

## Millisecond Pulsars in X-Ray Binaries

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**Abstract.** Despite considerable evidence verifying that millisecond pulsars are spun up through sustained accretion in low-mass X-ray binaries (LMXBs), it has proven surprisingly difficult to actually detect millisecond X-ray pulsars in LMXBs. There are only 5 accretion-powered millisecond X-ray pulsars known among more than 80 LMXBs containing neutron stars, but there are another 11 “nuclear-powered” millisecond pulsars which reveal their spin only during brief, thermonuclear X-ray bursts. In addition, 2 of the accretion-powered pulsars also exhibit X-ray burst oscillations, and their unusual properties, along with the absence of persistent pulsations in most LMXBs, suggest that the magnetic fields in many LMXBs may be hidden by accreted material. Interestingly, the nuclear-powered pulsars offer a statistically unbiased probe of the spin distribution of recycled pulsars and show that this distribution cuts off sharply above 730 Hz, well below the breakup spin rate for most neutron star equations of state. This indicates that some mechanism acts to halt or balance spin-up due to accretion and that submillisecond pulsars must be very rare (and are possibly nonexistent). It is unclear what provides the necessary angular momentum sink, although gravitational radiation is an attractive possibility.

### 1. Introduction

Since the discovery of the first millisecond radio pulsar (Backer et al. 1982), it has been believed that these old, weak-field ( $\sim 10^8$  G) pulsars were spun up to millisecond periods by sustained accretion onto neutron stars in low-mass X-ray binaries (NS/LMXBs; Alpar et al. 1982). It is known from accretion torque theory (e.g., Ghosh & Lamb 1979) and from observations of strong-field ( $> 10^{11}$  G) accreting neutron stars (Bildsten et al. 1997) that steady disk accretion onto a magnetized neutron star will lead to an equilibrium spin period

$$P_{\text{eq}} \sim 1 \text{ s} \left( \frac{B}{10^{12} \text{ G}} \right)^{6/7} \left( \frac{\dot{M}}{10^{-9} M_{\odot} \text{ yr}^{-1}} \right)^{-3/7}, \quad (1)$$

where  $B$  is the pulsar’s surface dipole magnetic field strength and  $\dot{M}$  is the mass accretion rate. Also, most neutron stars in LMXBs are old and have weak magnetic fields, based both on the occurrence of thermonuclear X-ray bursts (which require  $B < 10^{10}$  G; see Joss & Li 1980) and on their X-ray spectral (Psaltis & Lamb 1998) and timing properties (see, e.g., van der Klis 2000). Thus, as long as we accept that sustained accretion onto neutron stars can

somehow attenuate their strong birth fields down to  $\sim 10^8$  G strengths (see, e.g., Bhattacharya & Srinivasan 1995), it is natural to expect neutron stars in LMXBs to be spinning at millisecond periods. (Note that, although the general trend of Eq. [1] is expected to extend down to  $10^8$  G, the precise power-law dependences are likely to be modified; see Psaltis & Chakrabarty 1999).

A robust prediction of this model is that the neutron stars in LMXBs should be X-ray pulsars, since a  $10^8$  G field should be strong enough to truncate the Keplerian accretion disk and channel its flow onto the neutron star's magnetic poles. However, the detection of accretion-powered millisecond X-ray pulsars proved elusive for nearly two decades, with a series of X-ray missions failing to detect millisecond pulsations from NS/LMXBs down to stringent upper limits on the pulsed fraction (e.g., Vaughan et al. 1994). The launch of the *Rossi X-Ray Timing Explorer* (*RXTE*; Bradt, Rothschild, & Swank 1993; Jahoda et al. 1996) in December 1995 finally provided an instrument with sufficient flexibility and sensitivity to detect SAX J1808.4–3658, the first accretion-powered millisecond X-ray pulsar (Wijnands & van der Klis 1998; Chakrabarty & Morgan 1998), as well as several additional examples (see Table 1). A key element proved to be the highly flexible pointing and scheduling ability of *RXTE*. The Galactic X-ray sky is highly variable, with some sources lying dormant for years and only intermittently becoming active in X-ray emission. The combination of having both the *RXTE* All Sky Monitor to determine when an X-ray transient becomes active and the ability to rapidly repoint the main *RXTE* instruments at a newly active source were crucial in enabling the discovery of millisecond X-ray pulsars.

