An observational review of accretion-driven millisecond X-ray pulsars

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I present an observational review of the five currently 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. This makes SAX J1808.4–3658 the best studied example of the group. 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 time that such phenomena are observed in a system for which the neutron star spin frequency is exactly known. The other four systems were discovered within the last two years and only limited results have been published. Since new exiting results are to be expected in the future for all five sources, this review will only represent a snap-shot of the current observational knowledge of accretion-driven millisecond X-ray pulsars. A more extended and fully up-to-date review can be found at [http://zon.wins.uva.nl/~rudy/admxp/]

1. Introduction

Pulsars are born as highly-magnetised ($B \sim 10^{12}$ G), rapidly rotating ($P \sim 10$ ms) neutron stars which spin down on timescales of 10 to 100 million years due to magnetic dipole radiation. However, a number of millisecond ($P < 10$ ms) radio pulsars is known with ages of billions of years and weak ($B \sim 10^8−9$ G) surface magnetic fields. Since many of these millisecond pulsars are in binaries, it has long been suspected (see, e.g., [1] for an extended review) that they 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 [2] and references therein. The launch of the *Rossi X-ray Timing Explorer (RXTE)* brought the discovery of kilohertz quasi-periodic oscillations (kHz QPOs) [3,4] as well as nearly coherent oscillations (*burst oscillations*) during type-I X-ray bursts in a number of LMXBs (e.g., [5]), providing tantalisingly suggestive evidence for weakly magnetic neutron stars with millisecond spin periods (see [6] and [7] for more details about kHz QPOs and burst oscillations in LMXBs).

In 1998 April the first accretion-driven millisecond X-ray pulsar (SAX J1808.4–3658) was discovered [7] proving that indeed neutron stars in LMXBs can spin very rapidly. This conclusion was further strengthened by the discovery of four additional systems during the last two years [8,9,10,11]. Here, I will give a brief summary of our current observational knowledge of those accretion-driven millisecond X-ray pulsars.

2. SAX J1808.4–3658

2.1. The 1996 September outburst

In 1996 September, a new X-ray transient and LMXB was discovered with the Wide Field Cameras (WFCs) aboard the *BeppoSAX* satellite and the source was designated SAX J1808.4–3658 [12]. 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 [12,13]. The maximum luminosity during this outburst was $\sim 10^{36}$ ergs s$^{-1}$, significantly lower than the peak outburst luminosity of *classical* neutron star transients. This low peak luminosity showed that the source was part of the growing group of faint neutron-star X-ray transients [14]. The outburst continued for about three weeks, after which the source was thought to have returned to quiescence. However, recently it was found [15]...
that the source was detected on 1996 October 29 (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 (possible only sporadically), which might indicate behaviour for this source at the end of this outburst very similar to what has been seen during its 2000 and 2002 outbursts (§§ 2.3 and 2.4).

After it was found that SAX J1808.4–3658 harbours a millisecond pulsar (§ 1.1), the three observed X-ray bursts were scrutinized for potential burst oscillations [13]. 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 (§ 2.3).

2.2. The 1998 April outburst

On 1998 April 9, RXTE/PCA slew observations indicated that SAX J1808.4–3658 was active again [10]. Using public TOO observations of this source from 1998 April 11, it was discovered [1] that coherent 401 Hz pulsations 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 RXTE/PCA observations were made which were used by several groups to study different aspects of the source. I will only briefly mention those results and give references for details.

A detailed analysis of the coherent timing behaviour showed [17] 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 [17]. Studies of the X-ray spectrum [15,19,20] and the aperiodic rapid X-ray variability [21] 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 [17,19]. Cui et al. [22] and Ford [23] reported on the harmonic content, the energy dependency, and the soft phase lag of the pulsations.

Another interesting aspect is that the source first showed a steady decline in X-ray flux, which after ∼2 weeks suddenly accelerated [15,22]. This behaviour has been attributed to the fact that the source might have entered the 'propeller regime' in which the accretion is centrifugally inhibited [18]. However, after the onset of the steep decline the pulsations could still be detected [22] making this interpretation doubtful. A week after the onset of this steep decline, the X-ray flux levelled off [22,24], but as no further RXTE/PCA observations were made, the X-ray behaviour 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 (§§ 2.3, 2.4).

