency of 185 Hz (Fig. 2) on May 2nd when observations of the source were made using the \textit{RXTE}/PCA (Remillard et al. 2002). Galloway et al. (2002) reported on the detection of the 44-min orbital period of the system which is remarkably similar to that of XTE J1751–305. A minimum mass of 0.008 solar mass was obtained for the companion star and a pulse-frequency derivative of $(-9.2 \pm 0.4) \times 10^{-14}$ Hz s$^{-1}$. Galloway et al. (2002) suggested that this spin down torque may arise from
magnetic coupling to the accretion disk, a magneto-hydrodynamic wind, or gravitational radiation from the rapidly spinning neutron star. Assuming gravitational radiation as the driving force behind the mass transfer, Galloway et al. (2002) found a lower limit to the distance of 6 kpc. They also reported on the detection of a QPO at 1 Hz (Fig. 7). Full details of this QPO and the other aperiodic power-spectral components are presented by van Straaten et al. (2005). Just as they found for SAX J1808.4–3658, the frequency correlations for XTE J0929–314 were similar to those observed for the non-pulsating sources but with an offset in the frequencies of the highest-frequency components. These correlations allowed van Straaten et al. (2005) to identify those components as related to the kHz QPOs. Studying the correlated spectral and timing variability, they concluded that the behavior of XTE J0929–314 was consistent with that of an atoll source.

Juett et al. (2003) obtained high resolution spectral data using the Chandra gratings. Again the spectrum is well fitted by a power-law plus a black body component, with a power-law index of 1.55 and a temperature of 0.65 keV. Similar to XTE J1751–305, no emission or absorption features were found. No orbital modulation of the X-ray flux was found implying an upper limit on the inclination of 85°. Greenhill et al. (2002) reported the discovery of the optical counterpart of the system with a V magnitude of 18.8 on May 1st, 2002 (see also Caccella 2002). Castro-Tirado et al. (2002) obtained optical spectra of the source on May 6–8 in the range 350–800 nm and found emission lines from the C III- N III blend and H-alpha, which were superposed on a blue continuum. These optical properties are typical of X-ray transients during outburst. Rupen et al. (2002a) discovered the radio counterpart of the source using the VLA with 4.86 GHz flux of 0.3–0.4 mJy.

### 4.2 XTE J0929–314 in quiescence

Recently, Wijnands et al. (2005) also observed XTE J0929–314 in its quiescent state with Chandra. For this source, they detected 22 source photons (in the energy range 0.3–8 keV) in ∼24.4 ksec of on-source time. This small number of photons detected did not allow for a detailed spectral analysis of the quiescent spectrum, but they could demonstrate that the spectrum is harder than a simple thermal emission (which might have been due to the cooling neutron star that has been heated during outbursts). Assuming a power-law spectral model for the time-averaged (averaged over the whole observation) X-ray spectrum, they obtained a power-law index of ∼1.8 and an unabsorbed X-ray flux of ∼6 × 10⁻¹⁵ ergs s⁻¹ cm⁻² (for the energy range 0.5–10 keV), resulting in a 0.5–10 keV X-ray luminosity of ∼7 × 10³¹ (d/10 kpc)² ergs s⁻¹, with d the distance in kpc. The thermal component usually seen in quiescent neutron star LMXBs could not be detected, with a maximum contribution to the 0.5–10 keV flux of ∼30%. Wijnands et al. (2005) also found that the quiescent count rate of XTE J0929–314 was variable at the 95% confidence level, but no conclusive evidence was found for associated spectral variability. The properties of XTE J0929–314 in its quiescent state are remarkably similar to that observed for
SAX J1808.4–3658 (§2.5) which might suggest that such behavior is common among accretion-driven millisecond X-ray pulsars. However, recent work on several other weak quiescent neutron-star X-ray binaries (e.g., Jonker et al. 2004a, b; Tomsick et al. 2004), which do not exhibit pulsations during their X-ray outbursts, suggests that also such systems can resemble SAX J1808.4–3658 during quiescent (i.e., they could be almost as faint and hard as SAX J1808.4–3658 in quiescence; see Wijnands et al. 2005 for a in-dept discussion). Similar to what they did for XTE J1751–305, Wijnands et al. (2005) could constrain the neutron-star magnetic field strength in XTE J0929–314 to be $<3 \times 10^9 \frac{d}{10 \text{ kpc}}$ Gauss.