Along the way, *RXTE* detected other classes of rapid X-ray variability which also point to millisecond spins for these neutron stars but which also raised a number of new questions about the underlying physics.

## 2. Millisecond Variability in Accreting Neutron Stars

*RXTE* has identified three distinct classes of millisecond variability in accreting neutron stars:

- **Kilohertz quasi-periodic oscillations (kHz QPOs)** (van der Klis et al. 1996; see van der Klis 2000 for a review): These are pairs of relatively high- $Q$  peaks in the X-ray intensity power spectrum whose frequencies drift by hundreds of hertz (200–1200 Hz) as the source intensity varies, but whose separation frequency (typically a few hundred Hz) remains roughly constant (see example in left panel of Figure 1). This approximate separation frequency has a unique, reproducible value for each of the over 20 NS/LMXBs in which this phenomenon is observed. These oscillations are believed to arise in the inner accretion disk flow, where the dynamical time scale is of order milliseconds.
- **X-ray burst oscillations** (Strohmayer et al. 1996; see Strohmayer & Bildsten 2004 for a review): These are nearly coherent millisecond oscillations observed only during thermonuclear X-ray bursts (which typically last  $\sim 10$  s). The observed frequencies drift by a few Hz over  $\sim 5$  s during the bursts, asymptotically reaching a maximum frequency that is unique

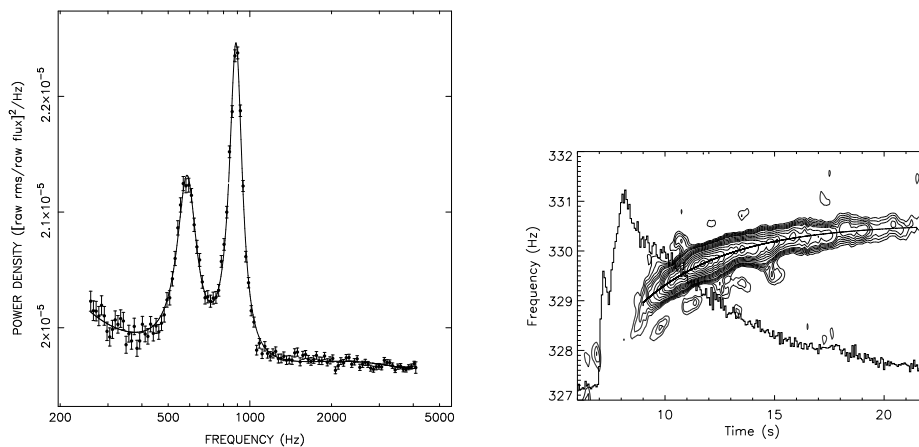


Figure 1. *Left*: Power spectrum of X-ray intensity showing kHz QPO pair in Sco X-1. Adapted from van der Klis et al. (1997). *Right*: X-ray burst oscillations in 4U 1702-43. The solid histogram shows the X-ray intensity history of the X-ray burst. The contours show the Fourier power level as a function of frequency and time, indicating a drifting oscillation starting at 328 Hz ( $t = 7$  s) and ending at 330.5 Hz. Adapted from Strohmayer & Markwardt (1999).

and reproducible for each of the 13 sources in which this phenomenon is observed (see right panel of Figure 1). These maximum frequencies lie in the 270–619 Hz range. The oscillation (at least at the burst onset) is understood as a temperature anisotropy caused by the nuclear burning, with the frequency drift interpreted as angular momentum conservation in a cooling, decoupled burning layer on the stellar surface (Strohmayer et al. 1997; Cumming & Bildsten 2000). Since their discovery, it was suspected that the millisecond oscillations were somehow tracing the stellar spin, but until recently there was some question about whether the oscillations might be a harmonic of the spin. A list of these sources is given in Table 1.

- **Persistent accretion-powered pulsations** (Wijnands & van der Klis 1998; see Wijnands 2004 for a review): These are the objects originally expected by the recycling hypothesis, NS/LMXBs whose persistent (non-burst) emission contains coherent millisecond pulsations (see example in Figure 2). Oddly, all five of the these pulsars (see Table 1) are in soft X-ray transients: accreting systems that lie dormant for years, with intermittent outbursts of accretion lasting about a month (these outbursts are understood to arise from an accretion disk instability; see Frank, King, & Raine 2002). Moreover, all five also have very short orbital periods<sup>1</sup> and very low mass accretion rates. Also, the pulsed amplitude of these systems

<sup>1</sup>As an aside, I also note that there are five LMXBs whose orbital periods are within 90 seconds of 42 minutes: three of the millisecond X-ray pulsars, the strong-field pulsar 4U 1626-67, and the quiescent LMXB NGC 6652B. This excess is statistically significant, and there is no selection effect for finding this period. What is so special about this particular orbital period?

