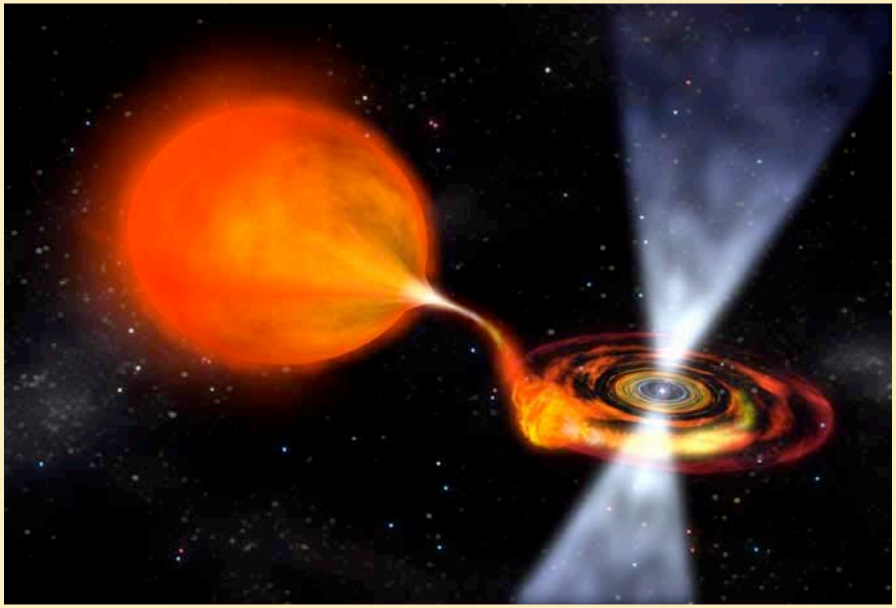

Illustration of a low-mass X-ray binary (LMXB)

An Overview of X-ray Timing of Accreting Neutron Stars (with Implications for Gravitational Wave Searches)

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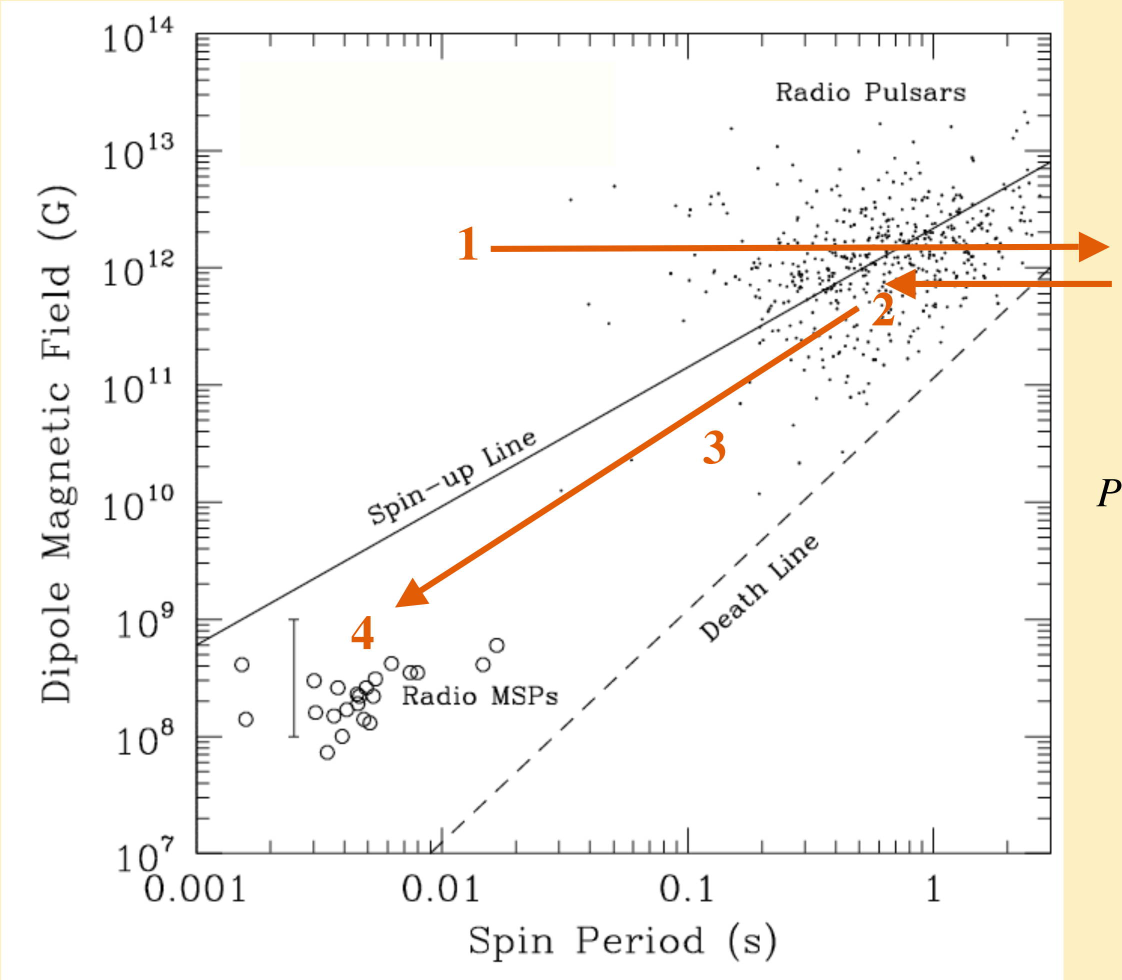
Monash:	Duncan K. Galloway
Amsterdam:	Alessandro Patruno, Michiel van der Klis, Rudy Wijnands
NASA/GSFC:	Craig B. Markwardt
NRL:	Paul S. Ray