5 XTE J1807–294

The fourth millisecond X-ray pulsar XTE J1807–294 with a frequency of 191 Hz, was discovered on February 21, 2003 (Markwardt et al. 2003a; Fig. 2). The peak flux was only 58 mCrab (2–10 keV, measured on February 21, 2003). The orbital period was determined (Markwardt et al. 2003c) to be ~40 minutes making it the shortest orbital period of all accretion-driven millisecond pulsars now known. Markwardt

Figure 10: The power spectrum of XTE J1807–294 as obtained using RXTE/PCA. The two simultaneous kHz QPOs are clearly visible.
et al. (2003c) reported the best known position of the source based on a Chandra observation. Using the RXTE/PCA data, kHz QPOs have been detected for this system and it was found that the frequency separation between the two kHz QPOs was consistent with being equal to the neutron-star spin frequency (Markwardt et al. 2005 in preparation; Fig. 10). This makes XTE J1807–294 consistent with the classification of Wijnands et al. (2003) of the neutron-star LMXBs into 'fast' and 'slow' rotators, with XTE J1807–294 a slow rotator. A detailed analysis of the correlations between the kHz QPOs and the low-frequency features (see Fig. 11) in this source will be reported by Linares et al. (2005, in preparation). The preliminary results of that analysis shows that also for XTE J1807–294 the frequency correlations are similar to those observed for the non-pulsating sources but with an offset in the frequencies of the highest-frequency components (similar to what was found for SAX J1808.4–3658 and possible XTE J0929–314; Van Straaten et al. 2005). Campana et al. (2003) reported on a XMM-Newton observation of this source taken on March 22, 2003. Assuming a distance of 8 kpc, the 0.5–10 keV luminosity during that observation was \(2 \times 10^{36}\) ergs s\(^{-1}\). They could detect the pulsations during this observation with a pulsed fraction of 5.8% in the 0.3−10 keV band (increasing with energy) and a nearly sinusoidal pulse profile. Furthermore, using the same data Kirsch et al. (2004; see also Kirsch & Kendziorra 2003) reported on the mass function of this system and found a minimal mass for the companion star of 0.007 \(M_\odot\) when assuming a canonical neutron star mass of 1.4 \(M_\odot\). The spectral data are well fit by a continuum model, assumed to be an absorbed Comptonisation model plus a soft component. The latter component only contributed 13% to the flux. Again no emission or absorption lines were found. No detections of the counterparts of the system at other wavelengths have been reported so far.