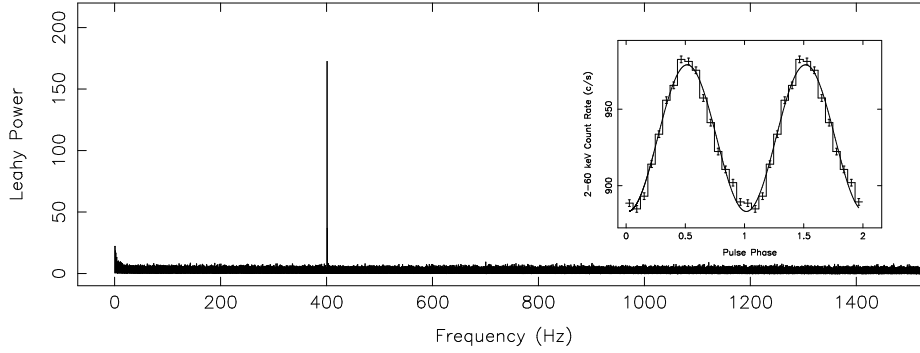


Figure 2. Fourier power spectrum showing coherent 401 Hz X-ray pulsations in the persistent pulsar SAX J1808.4–3658. The inset shows the highly sinusoidal pulse profile. Adapted from Wijnands & van der Klis (1998).

is about 6 percent, while the upper limit on the pulsed amplitude for most NS/LMXBs is 1 per cent or less, raising the question of what is different about this group of 5 pulsars: why is it so difficult to find persistent millisecond pulsations in most NS/LMXBs? It should be noted that none of the millisecond X-ray pulsars has been detected as a radio pulsar.

While both kHz QPOs and X-ray burst oscillations are often observed in the same source, until 2002 neither phenomena had ever been observed in accretion-powered millisecond pulsar. Since it was only in this latter class that the neutron star spin was definitively known, the relationship between these three classes of variability was not clear. Still, some patterns were clear. In particular, the separation frequency  $\Delta\nu_{\text{kHz}}$  organized the burst oscillation sources into two groups: the slow oscillators (with  $\nu_{\text{burst}} < 400$  Hz) all have  $\nu_{\text{burst}} \approx \Delta\nu_{\text{kHz}}$ , while the fast oscillators (with  $\nu_{\text{burst}} > 500$  Hz) all have  $\nu_{\text{burst}} \approx 2\Delta\nu_{\text{kHz}}$ . The photospheric radius expansion properties of the X-ray bursts also divide along these lines, with fast oscillations occurring preferentially in radius expansion bursts (Muno, Galloway, & Chakrabarty 2004). Since both  $\Delta\nu_{\text{kHz}}$  and  $\nu_{\text{burst}}$  are reproducible characteristics of a given source and the most likely mechanism for such a stable frequency is the stellar spin, there was considerable debate as to whether it is  $\Delta\nu_{\text{kHz}}$  or  $\nu_{\text{burst}}$  that is the fundamental spin frequency.

This question was finally settled by the detection in kHz QPOs in two accretion-powered X-ray pulsars in 2002 and 2003. In the rapid rotator SAX J1808.4–3658,  $\Delta\nu_{\text{kHz}}$  is half the 401 Hz spin frequency (Wijnands et al. 2003); while in the slow rotator XTE J1807–294,  $\Delta\nu_{\text{kHz}}$  roughly equals the 190 Hz spin frequency (Markwardt et al. 2004), verifying the odd phenomenology described above. (The possibility that the spin frequency in SAX J1808.4–3658 is actually 200.5 Hz was excluded by the very stringent non-detection of pulsations at this frequency; see Morgan et al. 2004.) In addition, X-ray burst oscillations were also detected in the 401 Hz pulsar SAX J1808.4–3658 (Chakrabarty et al. 2003) and the 314 Hz pulsar XTE J1814–338 (Strohmayer et al. 2003); in both cases,  $\nu_{\text{burst}}$  was equal to the spin frequency.