SAX J1808.4–3658 was not only detected and studied in X-rays but also in the optical, the IR, and in the radio. The optical/IR counterpart of SAX J1808.4–3658 (later named V4580 Sgr; [25]) was first discovered by Roche et al. [26] and subsequently confirmed by Giles et al. [27]. A detailed study of the optical behaviour during this outburst was reported by Giles et al. [28] and Wang et al. [29]. Both papers reported that the peak V magnitude of the source was ∼16.7 and the source decayed in brightness as the outburst progressed. The brightness of the source levelled off at around V ∼ 18.5 (I ∼ 17.9) about ∼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 behaviour suggests that the source was indeed still active for a long period after the main outburst.

It was also reported [28] that the optical flux was modulated at the 2-hr orbital period of the system. Modelling the X-ray and optical emission from the system using an X-ray-heated accretion disk model, a $A_e$ of 0.68 and an inclination of $\cos i = 0.65$ were obtained [24], resulting in a mass of the companion star of 0.05–0.10
M⊙. Some of the IR observations were 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 [24]. Such an event was also confirmed by the discovery of the radio counterpart [29]. The source was detected with a 4.8 GHz flux of ~0.8 mJy on 1998 April 27, but it was not detected at earlier or later epochs.

2.3. The 2000 January outburst
On 2000 January 21, SAX J1808.4–3658 was again detected [30] with the RXTE/PCA at a flux level of ~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 (Fig. 2). Due to solar constraints the source could not be observed before January 21 but likely a true outburst occurred before that date and only the end stages of this outburst was observed. This is supported by the very similar behaviour of the source observed near the end of its 2002 October outbursts (§2.4).

During the 2000 outburst, SAX J1808.4–3658 was observed (using RXTE) on some occasions at luminosities of ~10^{35} ergs s^{-1}, but on other occasions (a few days earlier or later) it had luminosities of ~10^{32} ergs s^{-1} (from BeppoSAX and XMM-Newton observations [31,32]). 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% rms amplitude) violent flaring behavior with a repetition frequency of about 1 Hz (§3.1); Fig. 1). During this episode of low-level activity, the pulsations at 401 Hz were also detected. The limited amount of observing time and the low count rates of the source did not allow for an independent determination of the binary orbital parameters and the pulse-frequency derivative.

The source was again detected in optical, albeit at a lower brightness than during the 1998 outburst [35]. This is consistent with the lower X-ray activity seen for the source. The source was frequently observed during this outburst and preliminary results were presented by Wachter et al. [36]. The main results are presented in Figure 2 (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. 2) was not accompanied by an X-ray flare. However, the optical and X-ray observations were not simultaneously, which means that a brief (of order a few days) X-ray flare could have been missed. During the earlier stages of the outburst, the X-ray and the optical behaviour of the source were not correlated (Fig. 2 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 at the late stages of the 1998 outburst, suggesting typical behaviour of the source.

2.4. The 2002 October outburst
In 2002 October, the fourth outburst of SAX J1808.4–3658 was detected [37] and immediately a very extensive RXTE/PCA observing campaign started. The main results are summarised below.

2.4.1. The X-ray light curve
The light curve for this outburst is shown in Figure 3. During the first few weeks, the source...
decayed steadily, until the rate of decline suddenly increased, very similar to what was observed during the 1998 outburst (§2.2). About 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 (§2.3). This 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 is typical source behaviour.

2.4.2. The pulsations

The pulsations could be detected at all flux levels with an amplitude of 3%–10%. The pulsar was spinning down at a constant rate (mean spin-down rate of $2 \times 10^{-13}$ Hz s$^{-1}$; [38]), despite a large dynamic range of X-ray flux. The magnitude of the pulse-frequency derivative exceeds the maximum value expected from accretion torques by a factor of 5. The timing history also contains a small glitch with a very rapid recovery time scale. There was no evidence for a 200.5 Hz subharmonic in the data (upper limit of 0.38% of the signal at 401 Hz; [39]) confirming the interpretation of 401 Hz as the pulsar spin frequency. A more detailed analysis will be presented elsewhere [40].

2.4.3. X-ray bursts and burst oscillations

During the first five days of the outburst, four type-I X-ray bursts were detected. During the rise and decay of each burst, but not during the peak, burst oscillations were observed [38]: the frequency in the burst tails was constant and identical to the spin frequency, while the oscillation in the burst rise showed evidence for a very rapid frequency drift of up to 5 Hz. This frequency behaviour 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 16 LMXBs (11 burst-oscillations sources and 5 pulsars) and
the highest spin frequency is 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 \cite{38}.

