Accreting millisecond X-ray pulsars: recent developments

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Abstract. It is now more than eleven years since the discovery of the first accreting millisecond
X-ray pulsar. Since then, eleven additional systems have been found, two of them during the
last year. Here I briefly discuss the most recent developments with respect to these systems.

Keywords. pulsars:X-ray – stars:neutron – X-rays:binaries

1. Introduction

Since the discovery of the first accreting millisecond X-ray pulsar (AMXP) in 1998
(Wijnands & van der Klis 1998), eleven additional systems have been found (see Table 1
and Section 2 for the two most recently discovered AMXPs). These systems are important
because they are the evolutionary link between millisecond radio pulsars and accreting
neutron stars in low-mass X-ray binaries†. In addition, by studying the pulsations in the
AMXPs, one hopes to learn about the physics of accretion onto a magnetized object and
about the properties of neutron stars. Currently all AMXPs are transients and one must
wait for the sources to go into outburst in order to study them and their pulsations.
Here I present some highlights of the most recent developments related to the study of
AMXPs.

2. The two most recently discovered AMXPs

In the months after the IAU General assembly, two new AMXPs were discovered. The
source IGR J17511–3057 was discovered by INTEGRAL in early September 2009 (Bal-
dovin *et al.* 2009) and soon afterwards it was found (using RXTE; Markwardt *et al.* 2009)
to be an AMXP. The neutron star in this system has a spin frequency of ∼245 Hz and
the orbital period of the system is ∼ 208 minutes (Markwardt *et al.* 2009; see also Table
1). In addition burst oscillations were observed (Watts *et al.* 2009) and a near infra-red
counterpart was discovered (Torres *et al.* 2009a,b). None of this makes this source excep-
tional; it would seem to be just a 'run-of-the-mill' AMXP. The second, recently discovered
AMXP does exhibit some atypical behavior. Heinke *et al.* (2009) reported the discov-
ery of a new X-ray transient in the gobular cluster NGC 6440 (the second one in this
cluster). An RXTE observation on this cluster showed that this transient is an AMXP.
The neutron star in this system has a spin period of ∼205 Hz and the orbital period is
∼57 min (Altamirano *et al.* 2009). These properties are not different from those of other
known AMXPs. However, it was found (Heink *et al.* 2009) that this source has only very
short outbursts (of order days) and the peak X-ray luminosity during outburst is only

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† Recently, a different type of 'link' between millisecond radio pulsars and neutron-star low–
mass X-ray binaries has been found (Archibald *et al.* 2009) opening up an additional, very
interesting window leading to understanding the relationship between the two types of sources.

Table 1. The currently known AMXPs with their basic characteristics and when the pulsations were first seen

Name	spin (Hz) (Hz)	binary period (min) (minutes)	$M_{c,min}$ ($M_\odot$)	When discovered
SAX J1808.4–3658	401	120	0.043	April 1998
XTE J1751—30 5	435	42	0.014	April 2002
XTE J0929–314	185	44	0.083	April 2002
XTE J1807–294	191	40	0.0066	February 2003
XTE J1814–338	314	258	0.17	June 2003
IGR J00291+5934	599	150	0.039	December 2004
HETE J1900.1–2455	377	84	0.016	June 2005
Swift J1756.9–2508	182	54	0.007	June 2007
Aql X-1	550	1140	?	August 2007
SAX J1748.9–2021	442	526	0.1	August 2007
NGC 6440 X-2	206	57	0.0067	August 2009
IGR J17511–3057	245	208	0.0011	September 2009

$\sim 10^{36}$ erg s^{-1} which makes it rather difficult to study in outburst. However, soon after it was discovered it was found that the source appears to be in outbursts roughly every month. This makes it the X-ray transient with the shorted known recurrence time (Heinke *et al.* 2009). The reason for this short recurrence time is not understood. Currently, monitoring campaigns using RXTE and Swift have begun to observe more outbursts of this source in order to study the evolution of its pulsations over time. Its frequent outbursts might give us unique insight into magnetic accretion if enough high-time resolution data during outburst can be collected. The discovery of this source also raises the question if many similar systems are missed, especially if they have similar short and weak outbursts but which are less frequent.