6 XTE J1814–338

The fifth system (XTE J1814–338) was discovered on June 5, 2003 and has a pulse frequency of 314 Hz (Markwardt et al. 2003b; Fig. 2), with an orbital period of 4.3 hr and a minimum companion mass of 0.15 solar mass (Markwardt et al. 2003d). This 4.3 hr orbital period makes it the widest binary system among the accretion-driven millisecond pulsars and also the one most similar to the general population of low-luminosity neutron star LMXBs (the atoll sources). XTE J1814–338 exhibited many type-I X-ray bursts, which showed burst oscillations with a frequency consistent with the neutron star spin frequency (Markwardt et al. 2003d, Strohmayer et al. 2003). A distance of \(\sim 8\) kpc was obtained from the only burst which likely reached the Eddington luminosity. The burst oscillations are strongly frequency- and phase-locked to the persistent pulsations (as was also seen for SAX J1808.4–3658; Chakrabarty et al. 2003) and two bursts showed evidence of a frequency decrease of a few tenths of a Hz during the onset of the burst, suggesting a spin down. Strohmayer et al. (2003) also reported on the detection of the first harmonic of the burst oscillations, which
is the first time that this has been seen in any burst-oscillation source. This harmonic could arise from two hot-spots on the surface, but Strohmayer et al. (2003) suggested that if the burst oscillations arise from a single bright region, the strength of the harmonic would suggest that the burst emission is beamed (possibly due to a stronger magnetic field strength than in non-pulsating LMXBs). Bhattacharyya et al. (2004) used the non-sinusoidal burst oscillation light curves to constrain the parameters of the neutron star in XTE J1814–338; they obtained a dimensionless radius to mass ratio of $Rc^2/GM = 3.9 - 4.9$ for the neutron star in this source. They find that the bursting hot spot on the neutron-star surface remains always large, with an angular radius $>25^\circ$. Their study also suggest that the inclination of the source is greater than $50^\circ$ and that the secondary companion is a hydrogen main sequence star that is significantly bloated (possibly due to X-ray heating).

Wijnands & Homan (2003) analyzed the RXTE/PCA data of the source obtained between June 8 and 11, 2003. The overall shape of the 3–60 keV power spectrum is dominated by a strong broad band-limited noise component (Fig. 7), which could be fitted by a broken power-law model with a broad bump superimposed on it at frequencies above the break frequency. These characteristics make the power spectrum of XTE J1814–338 very similar to that observed in the non-pulsing low-luminosity neutron-star LMXBs (the atoll sources) when they are observed at relatively low X-ray luminosities (i.e., in the so-called island state). This is consistent with the hard power-law X-ray spectrum of the source reported by Markwardt et al. (2003d). This resemblance of XTE J1814–338 to the atoll sources was further strengthened (Wijnands & Homan 2003) by the fact that the source is consistent with the relation between the break frequency and the frequency of the bump found for atoll sources by Wijnands & van der Klis (1999). Van Straaten et al. (2005) performed an in-depth analysis of all publicly available RXTE/PCA data of XTE J1814–338 to study the power-spectral components and the correlations between their characteristic frequencies. Using those correlations and by comparing them to other sources, they could identify several components that are related to the kHz QPOs. They also found that the frequency correlations were identical to the non-pulsating sources with no need for a frequency shift. This is similar to what they found for XTE J1751–305 but different from SAX J1808.4–3658 and XTE J0929–314 (and for XTE J1807–294 as found by Linares et al. 2005, in preparation). The reason(s) for this difference between accreting millisecond X-ray pulsars is not know (see Van Straaten et al. 2005 for an extended discussion). From the correlations between the spectral and timing variability it was confirmed that the behavior of XTE J1814–338 was consistent with that of an atoll sources (van Straaten et al. 2005; see also Wijnands & Homan 2003).

Wijnands & Reynolds (2003) reported that the position of XTE J1814–338 was consistent with the EXOSAT slew source EXMS B1810–337 which was detected on September 2nd, 1984. If this identification is correct, then its recurrence time can be inferred to be less than 19 years but more than 5 years (the time since the
RXTE/PCA bulge scan observations started in February 1999), unless the recurrence time of the source varies significantly. Krauss et al. (2003) reported the best position of the source based on a Chandra observation and on the detection of the likely optical counterpart of the source (with magnitudes of B = 17.3 and R = 18.8 on June 6). Steeghs (2003) reported on optical spectroscopy of this possible counterpart, specifically on the discovery of prominent hydrogen and helium emission lines, confirming the connection between the optical source and XTE J1814–338.

