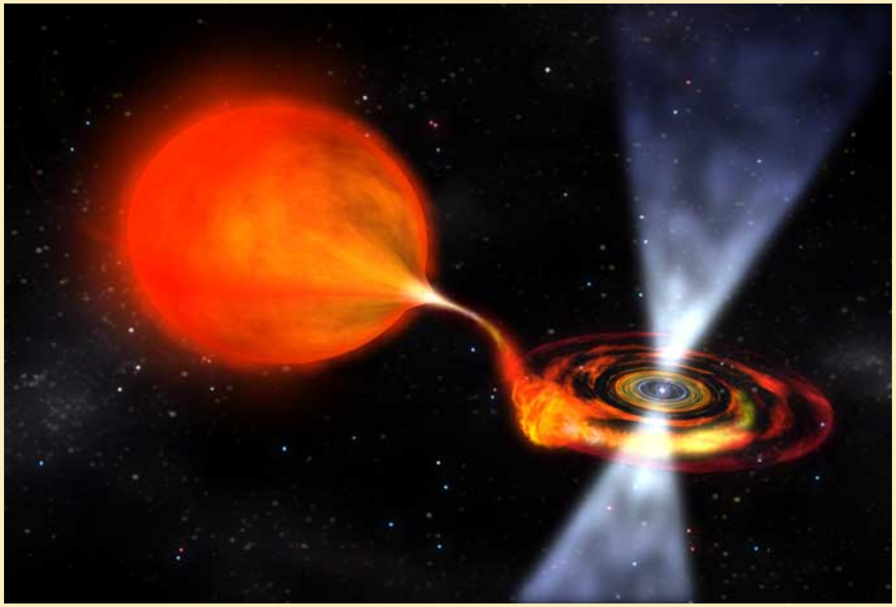
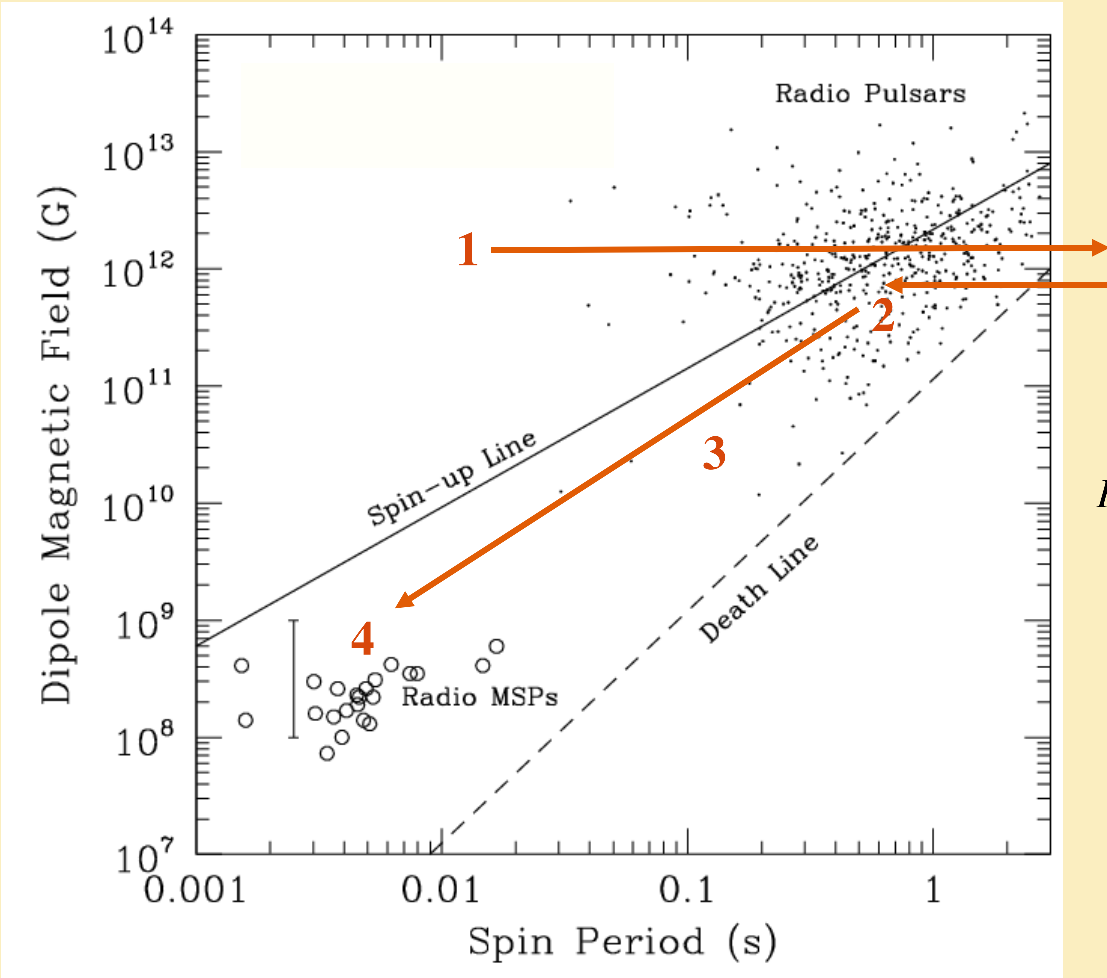
Accreting Millisecond Pulsars and RXTE:
Selected highlights from a 16-year history