With twelve AMXPs now known, the neutron-star spin distribution can be studied in low-mass X-ray binaries. By including also the neutron-star spin measurements obtained from nearly coherent oscillations during type-I X-ray bursts (the so-called burst oscillations) the sample of sources now reaches about thirty. It was noted with a smaller sample (e.g., Chakrabarty *et al.* 2003 and references to that paper) that the neutron-star spin distribution in low-mass X-ray binaries (and also in the millisecond radio pulsars) appears to cut-off at around 600 to 700 Hz, with no neutron stars spinning faster than that† despite the fact that the break-up frequency of neutron stars is significantly larger. By using the full list of spin frequencies currently available, this conclusion still holds (see, e.g., Fig.1 which shows the sample complete until the summer of 2009 but does not include the most recent discoveries which are still consistent with this general picture). Currently, it is unclear what is the underlying physics. The most exciting explanation (although probably not the correct one) proposes that the spinning up of the neutron star in low-mass X-ray binaries is halted by the emission of gravitational waves from the stars (see Chakrabarty 2005 and Chakrabarty *et al.* 2003 and the papers referring to these two papers for a discussion of the various models).

† One system has a rather marginal indication of a burst-oscillation frequency (and thus a neutron-star spin) larger than 1000 Hz, but this result is highly debated and needs to be confirmed. I will not discuss this system further.
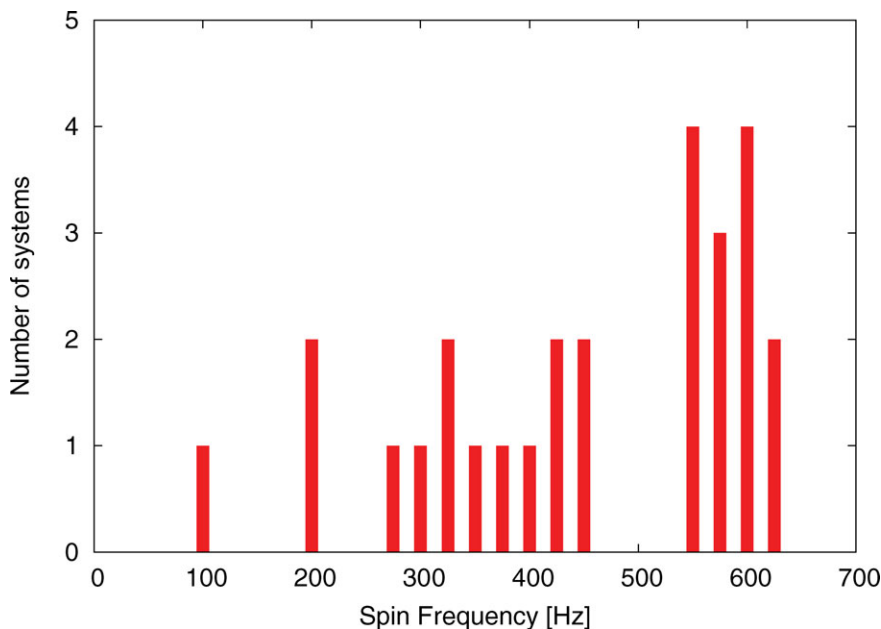
Figure 1. The number of AMXPs and burst oscillation sources (as of summer 2009) versus the observed frequency of the neutron stars (as inferred from the frequency of the pulsations or the burst oscillations). Figure made by Alessandro Patruno for the purpose of my presentation at the meeting.

3. Timing noise

One of the main reasons to study AXMPs is to determine the reaction of the neutron star to the accretion of matter. The usual way to investigate this is to search for changes in the pulse frequency (i.e., to determine a spin-frequency derivative or set upper limits on any). However, the measurement of such a frequency derivative has been severly hampered by an unmodeled component in the pulse arrival times which has been called 'timing noise' (named after a similar phenomenon, albeit on much longer time scales, seen in several radio pulsars). The presence of this timing noise has raised serious concerns about the validity of any frequency derivative reported in the literature. Recently, it has been shown that it is possible to attribute most of this timing noise to a phase offset of the pulsations that varies in correlation or anti-correlation with the X-ray flux (Patruno *et al.* 2009). If confirmed, this correlation could bias the measured spin frequencies and could artifically introduce a frequency derivative. Therefore it is very important to study all AMXPs (and hopefully also new ones) in detail to either confirm or reject this correlation. A confirmation would seriously inhibit our ability to measure any true spin period changes.. Interestingly, theoretically, these effects can rather easily be explained by assuming a wandering hot spot whose location depends on the accretion rate or by a systematic variations of the pulse profile (Patruno *et al.* 2009; Lamb *et al.* 2009, Poutanen *et al.* 2009).