These new observations lead to three conclusions:

- X-ray burst oscillations directly trace the neutron star spin (and are not higher harmonics of a fundamental), and may thus be thought of as nuclear-powered pulsations.
- The kHz QPO separation frequency  $\Delta\nu_{\text{kHz}}$  is sometimes roughly the spin frequency (in slow rotators) and sometimes roughly half the spin frequency (in fast rotators). The origin of these QPOs is uncertain, but the underlying mechanism clearly has some coupling to the stellar spin.
- Most neutron stars in LMXBs are indeed spinning at millisecond periods, but for some reason only a small fraction of them are visible as persistent, accretion-powered millisecond pulsars.

This last point is puzzling, since one would expect a  $10^8$  G accreting neutron star to be a pulsar. There have been several possible explanations discussed for why most NS/LMXBs are not pulsars. One possibility is that the most of the NSs have magnetic fields that are too weak to channel the accretion flow, although there is evidence for radio pulsars with fields much weaker than  $10^8$  G. Another possibility is that the neutron stars in non-pulsing LMXBs are surrounded by a scattering medium that attenuates pulsations (Brainerd & Lamb 1987; Kylafis & Phinney 1989). Indeed, Titarchuk, Cui, & Wood (2003) have recently argued that the data support this argument, although there is not yet a consensus on this point (Heindl & Smith 1998; Psaltis & Chakrabarty 1999). A third possibility is that gravitational self-lensing might attenuate the pulsations (Wood, Ftaclas, & Kearney 1988; Meszaros, Riffert, & Berthiaume 1988). In the next section, I will discuss recent evidence that suggests that magnetic field strength may indeed be the relevant factor.

### 3. SAX J1808.4–3658: Evidence for a Range of LMXB Magnetic Field Strengths

It is instructive to compare the behavior of the X-ray burst oscillations observed in the pulsar SAX J1808.4–3658 with those observed in the non-pulsing LMXBs. In SAX J1808.4–3658, strong millisecond oscillations around the 401 Hz spin frequency were observed during 4 X-ray bursts in 2002, with very similar characteristics in each burst (Chakrabarty et al. 2003). An example is shown in Figure 3. First, a rapidly drifting oscillation (increasing from 397 to 403 Hz) was detected during the burst rise. Second, no oscillations were detected during the radius expansion phase of the burst (typical of other burst oscillation sources as well). Finally, a strong oscillation reappeared during the cooling phase of the burst, at a constant frequency nearly equal to the spin frequency (which was known precisely from the pre-burst persistent pulsations), but exceeding it by one part in 70000.

This observed frequency drift demonstrates that this is a similar phenomena as the burst oscillations observed in other (non-pulsing) neutron stars, although the oscillations in SAX J1808.4–3658 have some very unusual traits: the drift time

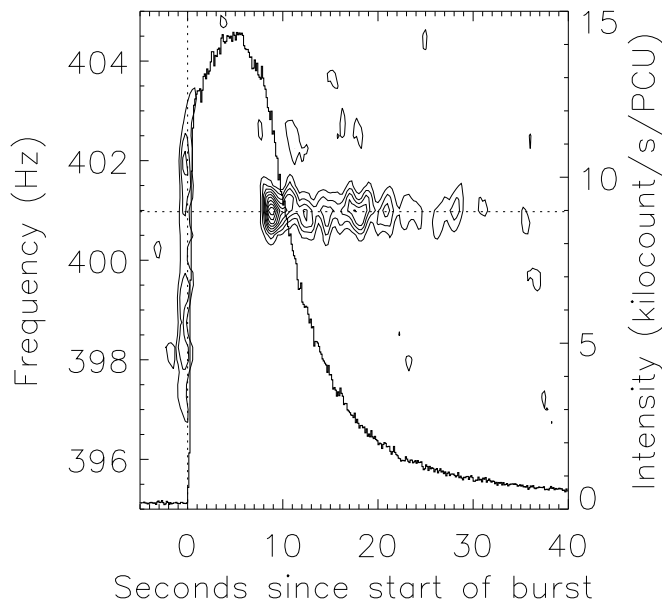


Figure 3. X-ray burst oscillation in the pulsar SAX J1808.4–3658. The histogram shows the X-ray intensity during the thermonuclear X-ray burst. The contours show the Fourier power levels as a function of frequency and time. The horizontal dotted line indicates the (known) pulsar spin frequency. A rapidly drifting oscillation is detected during the burst rise and overshoots the spin rate. A stationary oscillation near the spin rate is detected in the burst tail. Adapted from Chakrabarty et al. (2003).