Deepto Chakrabarty *(MIT)*



RXTE Symposium
NASA Goddard Space Flight Center
March 30, 2012

Pre-RXTE: X-ray Pulsars were presumed progenitors of msec radio pulsars



1. Pulsars born with $B \sim 10^{12}$ G, $P \sim 20$ ms. Spin-down due to radiative loss of rotational K.E.

2 If in binary, then companion may eventually fill Roche lobe (**"X-ray binary"**). Accretion spins up pulsar to equilibrium spin period

$$P_{\mathrm{eq}} \approx 1\ \mathrm{s} \left(\frac{B}{10^{12}\ \mathrm{G}}\right)^{6/7} \left(\frac{\dot{M}}{10^{-9} M_{\mathrm{Sun}}/\mathrm{yr}}\right)^{-3/7}$$

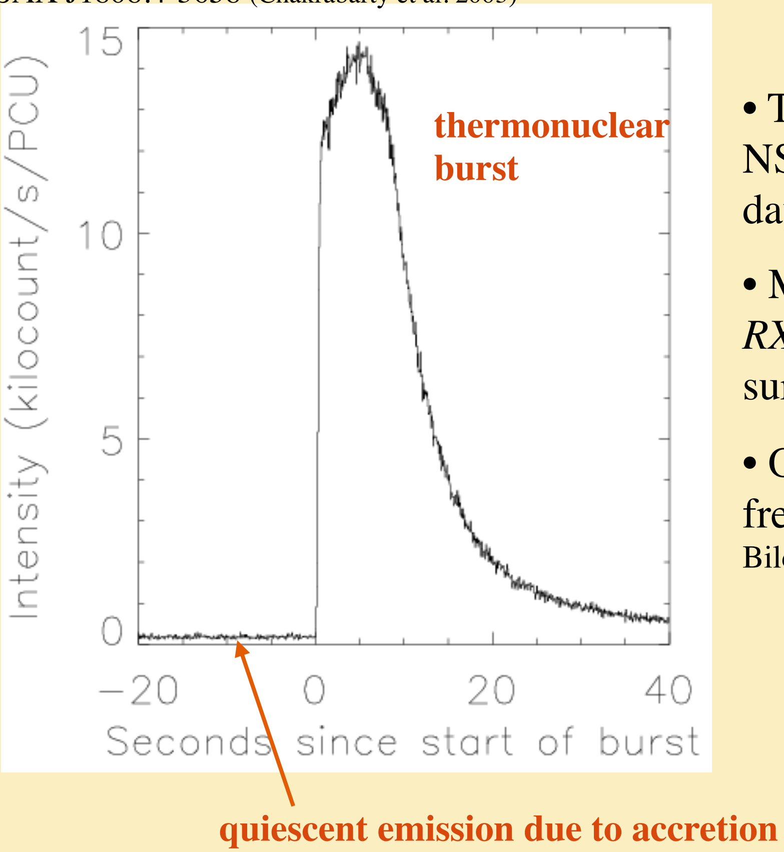
3 Sustained accretion ($\sim 10^9$ yr) attenuates pulsar magnetic field to $B \sim 10^8$ G, leading to equilibrium spin $P \sim$few ms

4 At end of accretion phase (companion exhausted or binary disrupted), millisecond radio pulsar remains

In regions 2, 3, 4 in above plot, accretion-powered X-ray pulsations expected. Thus, expect to see millisecond X-ray pulsations in LMXBs: search for these with RXTE!

Nuclear-Powered Millisecond X-Ray Pulsars (X-Ray Burst Oscillations)

SAX J1808.4-3658 (Chakrabarty et al. 2003)