7 IGR J00291+5934

Very recently, on December 2, 2004, the European Gamma-ray satellite INTEGRAL discovered a new X-ray transient named IGR J00291+5934 (Eckert et al. 2004). A day later, RXTE observed the source and it was found that this source harbors a 598.88 Hz accretion-driven millisecond X-ray pulsar (Markwardt et al. 2004a; see Galloway et al. 2005 for the analyze of all data obtained for this source). The pulsed amplitude was approximately 6% with no evidence for harmonics. The amplitude decreased with increasing photon energy and the soft photons arrive later than the hard ones (by up to 85 µs; Galloway et al. 2005) The X-ray spectrum could be fitted with an absorbed power-law model with photon index of 1.7 and a column density of $7 \times 10^{21}$ cm$^{-2}$. In Figure 7 the power spectrum between 0.001 and 10,000 Hz is show of the source, clearly showing significant aperiodic variability (see also Markwardt et al. 2004a). Interestingly, of all six accreting millisecond X-ray pulsars the break in the power spectrum is at the lowest frequency for IGR J00291+5934: during the peak of the outburst the break frequency for this source was $\sim 0.01$ Hz compared to $>0.1$ Hz for the other sources at their outburst peaks. Markwardt et al. (2004b) used additional RXTE observations to determine that the orbital period of the system was $\sim 2.45$ hours and they obtained a mass function of $(2.81 \pm 0.02) \times 10^{-5}$ M$_{\odot}$ (see also Galloway et al. 2005). For a neutron star mass of 1.4 M$_{\odot}$ this results in a lower limit on the mass for the companion star of 0.038 M$_{\odot}$, possible a brown dwarf (Galloway et al. 2005). The source reached its peak flux (29 mCrab; 2–10 keV) on December 3, 2004, after which the fluxes decreased in a linear way, until around December 11, 2004, when the rate of decline had increased slightly (Swank & Markwardt 2004). On December 14, 2004, Chandra performed a brief ($\sim 18$ ksec) observation of the source using the ACIS-S/HETG combination. Nowak et al. (2004) reported that the source was at a flux level of $\sim 1$ mCrab and its X-ray spectrum could be well-fitted by an absorbed power-law model with a column density of $\sim 3 \times 10^{21}$ cm$^{-2}$ and a photon index of $\sim 1.9$. A possible iron line feature was also reported by the same authors. The flux value confirmed the steady decline as seen by Swank & Markwardt (2004) and soon after this the source could not be detected anymore with RXTE/PCA (see Galloway et al. 2005 for the full X-ray light curve of the source during this outburst). No X-ray bursts, dips, eclipses, or kHz QPOs (with upper limits of $\sim 1\%$ rms) were found (Galloway et al. 2005).
Figure 11: The RXTE/ASM light curve of IGR J00291+5934 during the most recent (December 2004) outburst (top panel; near day 3260) and its likely September 2001 outburst (bottom panel; near day 2080). These light curves were made using the public ASM data available at [http://xte.mit.edu/ASM_lc.html](http://xte.mit.edu/ASM_lc.html). The count rates are for the 2–12 keV energy range and are daily averages.

An optical counterpart was proposed by Fox & Kulkarni (2004; see this reference for a finding chart) with an R magnitude during outburst of $\sim 17.4$. The detection of broad emission lines of HeII and H$\alpha$ from this tentative optical counterpart strongly support this identification (Roelofs et al. 2004; see also Filippenko et al. 2004). Pooley (2004) found a 1.1 mJy radio source (15 GHz) at a position consistent with that of the optical counterpart which likely is the radio counterpart of the source which faded during the outburst (Fender et al. 2004, who also detected the source at 5 GHz at a flux of $\sim 250 \mu$Jy), although the decay did not seem to be very rapid (Rupen et al. 2004). Steeghs et al. (2004) reported the detection of a decaying infrared counterpart of the source.