scale is an order of magnitude faster than in the other neutron stars (compare right panel of Figure 1), and the maximum oscillation frequency is reached during the burst rise, inconsistent with angular momentum conservation in a cooling, contracting burning shell. In fact, as evident in Figure 3, the oscillation *overshoots* the spin frequency during the burst rise. The rapid, overshooting drift probably indicates that SAX J1808.4–3658 has a stronger magnetic field than the other burst oscillation sources (Chakrabarty et al. 2003), since a sufficiently strong field will suppress rotational shearing in the burning layer and may act as a restoring force. Strohmayer et al. (2003) also interpreted the frequency evolution of the burst oscillations in the pulsar XTE J1814–338 as evidence for a stronger than normal magnetic field in that LMXB.

This magnetic field argument is especially appealing as only SAX J1808.4–3658 and XTE J1814–338, among a total of 13 burst oscillation sources (and two of only five systems out of a total of over 80 NS/LMXBs), show persistent pulsations in their non-burst emission. The absence of persistent pulsations in most of these systems suggests that they lack a sufficiently strong magnetic field for the accretion flow to be magnetically channeled. Indeed, it has been proposed that the absence of persistent pulsations in most NS/LMXBs is due to diamagnetic screening of the neutron star magnetic field by freshly accreted material, which would occur above a critical value of  $\dot{M}$  at a few percent of the Eddington rate (Cumming, Zweibel, & Bildsten 2001). In this context, it is interesting to note

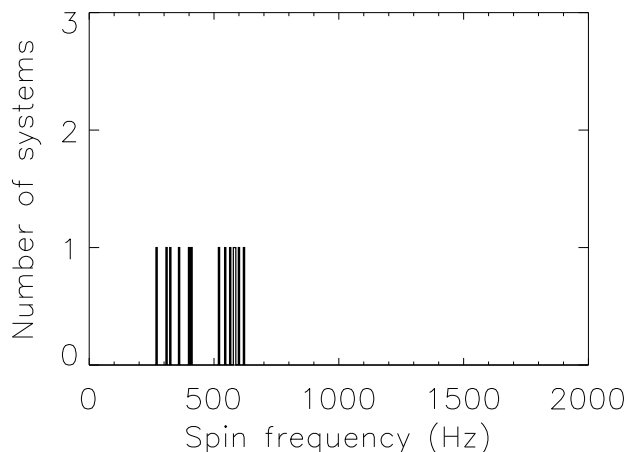


Figure 4. The spin frequency distribution of nuclear-powered millisecond X-ray pulsars. There is a sharp drop off in the population at spins above 730 Hz. *RXTE* has no significant selection effects against detecting oscillations as fast as 2000 Hz, making the absence of fast rotators extremely statistically significant. Based on results from Chakrabarty et al. (2003).

that all five of the persistent millisecond X-ray pulsars lie at the low end of the  $\dot{M}$ -distribution for LMXBs. Thus, while all the NS/LMXBs may have underlying surface field strengths of  $\sim 10^8$  G (see, e.g., Psaltis & Chakrabarty 1999), it may be that the non-pulsing LMXBs have *effective* field strengths that are much lower due to screening by accreted material. Presumably, the underlying field would emerge when the accretion eventually halts; thus, this idea is still consistent with the absence of millisecond radio pulsars with fields much weaker than  $10^8$  G.

#### 4. The Underlying Spin Distribution of Recycled Pulsars

Having observationally verified that millisecond pulsars are spun up or “recycled” in LMXBs, it is interesting to ask what the underlying spin distribution of recycled pulsars is, and whether there is any limit to the recycling process. One might expect the distribution of spin frequencies to simply reflect the range of equilibrium spins corresponding to the magnetic field strength distribution in LMXBs. However, if the effective field strength of most NS/LMXBs is considerably below  $10^8$  G as discussed above, then the resulting boundary layer accretion onto the neutron star might be capable of spinning up the pulsar to submillisecond periods. Certainly, a strict upper limit on the neutron star spin rate is given by the centrifugal breakup limit, up to 3 kHz depending upon the neutron star equation of state (Cook, Shapiro, & Teukolsky 1994; Haensel, Lasota, & Zdunik 1999).