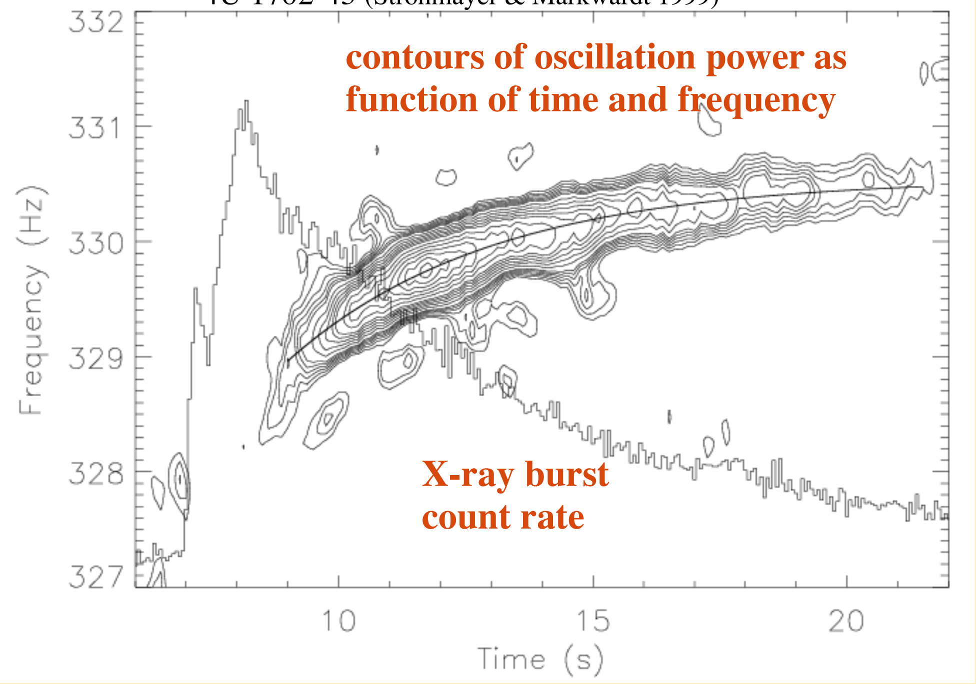


• Thermonuclear X-ray bursts due to unstable nuclear burning on NS surface, lasting tens of seconds, recurring every few hours to days.

• Millisecond oscillations discovered during some X-ray bursts by *RXTE* (Strohmayer et al. 1996). Spreading hot spot on rotating NS surface yields "nuclear-powered pulsations".

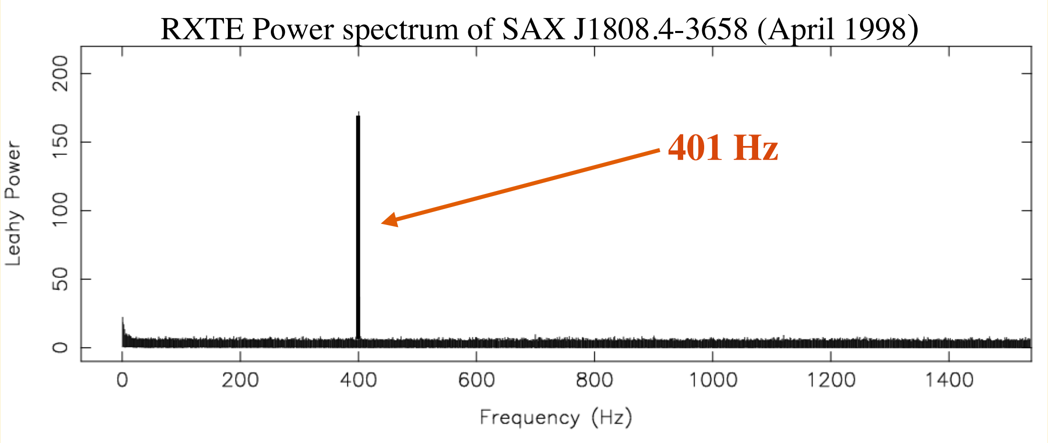
• Oscillations in burst tail not yet understood. Along with frequency drift, may be due to surface modes on NS. (Heyl; Piro & Bildsten; Cooper & Narayan)

4U 1702-43 (Strohmayer & Markwardt 1999)

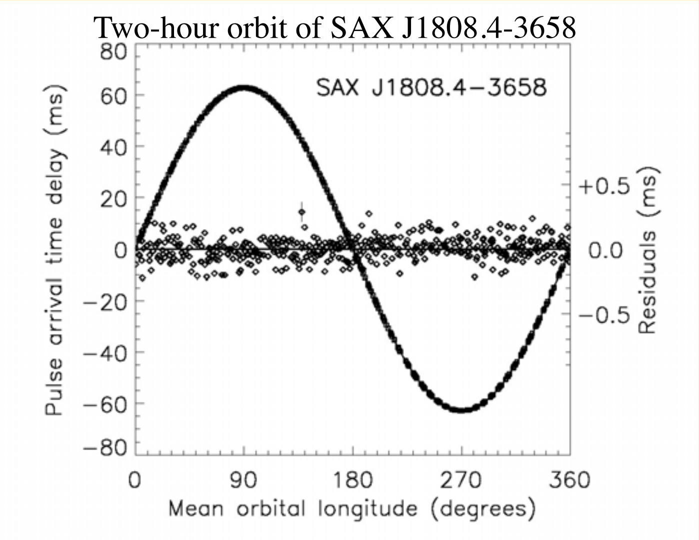


• Burst oscillations suspected to be tracing spin, but coherence not really testable owing to short duration of oscillation.