Life History of Pulsars: Spin and Magnetic Evolution



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

2 If in binary, then companion may eventually fill Roche lobe. Accretion spins up pulsar to equilibrium spin period

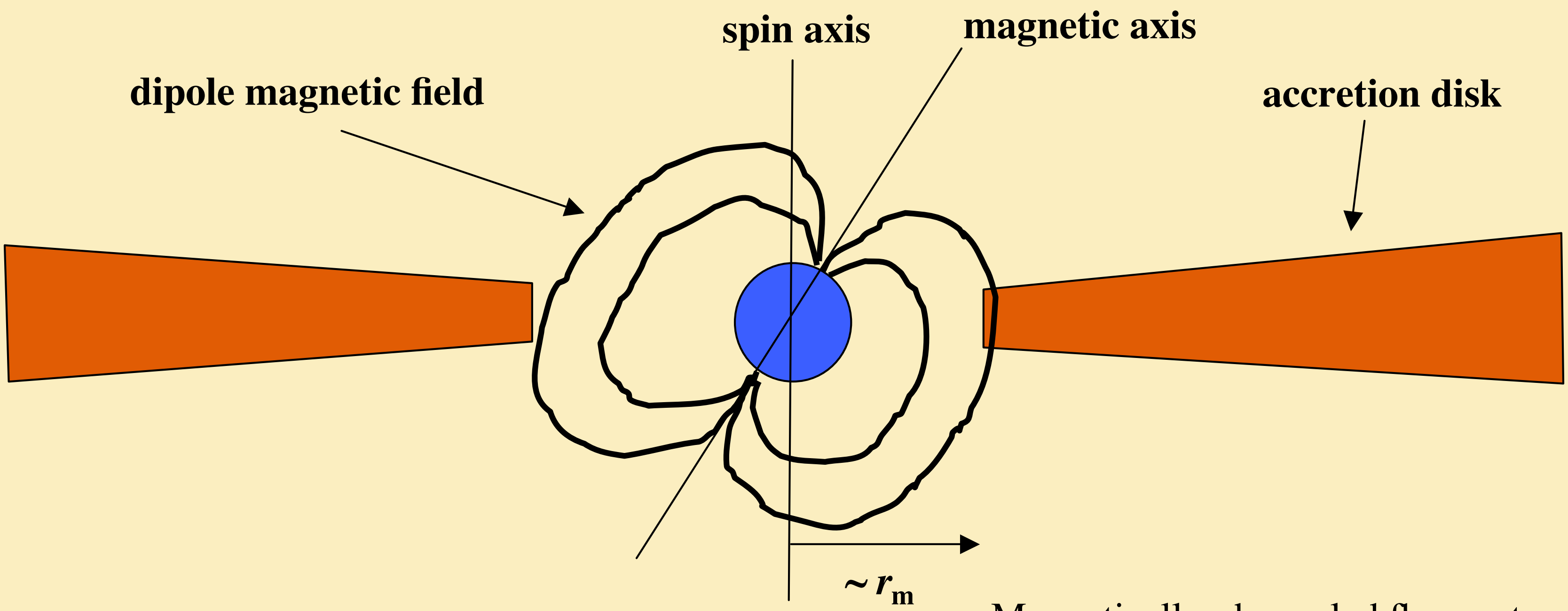
$$P_{\rm eq} \approx 1\ {\rm s} \left(\frac{B}{10^{12}\ {\rm G}}\right)^{6/7} \left(\frac{\dot{M}}{10^{-9}\, M_{\rm Sun}\,/{\rm yr}}\right)^{-3/7}$$