After the discovery of this new source, Remillard (2004) constructed a mission-long light curve using the RXTE/ASM data and found that in November 26–28, 1998, and in September 11–21, 2001, the source might have exhibited other outbursts...
(see Fig. 11 for the RXTE/ASM light curve of the December 2004 and September 2001 outbursts of the source). If confirmed this would give a recurrence time for the outburst of approximately 3 years. In ’t Zand & Heise (2004) did not detected the source with the WFCs aboard BeppoSAX during a net exposure time of 2.9 Msec on the source. The RXTE/ASM detections reported by Remillard (2004) were not covered; the first WFCs data were obtained 16 days and 11 days after the two possible outbursts, respectively, and it is well possible that the source had by then decayed below the sensitivity limit of the WFCs.

8 Theoretical work

This chapter is intended to be an observational overview, thus I will not go into detail on the theoretical papers published on accretion-driven millisecond pulsars. Instead, I will briefly list some of those papers, most of which focus on SAX J1808.4–3658 since the other five systems have only been found recently (with IGR J00291+5934 discovered very recently). Since the discovery of SAX J1808.4–3658, several studies have tried to constrain the properties (i.e., radius, mass, magnetic field strength) of the neutron star in this system (Burderi & King 1998; Psaltis & Chakrabarty 1999; Bhattacharyya 2001), while others proposed that the compact object is not a neutron star at all, but instead a strange star (see, e.g., Li et al. 1999; Datta et al. 2000; Zdunik et al. 2000 and references there-in). Other studies focused on the evolutionary history of SAX J1808.4–3658 (Ergma & Antipova 1999) or on the nature of the companion star (Bildsten & Chakrabarty 2001, who suggested a brown dwarf companion star). Recently, Nelson & Rappaport (2003) investigated the evolutionary history of ultracompact binaries such as XTE J0929–314 and XTE J1751–305 (they focused on those two systems but likely their conclusions can also be applied to XTE J1807–294). Rappaport et al. (2004) investigated how accretion could occur in millisecond X-ray pulsars and they postulated that those systems can continue to accrete from a thin disk, even for accretion rates that place the magnetospheric radius well beyond the co-rotation radius.

The discovery of the accretion-driven millisecond pulsars raises an important question: why are those systems different from other neutron star LMXBs for which no pulsations have been found. Cumming et al. (2001; see also Rai Choudhuri & Konar 2002; Cumming 2004) suggested that the low time-averaged accretion rate of SAX J1808.4–3658 might explain why this source is a pulsar. Although the remaining four pulsars were not know at the time of writing of that paper, the same arguments can be used for those systems: when the time-averaged accretion rate is sufficiently high, the neutron star magnetic field might be buried by the accreted matter and does not have time to dissipate through the accreted material. However, for the millisecond X-ray pulsars the time-averaged accretion rate is sufficiently low that the magnetic field dissipation can indeed happen, giving those systems a magnetic field still strong enough to disturb the flow of the accreted matter.
However, more neutron-star LMXBs with low time-averaged accretion rate must be found and studied in detail to verify that they all indeed harbor a millisecond pulsar. If an exception is found, the screening model might only be part of the explanation and alternative ideas need to be explored (see, e.g., Titarchuk et al. 2002).

9 Conclusion

From this review it is clear that RXTE has played a vital role in the discovery and study of accretion-driven millisecond X-ray pulsars. The detailed studies performed with RXTE for those systems have yielded breakthroughs in our understanding of kHz QPOs and burst oscillations. Furthermore, three of these accreting pulsars are in ultrashort binaries which will constrain evolutionary paths for this type of systems (e.g., see Nelson & Rappaport 2003). However, it is also clear that the six systems do not form a homogeneous group; their pulsation frequencies span the range between 185 Hz and 599 Hz (Fig. 2), their orbital periods fall between 40 minutes and 4.3 hours, their X-ray light curves are very different (Fig. 5), and also their aperiodic variability properties (Fig. 4). More, well studied outbursts of the currently known systems are needed as well as discoveries of additional systems. At the moment only RXTE is capable of performing the necessary timing observations. After RXTE, an instrument with similar or better capabilities is highly desirable for our understanding of accretion-driven millisecond pulsars and their connection with the non-pulsating neutron-star LMXBs.

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