SAX J1808.4-3658: The First Accretion-Powered Millisecond Pulsar



Wijnands & van der Klis 1998

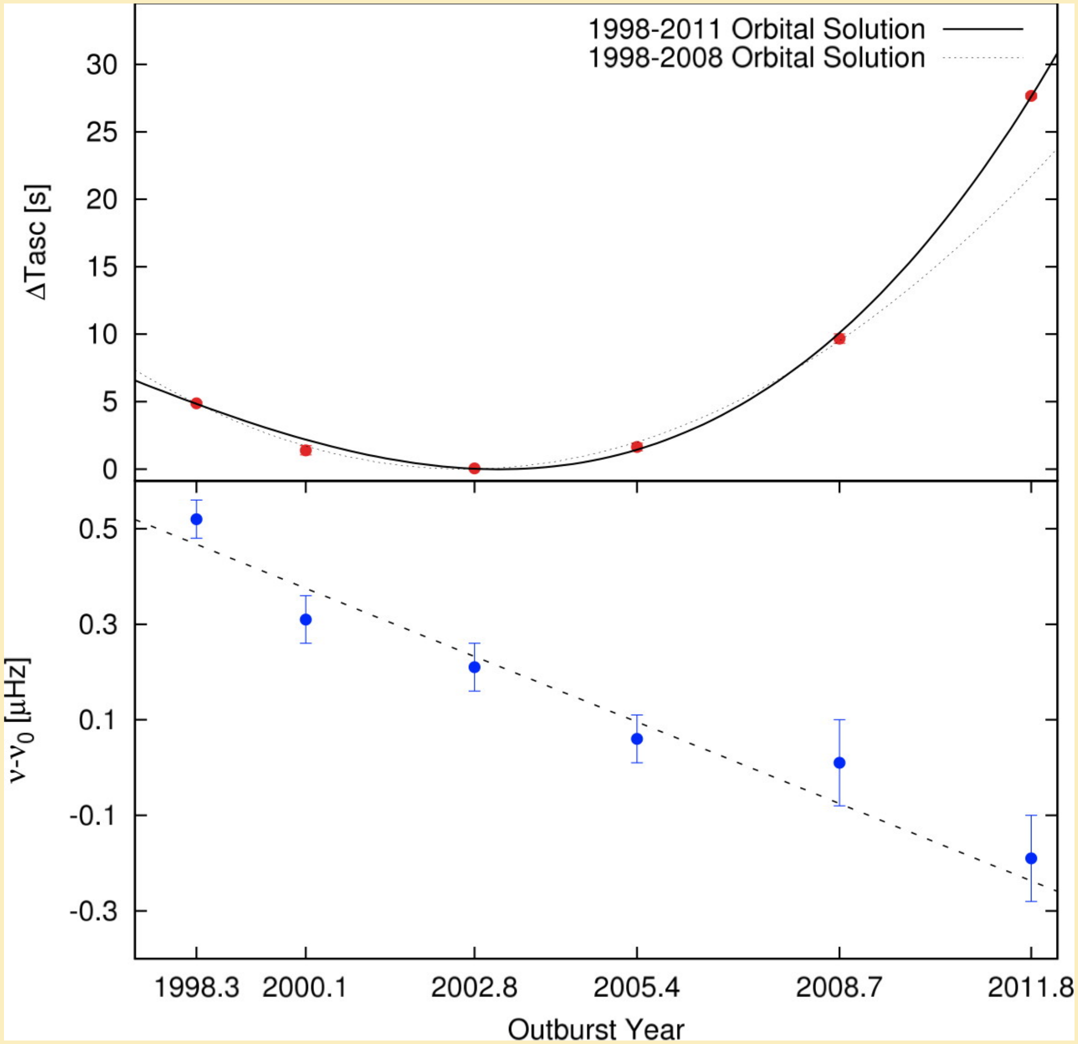


Chakrabarty & Morgan 1998

- Pulsar discovered in April 1998. (Source observed by BeppoSAX in Sept 1996)
- Persistent X-ray pulsations at 401 Hz spin rate of neutron star.
- Circular binary orbit with 2 hr period
- Magnetic field strength estimate ~10^8 G.
- X-ray transient (turns out to be typical). This one now seen in 6 outbursts with RXTE.
- Other aspects: secular spin-down, orbital evolution. Optical counterpart (brown dwarf donor). Energy-dependent pulse phase lags.

Spin and Orbital Evolution of SAX J1808.4-3658

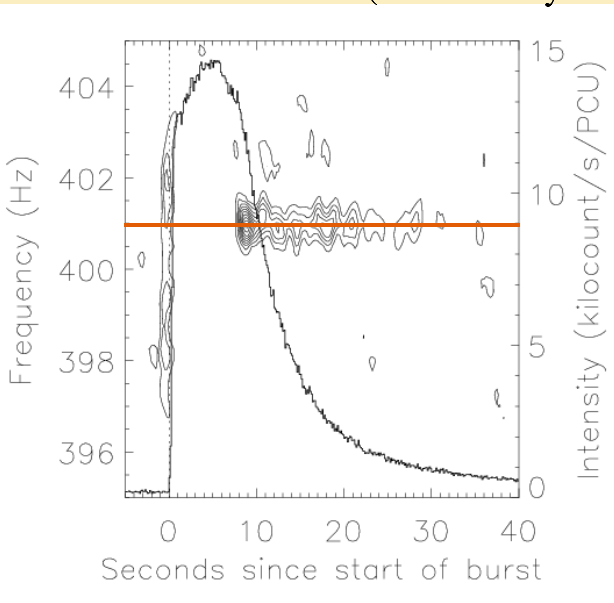
Patruno et al. (2012)