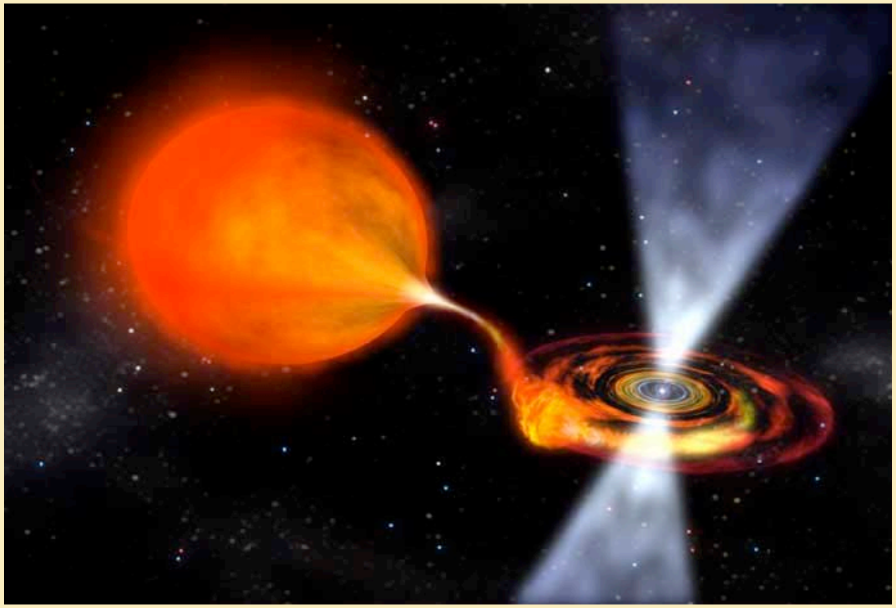
3 Sustained accretion (~10^{9} yr) attenuates pulsar magnetic field to B~10^{8} G, leading to equilibrium spin P~few ms

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

For accreting pulsars, X-ray observations can measure spin by tracing rotating “hot spots”. If these X-ray pulsations persist for long enough, can also measure binary orbital parameters.