2.4.4. The kHz QPOs

Wijnands et al. \cite{39} reported on the discovery of two simultaneous kHz QPOs during the peak of the outburst, with frequencies of \(\sim 700\) and \(\sim 500\) Hz (during the meeting, this result was presented by Michiel van der Klis; Fig. 4 top). 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 model. The lower-frequency kHz QPO was only seen during the peak of the outburst (2002 October 16) but the higher-frequency kHz QPO could be traced throughout the main part of the outburst \cite{39}. Besides the twin kHz QPOs, a third kHz QPO was found with frequencies \(\sim 410\) Hz just exceeding the pulse frequency \cite{39} Fig. 4 bottom]. The nature of this QPO is unclear but it might be related to the side-band kHz QPO seen in several other sources \cite{41}.

Wijnands et al. \cite{39} pointed out that there seem to be two classes of neutron-star LMXBs: the 'fast' and the 'slow' rotators. The fast rotators have spin frequencies \(>\sim 400\) 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 \(<\sim 400\) Hz and a frequency separation roughly equal to the spin frequency. These new kHz QPO results have already spurred new theoretical investigations in the kHz QPO nature, involving spin induced resonance in the disk \cite{39,42,43}.

2.4.5. 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. 5). Similar phenomena have been observed in other non-pulsating systems and are likely related to the noise components seen in SAX J1808.4–3658. For a discussion about the low-frequency QPOs and their connection to the kHz QPOs, I refer to the contribution by Steve van Straaten in this proceedings.

2.4.6. 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. 6), 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. The mechanism behind these violent flares is not yet known and a detailed analysis of this phenomenon is in progress.

2.4.7. Observations at other wavelengths

Rupen et al. [44] reported the detection of the source at radio wavelengths. On 16 October 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 [45] reported that on 16 October 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 [46,47,48]. 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 [48]. Campana et al. [49] 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 of SAX J1808.4–3658. Very likely the source was indeed detected during those observations.

Using XMM-Newton, Campana et al. [49] 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 [49]. It has been argued [41,49] that the propeller mechanism, which might explain (some of) the hard X-ray emission in quiescence, is likely not 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 out-flowing from the companion [41,49]. The quiescent X-rays could also be due to direct dipole radiation from the radio pulsar [50].

The quiescent optical counterpart of SAX J1808.4–3658 was studied by Homer et al. [51]. They reported that on 1999 August 10 the orbital modulation was still present in white light observations (estimated V magnitude of $\sim 20$), with an 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 signifi-
cant 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 [62].

3. XTE J1751–305

The second accretion-driven millisecond pulsar (XTE J1751–305) was discovered on 2002 April 3 [8]. Its spin frequency is 435 Hz 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 M⊙ and a pulse-frequency derivative of < 3 × 10^{-13} 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°, resulting in a companion mass of 0.013–0.035 M⊙, suggesting a heated helium dwarf [8].

The source reached a peak luminosity of >2×10^{37} 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 ~7 days (compared to ~14 days for SAX J1808.4–3658) resulting in a low outburst fluence of only ~2.5 × 10^{-3} ergs cm^{-2} [8]. 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 [59] and the burst likely originated from the bright X-ray transient in Terzan 6 (however, this transient did not produce the re-flare, which can still have come from XTE J1751–305). Chandra also briefly observed the source, resulting in an arcsecond position, and a previous outburst in 1998 June was detected using archival RXTE/ASM data [8], suggesting a tentative recurrence time of ~3.8 years.

Miller et al. [61] 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 ~1.44) but with a 17% contribution to the 0.5–10 keV flux by a soft thermal (black-body) component with temperature of ~1 keV. Searches for the optical and near-infrared counterparts were performed but no counterparts were found [55], 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.