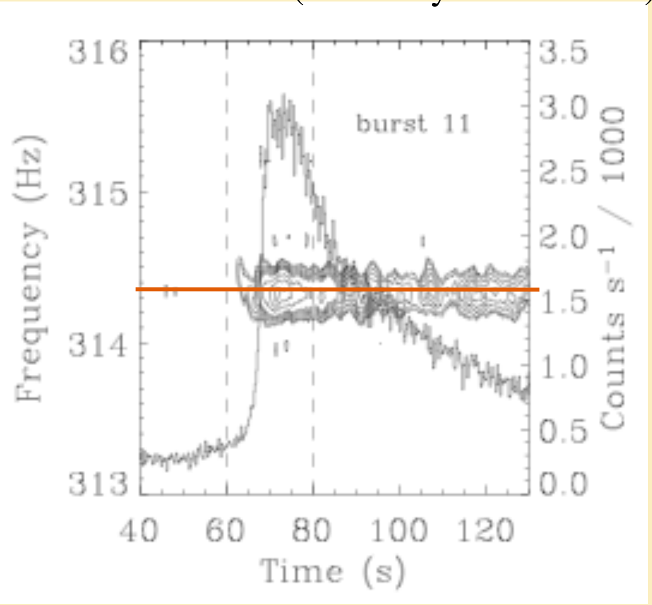
Secular spin-down consistent with magnetic dipole spin-down of pulsar between outbursts. Accelerating orbital expansion not completely understood: angular momentum exchange between pulsar and companion? (Comparison to black-widow pulsars?)

Burst oscillations in accretion-powered millisecond pulsars

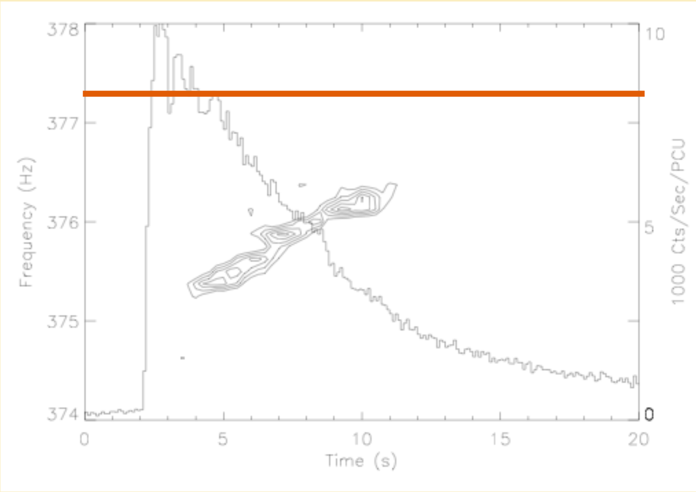
SAX J1808.4-3658 (Chakrabarty et al. 2003)



XTE J1814-334 (Strohmayer et al. 2003)



HETE J1900.1-2455 (Watts et al. 2009)



- Verifies that burst oscillations basically trace the spin frequency (at least within a few Hz)

What causes X-ray burst oscillations, and how are they coupled to spin?

• Nuclear burning ignition at a point on stellar surface should lead to pulsations in early phase of burst. This is consistent with measurements of burst oscillation during burst rise (Strohmayer et al. 1996, 1997).

• Oscillations during burst tail occur after burning has spread over entire surface, and so must have a different explanation. May be due to surface modes on NS. (Heyl; Piro & Bildsten; Cooper & Narayan). Could modes also explain early-phase oscillations?

• What causes frequency drift?

Accretion-Powered Millisecond Pulsars

Year	Object	ν_{spin}	P_{orb}	Remarks
1998	SAX J1808.4-3658	401 Hz	2.01 hr	Burst osc
2002	XTE J1751-305	435 Hz	0.71 hr	
2002	XTE J0929-314	185 Hz	0.73 hr	
2003	XTE J1807-294	191 Hz	0.68 hr	
2003	XTE J1814-338	314 Hz	4.27 hr	Burst osc
2004	IGR J00291+5934	599 Hz	2.46 hr	
2005	HETE J1900.1-2455	377 Hz	1.39 hr	Burst osc; Intermittent
2007	Swift J1756.9-2508	182 Hz	0.91 hr	
2007	SAX J1748.9-2021 (NGC 6440)	442 Hz	8.76 hr	Intermittent
2007	Aql X-1	550 Hz	19 hr	Burst osc; Intermittent
2009	NGC 6440 X-2	205 Hz	0.96 hr	
2009	IGR J17511-3057	245 Hz	3.47 hr	Burst osc
2010	Swift J1749.4-2807	518 Hz	8.81 hr	Eclipsing
2010	IGR J17480-2446 (T5X2)	11 Hz	21.3 hr	Burst osc. Slow pulsar.
2011	IGR J17498-2921	401 Hz	3.80 hr	Burst osc

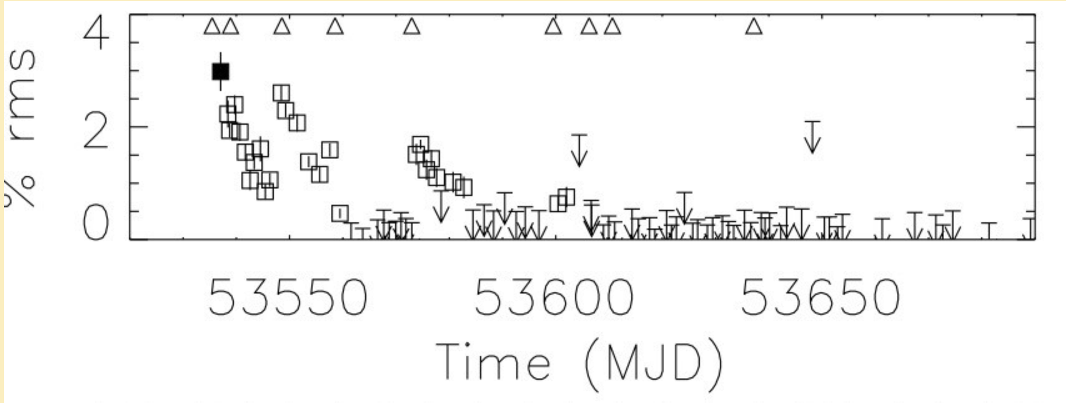
All these sources are transients, only a few seen multiple times. We got better at finding them. Bulge scans helped!