Accretion-Powered X-Ray Pulsars





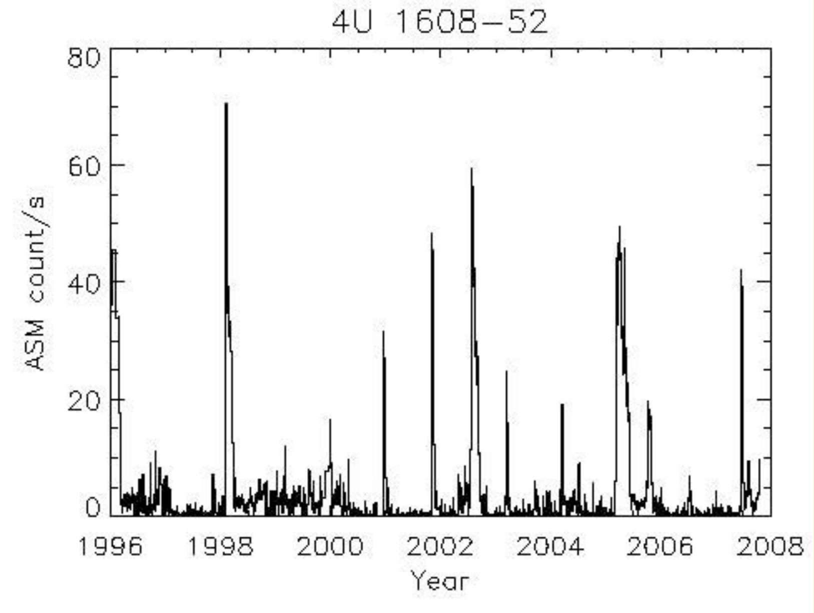
- Magnetically-channeled flow onto polar caps, hits at $\sim 0.1\,c$. (Requires $B > 10^8$ G)
- Gravitational potential energy released as X-rays,

$$L = \dot{M}\left(\frac{GM}{R}\right)$$

- Misaligned magnetic dipole axis: pulsations at spin period from X-ray hot spots at poles.
- Accretion adds mass and angular momentum to NS (measure torque)

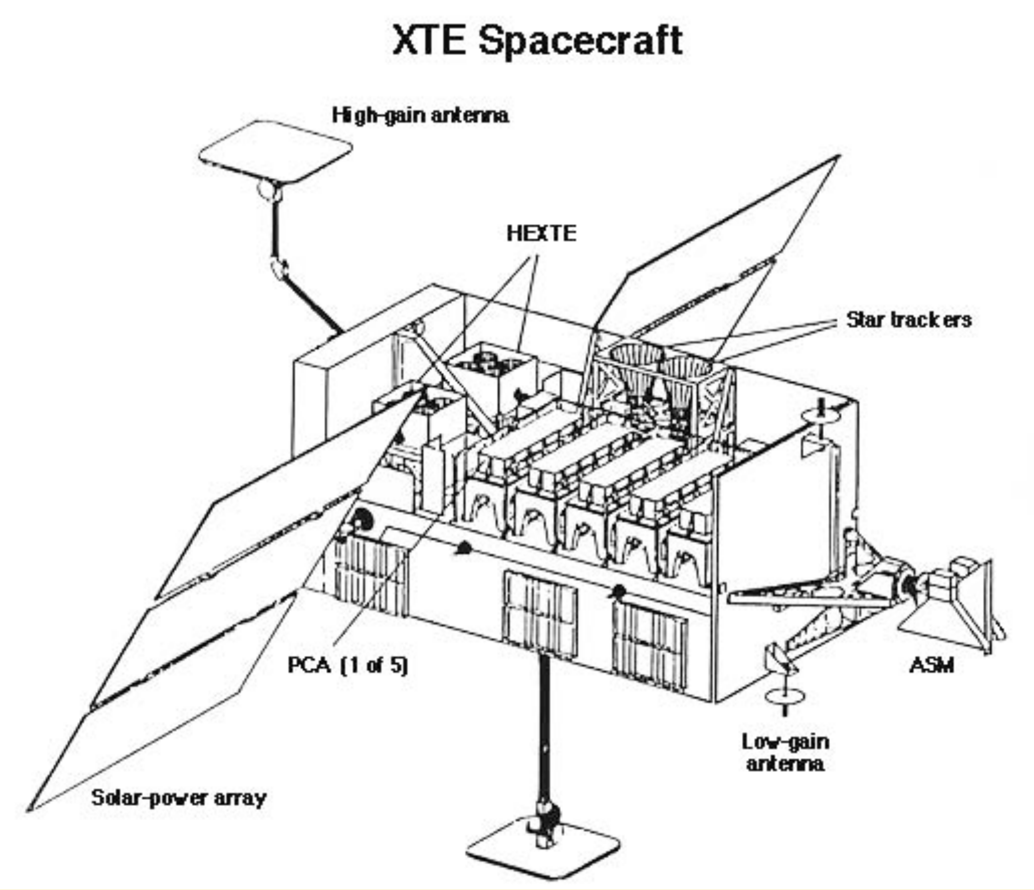
X-Ray Sources: Persistent versus Transient