Although the substantial known population of millisecond radio pulsars in principle provides an ideal probe of the spin distribution of recycled pulsars, severe observational selection effects have historically made it difficult to make a statistically accurate estimate. However, the burst oscillation sources (nuclear-powered pulsars) are an ideal probe: they are bright and easily detected throughout the Galaxy, their signals are short-lived enough to avoid modulation losses due to orbital Doppler smearing, and *RXTE* has no significant selection effects against detecting oscillations as fast as 2 kHz.

The spin frequencies (see Table 1) of the 13 known nuclear-powered millisecond pulsars are plotted in Figure 4. (The three non-bursting, accretion-powered millisecond pulsars are omitted to keep the sample unbiased.) The spins are consistent with a uniform distribution within the observed 270–619 Hz range. The absence of any pulsars at lower frequencies is not surprising, since such low equilibrium spin rates would require somewhat higher magnetic field strengths, which would then suppress the thermonuclear X-ray bursts necessary for burst oscillations. However, the absence of spins above 619 Hz is extremely significant, given that there is no significant loss of *RXTE* sensitivity out to 2 kHz. Under the simple assumption of a uniform distribution out to some maximum value, the observed distribution yields an maximum spin frequency of 730 Hz (95% confidence; Chakrabarty et al. 2003). This limit is consistent with the fastest known millisecond radio pulsar, PSR B1937+21, which has  $P_{\text{spin}} = 641$  Hz. This limit is also well below the breakup frequency for nearly all equations of state for rapidly rotating neutron stars. Recent radio pulsar surveys, in which selection effects are accounted for, are independently finding similar evidence for a maximum spin frequency around 700 Hz, as reported at this meeting (McLaughlin et al., in this volume; Camilo & Rasio, in this volume).

It is thus clearly demonstrated observationally that the population of pulsars with spins above 730 Hz must drop off dramatically (although not necessarily to zero: the existence of submillisecond pulsars is *not* excluded, but such objects are evidently at best very rare). It remains unclear what causes this drop off. Magnetic spin equilibrium can only account for the observed distribution if the entire sample has surface magnetic field strength  $\sim 10^8$  G. However, as noted above, fields this strong should be dynamically important for the accretion flow and lead to persistent millisecond pulsations, making it difficult to understand the lack of pulsations in most NS/LMXBs and instead suggesting a wider range of magnetic field strengths.

Alternatively, several authors have shown that gravitational radiation can carry away substantial angular momentum from accreting neutron stars, driven by excitation of an *r*-mode instability in the neutron star core (Wagoner 1984; Andersson, Kokkotas, & Stergioulas 1999), or by a rotating, accretion-induced crustal quadrupole moment (Bildsten 1998), or by large (internal) toroidal magnetic fields (Cutler 2002). These losses can balance accretion torques for the relevant ranges of spin and  $\dot{M}$ , and the predicted gravitational radiation strengths are near the detection threshold for, e.g., the planned Advanced LIGO detectors (Bildsten 2003). Such a detection would rely on operating a narrow-band search in a known frequency range, but this approach has the advantage of searching for a persistent signal that can be integrated, unlike the transient signals like those produced by binary mergers.



Table 1. Millisecond Pulsars in X-Ray Binaries

Object	Spin Frequency (Hz)	Orbital Period
ACCRETION-POWERED PULSARS		
XTE J0929–314	185	43.6 min
XTE J1807–294	191	41 min
XTE J1814–338	314	4.27 hr
SAX J1808.4–3658	401	2.01 hr
XTE J1751–305	435	42.4 min
NUCLEAR-POWERED PULSARS (Burst Oscillations)		
4U 1916–05	270	50 min
XTE J1814–338	314	4.27 hr
4U 1702–429	330	?
4U 1728–34	363	?
SAX J1808.4–3658	401	2.01 hr
SAX J1748.9–2021	410	?
KS 1731–260	524	?
Aql X-1	549	19.0 hr
X1658–298	567	7.11 hr
4U 1636–53	581	3.8 hr
X1743–29	589	?
SAX J1750.8–2900	601	?
4U 1608–52	619	?

It will be of considerable interest to measure the shape of the spin distribution more accurately, in order to determine whether we are observing a gradual fall off, an abrupt cutoff, a pile up, etc. — at present, the data cannot distinguish between these possibilities, and thus cannot meaningfully discriminate between theoretical models. In the long run, it is likely to be the radio systems that provide the best measurement of the distribution, based simply on ease of detectability and the available instrumentation.

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