Old problem: Why is it difficult to find accretion-powered millisecond pulsars?
Updated: Why do we only find them in low-accretion-rate LMXB transients?

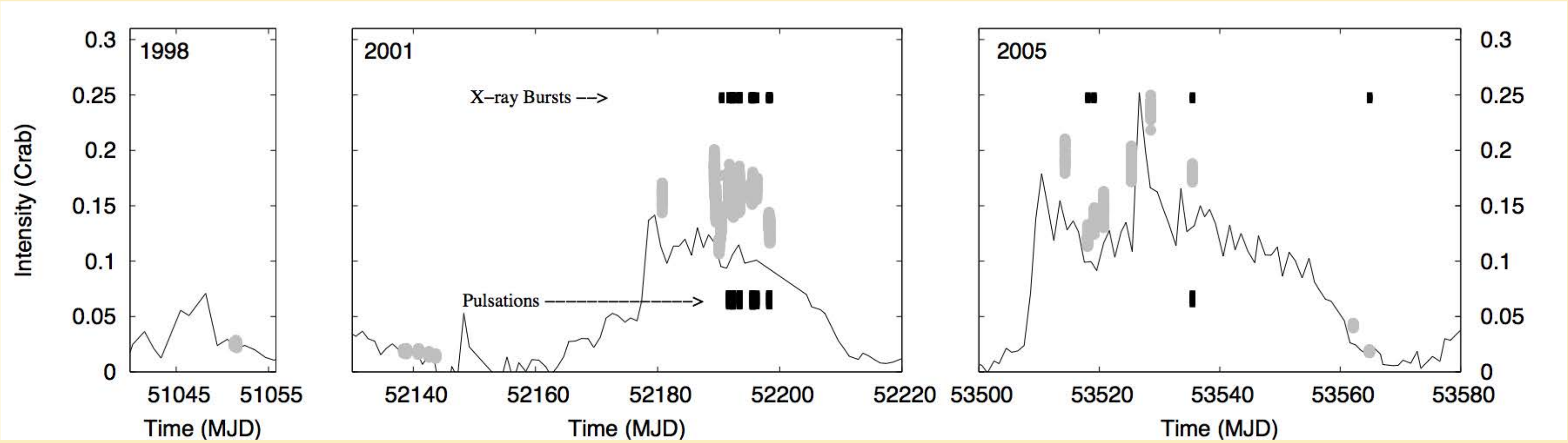
- Orbital Doppler smearing?
    - Many searches using acceleration techniques
    - Detected systems only mildly affected; for same pulsed fraction, should not be serious
- Scattering/obscuration? (Brainerd & Lamb 1987; Kylafis & Phinney 1989)
    - Suggestion that detected pulsars have low optical depths (Titarchuk et al. 2002)
    - More detailed analysis finds no correlation (Gogus et al. 2007). Scattering not the answer.
- Non-magnetic accretion flow?
    - Intrinsically weak magnetic fields? How to reconcile with millisecond radio pulsar population?
    - Screening of magnetic field by accretion? (Cumming, Zwiebel, & Bildsten 2001) Fields only penetrate for very low accretion rates, intrinsic field reemerges when accretion ends.
- Gravitational self-lensing? (Wood, Ftaclas, & Kearney 1988; Meszaros, Riffert, & Berthiaume 1988)
    - Suggestion that detected pulsars, being in transients, are systematically less massive. Higher accreted mass leads to increased self-lensing, suppressing pulsation. (Ozel 2009).
- New issue: Intermittency of pulsations.

“Intermittent” accretion-powered millisecond pulsars

Intermittent pulsar HETE J1900.1-2455 (Galloway et al. 2007): Active outburst for >1 yr, but pulsations only during first few months. Enhanced amplitude shortly after X-ray bursts during that time.



Intermittent pulsar SAX J1748.9-2021 (Altamirano et al. 2007; Gavriil et al. 2007; Patruno et al. 2009). Pulsations detected intermittently during 2 of 3 outbursts. Some correlation with presence of X-ray bursts.



Intermittent pulsar Aql X-1 (Casella et al. 2007): Detected for 150 s out of ~1.5 Ms!!! Are these accretion-powered pulsations or something else?