- Low-mass X-ray binaries with low accretion rates are subject to an ionization instability in their accretion disk. This leads to episodic accretion: **X-ray transients**



- Duty cycle is low: X-ray transients lie dormant for months or years, then become active for a few days or weeks when accretion disk instability is triggered.
- All known accretion-powered millisecond pulsars are X-ray transients. Cannot continuously monitor spin and orbital evolution in these systems.

NASA Rossi X-Ray Timing Explorer (RXTE)



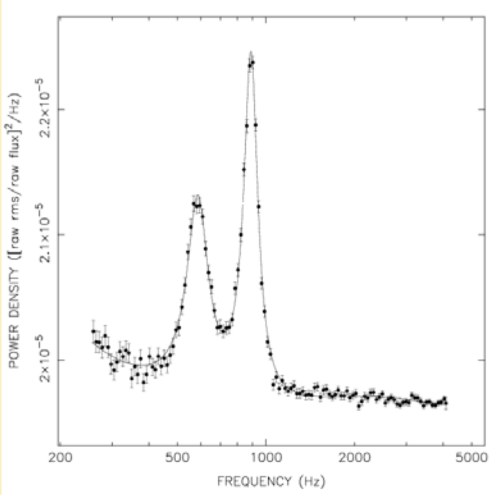
- Built by NASA/GSFC, MIT, and UC San Diego
- Launched Dec. 1995, will operate until at least 2009
- Main instrument: 6000 cm^2 proportional counter array (PCA), 2-60 keV, μs time resolution
- All-sky monitor (ASM) for activity alerts on transients
- Rapid repointing possible (X-ray transients)
- Other major X-ray missions (e.g., Chandra, XMM-Newton) incapable of msec timing of bright X-ray binaries

Millisecond Variability in Low-Mass X-Ray Binaries

Three distinct types of rapid variability identified by the Rossi X-Ray Timing Explorer:

1. Kilohertz quasi-periodic oscillations (kHz QPOs)
2. X-ray burst oscillations
3. “Bona fide” accretion-powered millisecond X-ray pulsars

1



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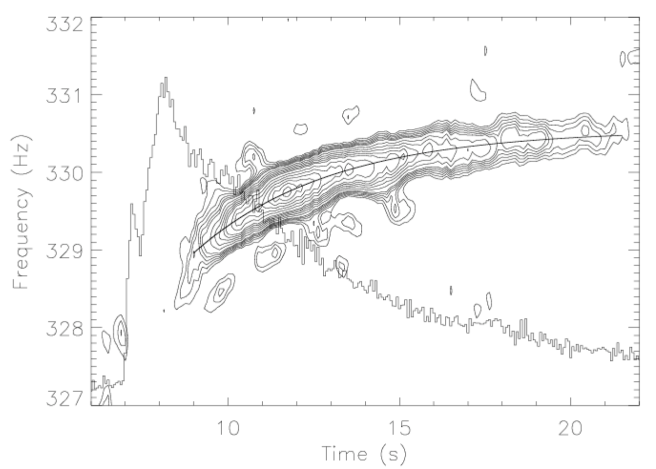