4. XTE J0929–314

The third accretion-driven millisecond X-ray pulsar XTE J0929–314 was already detected with the RXTE/ASM on 13 April 2002 [56] but was only found to be harbouring a millisecond pulsar with a pulsations frequency of 185 Hz on 2 May when observations of the source were made using the RXTE/PCA [57]. Galloway et al. [9] 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 M⊙ was obtained for the companion star and a pulse-frequency derivative of (−9.2 ± 0.4) × 10^{-14} Hz s^{-1}. Galloway et al. [9] suggested that this spin down torque may arise from magnetic coupling to the accretion disk, a magnetohydrodynamic wind, or gravitational radiation from the rapidly spinning neutron star. Assuming gravitational radiation as the driving force behind the mass transfer, Galloway et al. [9] found a lower limit to the distance of 6 kpc. Juett et al. [58] 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. [59] reported the discovery of the optical counterpart of the system with a V magnitude of 18.8 on 1 May 2002. Castro-Tirado et al. [60] 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. [51] discovered the radio counterpart of the source using the VLA with 4.86 GHz flux of 0.3–0.4 mJy.

5. XTE J1807–294

The fourth millisecond X-ray pulsar XTE J1807–294 with a frequency of 191 Hz, was discovered on 21 February 2003 [10]. The peak flux was only 58 mCrab (2–10 keV, measured on 21 February). The orbital period was determined [52] to be ∼40 minutes making it the shortest period of all accretion-driven millisecond pulsars now known. Using a Chandra observation, Markwardt et al. [52] reported the best known position of the source. Using the RXTE/PCA data, kHz QPOs have been detected for this system and the results obtained from a full analysis of those data will be reported elsewhere [53]. Campana et al. [64] reported on an XMM-Newton observation of this source taken on 22 March 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 (see also [65]). 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 so far been reported.

6. XTE J1814–338

The fifth system (XTE J1814–338) was discovered on 5 June 2003 and has a pulse frequency of 314 Hz [11], with an orbital period of 4.3 hr and a minimum companion mass of 0.15 M$_\odot$ [66]. 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 the low-luminosity neutron star LMXBs (the atoll sources). Many type-I X-ray bursts were seen during which burst oscillations were found with a frequency consistent with the neutron star spin frequency [66, 67]. A distance of ∼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; [38]) and two bursts exhibited evidence for a frequency decrease of a few tenths of a Hz during the onset of the burst, suggesting a spin down. Strohmayer et al. [67] also reported on the detection of the first harmonic of the burst oscillations, which is the first time that this has been found for any burst-oscillation source. This harmonic could arise from two hot-spots on the surface, but they 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 (possible due to a stronger magnetic field strength than in non-pulsating LMXBs).

Wijnands & Homan [68] analysed the RXTE/PCA data of the source obtained between 8 and 11 June 2003. The overall shape of the 3-60 keV power spectrum is dominated by a strong broad band-limited noise component (Fig. 4), which could be fitted by a broken power-law model with a broad bump superimposed on it.

![Figure 6. The broad-band noise observed for XTE J1814–338 [68].](image-url)
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. [66]. No kHz QPOs were found, although the upper limits were not very stringent.

Wijnands & Reynolds [69] reported that the position of XTE J1814–338 was consistent with the EXOSAT slew source EXMS B1810–337 which was detected on 2 September 1984. If XTE J1814-338 can indeed be identified with EXMS B1810-337, then its recurrence time can be inferred to be less than 19 years but more than 4.5 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. [70] reported the best position of the source as obtained using Chandra 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 [71] reported on optical spectroscopy of this possible counterpart and prominent hydrogen and helium emission lines were detected, confirming the connection between the optical source and XTE J1814–338.

7. Theoretical work

The lack of space for this review does not allow me to go into detail on the theoretical papers published on accretion-driven millisecond pulsars. Here, I will only briefly list some of those papers, which mostly focus on SAX J1808.4–3658 since the other four systems have only been found 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 [72,73,74], while others proposed that the compact object is not a neutron star at all, but instead a strange star (see, e.g., [75,76,77] and the references in those papers). Other studies focused on the evolutionary history of this system [78] or on the nature of the companion star [79, who suggested a brown dwarf companion star].

The discovery of the accretion-driven millisecond pulsars raises the important question as to why those systems are different from the other neutron star LMXBs for which not pulsations have been found. Cumming et al. [80]; see also [81] 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 also 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 pulsars the time-averaged accretion rate is sufficiently low that this can indeed happen and therefore those systems have a magnetic field which is still strong enough to disturb the flow of the accreted matter. However, more neutron-star LMXBs with low time-averaged accretion rate have to be found and studied in detail to investigate whether they all harbour a millisecond pulsar or if there are also systems with low time-averaged accretion rates that do not harbour a millisecond pulsar. In the latter scenario, the screening idea might only be part of the explanation and alternative ideas need to be explored (see, e.g., [82]).

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