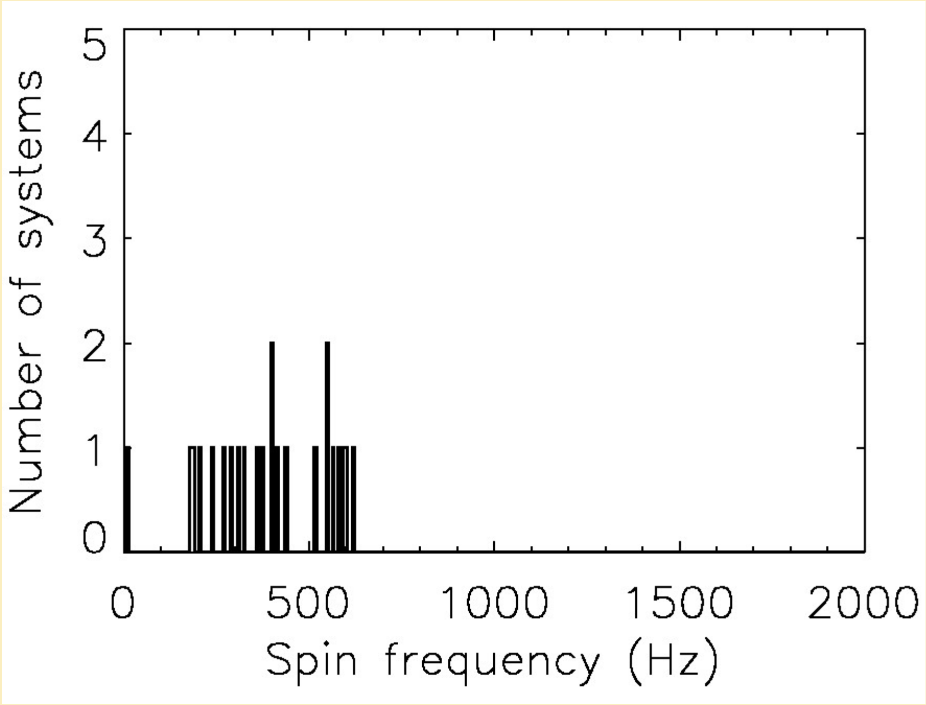
How to explain intermittency in accretion-powered pulsations?

- Must be related to something that changes on short time scales (not orbital smearing or self-lensing)
- Magnetic screening by matter (controlled by short-term accretion rate)? Perhaps in HETE J1900.1-2455, but probably not in SAX J1748.9-2021 given location of pulsations in outburst history.
- Changes in size, shape, and/or location of “hot spot” due to accretion flow instabilities?
    - At small magnetic inclination angles, 3-D MHD simulations suggest that there is a regime of unstable accretion flow such that the X-ray “hot spot” moves around erratically near the magnetic pole (Romanova et al. 2003, 2004, 2008).
    - Also at these small magnetic inclinations, small changes in the location of the hot spot can lead to suppression of observable X-ray pulsations (Lamb et al. 2009).
    - Such behavior might explain the abrupt jumps in pulse phase and changes in pulse shape observed in the short-term X-ray timing of several accretion-powered millisecond pulsars, particularly SAX J1808.4-3658 (Burderi et al. 2006; Hartman et al. 2008, 2009)
- What role does thermonuclear X-ray burst activity play?
- Is the extremely rare Aql X-1 pulsation the same phenomenon, or something different?
- Is the mechanism responsible for intermittency the same reason that all the known accretion-powered millisecond pulsars are in low-accretion-rate transients?

Disk-magnetosphere interaction and accretion torques

- Accretion-induced spin-up torques have been reported in several accretion-powered millisecond pulsars. However, some of these systems show strong, systematic pulse shape variability that can mimic or mask spin frequency changes, or simply make them difficult to measure reliably.
- In SAX J1808.4-3658, there was disagreement between Burderi et al (2006) and Hartman et al. (2008) about whether the data could be reliably interpreted to infer accretion torques, given the pulse shape variability.
- Several models have been proposed to explain the pulse shape variability in this source: Lamb et al. (2009), Poutanen et al. (2009), Kajava et al. (2011).
- Accretion torques have been reported in several other sources. Some of these have well-behaved pulse shapes and some do not:
    - IGR J00291+5934 (Burderi et al. 2007)
    - XTE J1751-305 (Papitto et al. 2008)
    - XTE J1807-294 (Riggio et al. 2008, but see also Patruno et al. 2010)
    - IGR J17511-3057 (Riggio et al. 2011)

Spin distribution of accreting millisecond pulsars



• 27 systems, including both burst oscillation sources and accretion-powered pulsars

• Most objects clustered in the 100-700 Hz range. Cluster is consistent with a uniform distribution.

• One object with slow spin (11 Hz; Terzan 5 X-2 = IGR 17480-2446; Strohmayer & Markwardt 2010, Altamirano et al. 2010). Inconsistent with uniform distribution at 2-sigma level, but arguably drawn from a different population.

• No objects with rapid spin >700 Hz. Compare with expected break-up limit of ~2000 Hz. Assuming emission properties are not spin-dependent, there is no significant selection effect here.

What can we learn from the fast end of the spin distribution?

• **What is the distribution of magnetic field strengths in NS/LMXBs?** The detailed shape of the spin distribution might answer this question, if one can untangle the accretion rate contribution.