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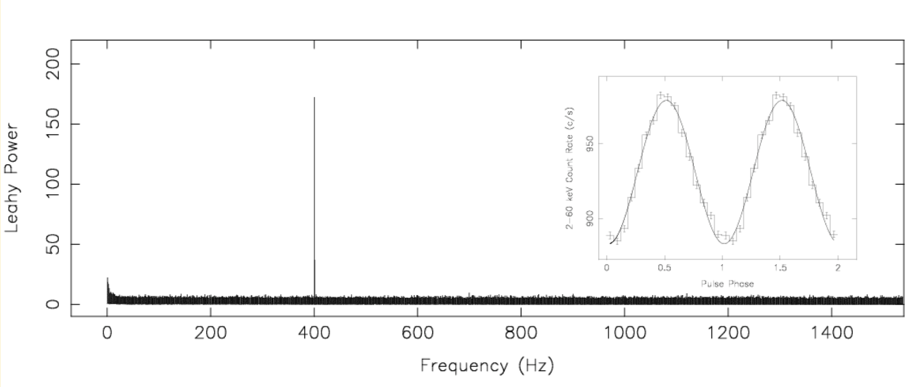
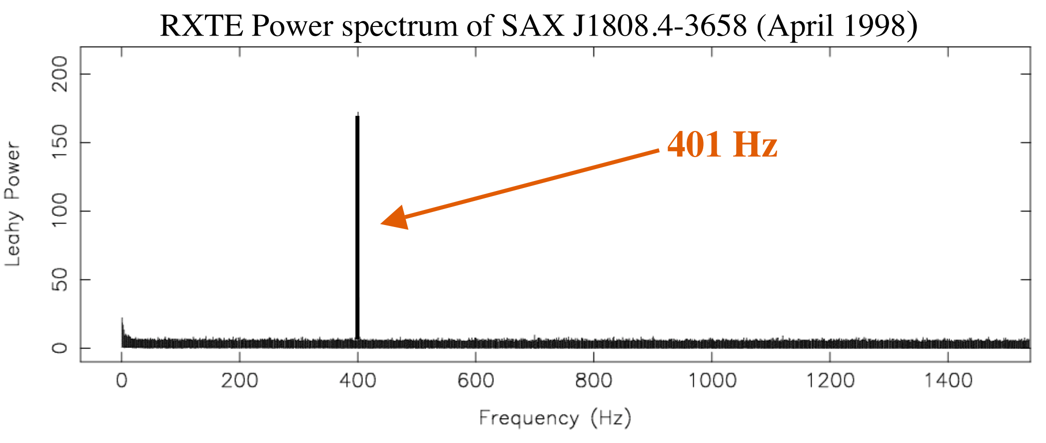
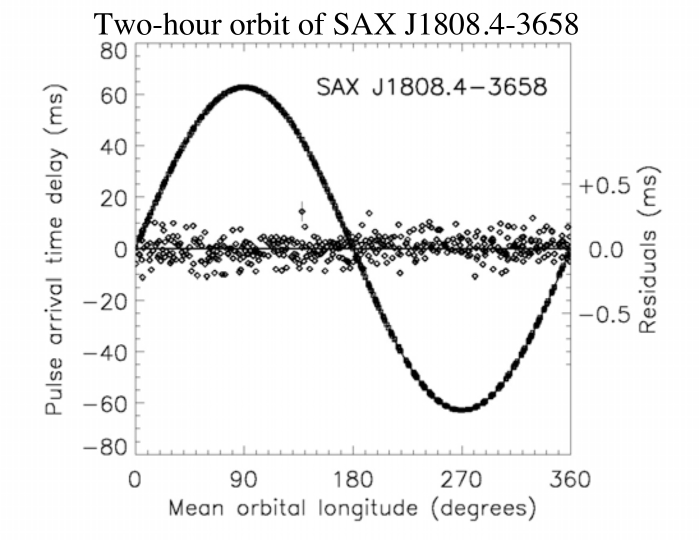


“Bona Fide” Accretion-Powered Millisecond X-Ray Pulsars


RXTE Power spectrum of SAX J1808.4-3658 (April 1998)