4. Why only so few accreting millisecond X-ray puslars

Despite decades of observations, it is still unclear why only a dozen of the more than 150 known neutron-stars low-mass X-ray binaries exhibit pulsations. Aside from the pulsations, the other properties of the AMXPs look remarkably similar to those observed
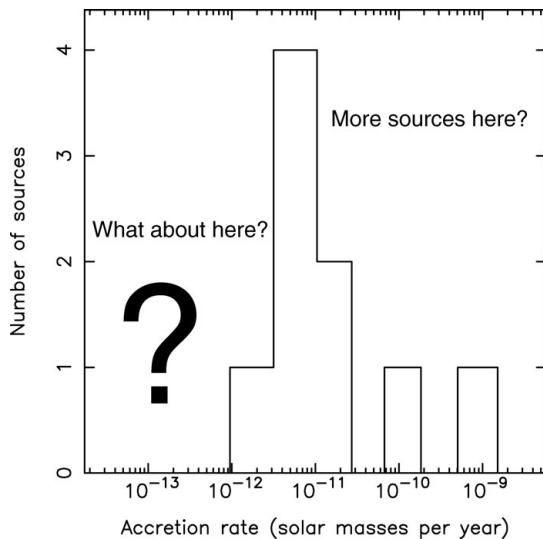
Figure 2. The number of AMXPs (as of summer 2009 and not including Aql X-1) versus their time averaged accretion rate.

from the non-pulsating sources, indicating that the difference between the two classess should be subtle. One possiblity is that the neutron stars in the non-pulsating systems have no or only a very weak magnetic field or that their magnetic axis is aligned with their spin axis. However, if this idea is correct, then those systems cannot be the progenitors of the millisecond radio pulsars unless a mechanism is available which would increase the magnetic field or misalign it with the rotation axis after the accretion has halted. Alternatively, it has been proposed that in the non-pulsating systems the pulsations (which are intrinsically there) are scatterred in a Comptonizing medium (e.g., Titarchuk *et al.* 2002) but it has been suggested that this cannot work for all systems (e.g., Göğüş *et al.* 2007; but see Titarchuk *et al.* 2007).

Based on the rather low time-averaged accretion rate ($\langle \dot{M} \rangle$) of the first AMXP discovered (SAX J1808.4–3658), Cumming *et al.* (2001) suggested that if $\langle \dot{M} \rangle$ 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 SAX J1808.4–3658 $\langle \dot{M} \rangle$ is sufficiently low that the magnetic field dissipation can indeed happen, giving it a magnetic field still strong enough to disturb the flow of the accreted matter. Intriguinly, nearly all of the AMXPs discovered after this (see Figure 2) have indeed rather low $\langle \dot{M} \rangle$ which would support this idea. The only outlayers are the so-called intermittent AMXPs which do not always exhibit pulsations. Those systems have high time averaged accretion rates and the intermittency of their pulsations might be related to that. Still, things are not fully clear and the burying model does have problems explaining those systems (see the discussions in Galloway *et al.* 2007, Casella *et al.* 2008, and Altamirano *et al.* 2008).

In order to make progress in our understanding of the reason (or reasons) why only such a small percentage of the neutron-star low-mass X-ray binaries exhibit pulsations, more AMXPs need to be discovered. When looking at Figure 2 (adapted from Wijnands 2008a), two strategies can be envisaged to try to enlarge the sample of AMXPs. Firstly, one should investigate the brighter transients with typically high $\langle \dot{M} \rangle$ ($> 10^{-10} \ M_\odot \ \mathrm{yr}^{-1}$) in detail for possible short lived episodes during which they migh exhibit pulsations. Some searches have been performed already using the RXTE archive but so far no new AMXP has been found. However, such searches still need to be fully optimized and several

AMXPs might still be lurking in the RXTE archive. Secondly, if indeed most AMXPs have low $\langle \dot{M} \rangle$, one might assume (see Wijnands 2008a and references therein) that those neutron-star low-mass X-ray binaries with a very low $\langle \dot{M} \rangle$ ($< 10^{-11} M_\odot$ yr^{-1}) might also exhibit coherent pulsations when in outburst. The fact that NGC 6440 X-2 might have a $\langle \dot{M} \rangle$ as low as $\sim 10^{-12} M_\odot$ yr^{-1} (Heinke *et al.* 2009) would support that idea. However, those systems are difficult to find. RXTE might not be sensitive enough to detect the pulsations leaving only XMM-Newton to be used (see discussion in Wijnands 2008b). Therefore, the discovery of those systems and the search for possible pulsations is quite challenging but could yield very important results which would help us to understand why only so few systems pulsate.

Acknowledgements

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