• **Is there a minimum magnetic field after sustained accretion?**

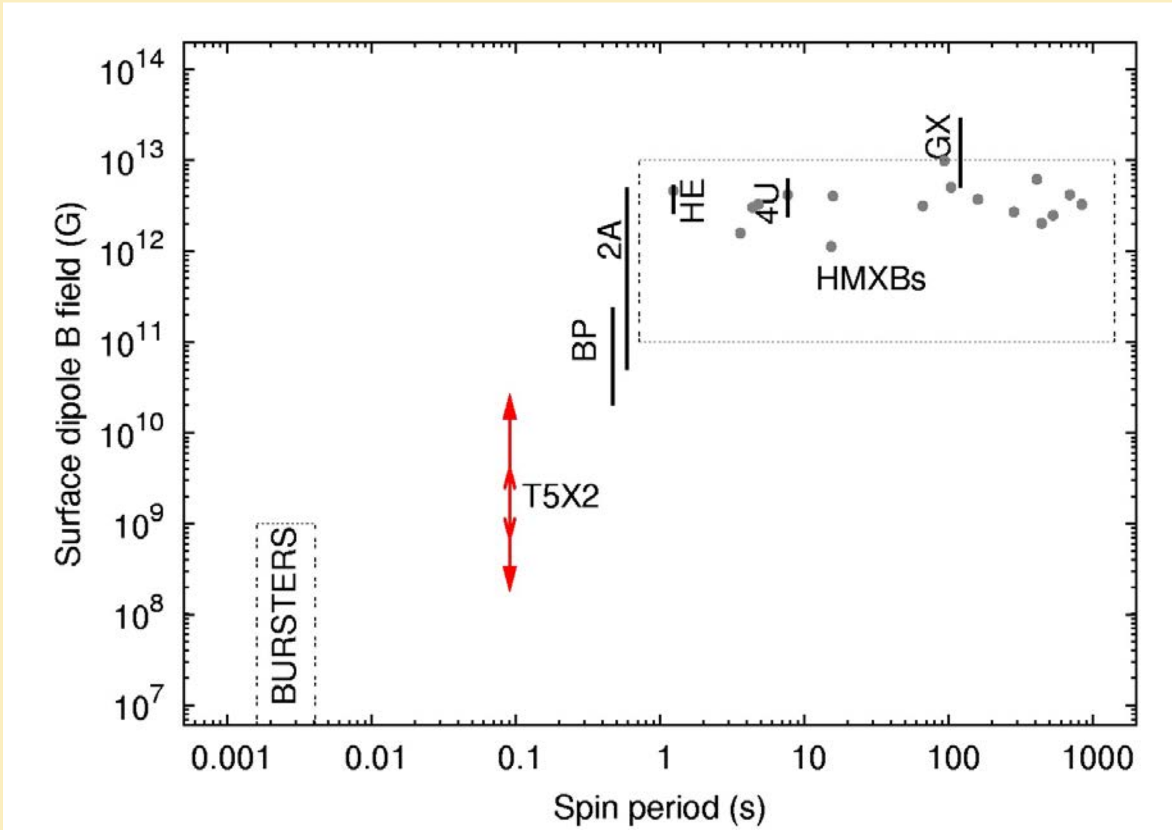
- How far do the fields decay during the recycling process?
- A minimum field could explain the high-spin cutoff.
- Can a minimum field be reconciled with the presence/absence of persistent pulsations? What about magnetic screening by accretion (e.g. Cumming & Bildsten 2000)

• **Are there any submillisecond pulsars?**

- Discovery could significantly constrain NS equation of state
- Are these object rare/non-existent, or are they somehow hidden?

Increasing the sample of accreting millisecond pulsars will help explore these questions.

What about the slow end of the spin distribution?



Linares et al. 2012

• The discovery of the 11 Hz pulsar in Terzan 5 opens up an unexplored regime: the transition region between young slow pulsars and recycled millisecond pulsars.

• How does pulsar recycling and accretion-induced magnetic field decay actually work?

What can we learn from the slow end of the spin distribution?

- **How does accretion-induced field decay work?**
  - What is the decay time scale?
  - How does field strength vary with accreted mass?
  - How much time is spent in the recycling transition region?
  - Are intermediate-field pulsars rare because of short time scale or because they are somehow hidden? Persistent versus transient systems (super-Eddington vs sub-Eddington accretion?)
- **What magnetic field strength is required to suppress type-I bursts?**
  - Magnetic channeling expected to increase local accretion rate, stabilize burning (Joss & Li 1980)
  - Slowly rotating bursters are ideal targets for detection of photospheric absorption lines (alternate approach to neutron star equation of state measurement)

Original RXTE mission proposal: 1980

Launch of RXTE: December 30, 1995

End of RXTE science operations: January 5, 2012

Special thanks to the key people who made RXTE happen and thrive:

- Instrument principal investigators: Jean Swank, Hale Bradt, Rick Rothschild
- "Next generation" who stepped up into leadership: Tod Strohmayer, Al Levine, Ron Remillard
- Experiment data system: Ed Morgan
- TOO masters: Evan Smith, Divya Pereira, and the RXTE operations team at GSFC
- Articulating the pre-launch science case: Fred Lamb
- Much larger group of scientists, students, engineers, and technicians at GSFC, MIT, and UCSD who made everything work