Wijnands & van der Klis 1998

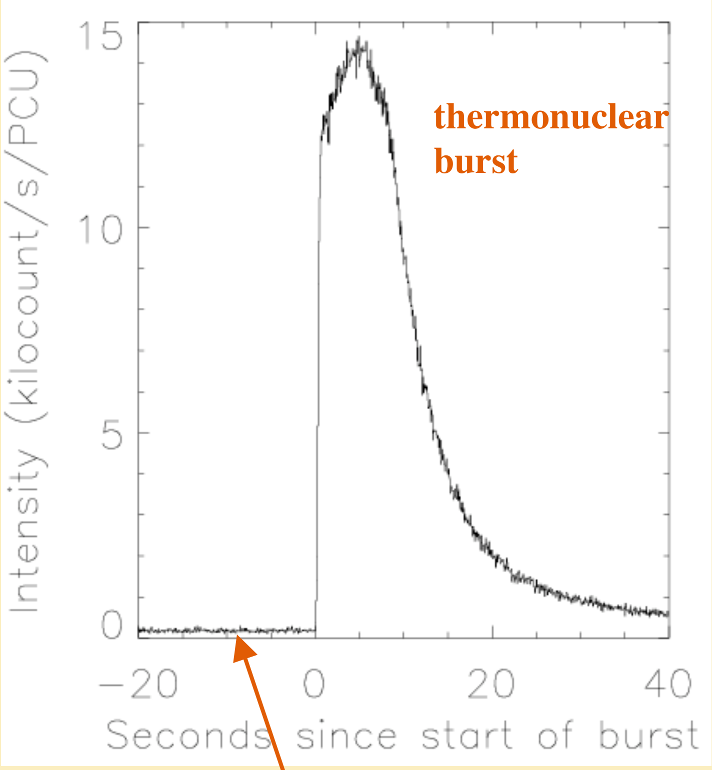

Two-hour orbit of SAX J1808.4-3658

Chakrabarty & Morgan 1998

- Can measure spin and orbital parameters.
- 10 known examples, generally all X-ray transients with low mass accretion rates.
- In an X-ray transient, spin/orbital parameters can only be measured during a transient outburst (typically lasting a few weeks and separated by years). Of the 10 known examples, only ONE has been observed in multiple outbursts. (The others all evidently have long recurrence times.)

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

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



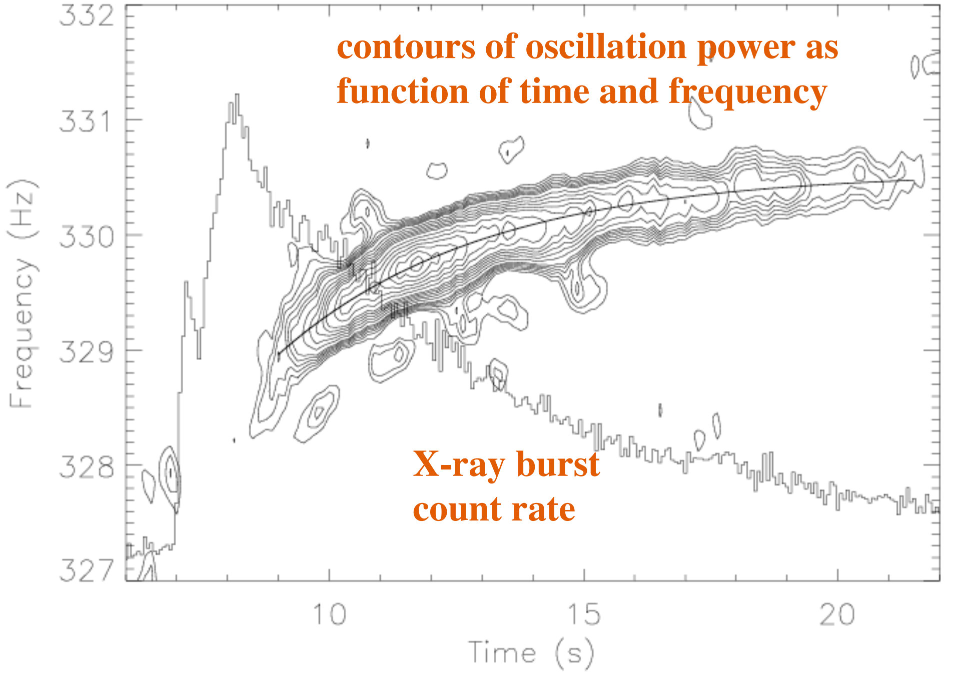
thermonuclear burst

quiescent emission due to accretion

- 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)

- Burst oscillations reveal spin, but not possible to measure orbital parameters or spin evolution, since bursts only last a few tens of seconds.

4U 1702-43 (Strohmayer & Markwardt 1999)

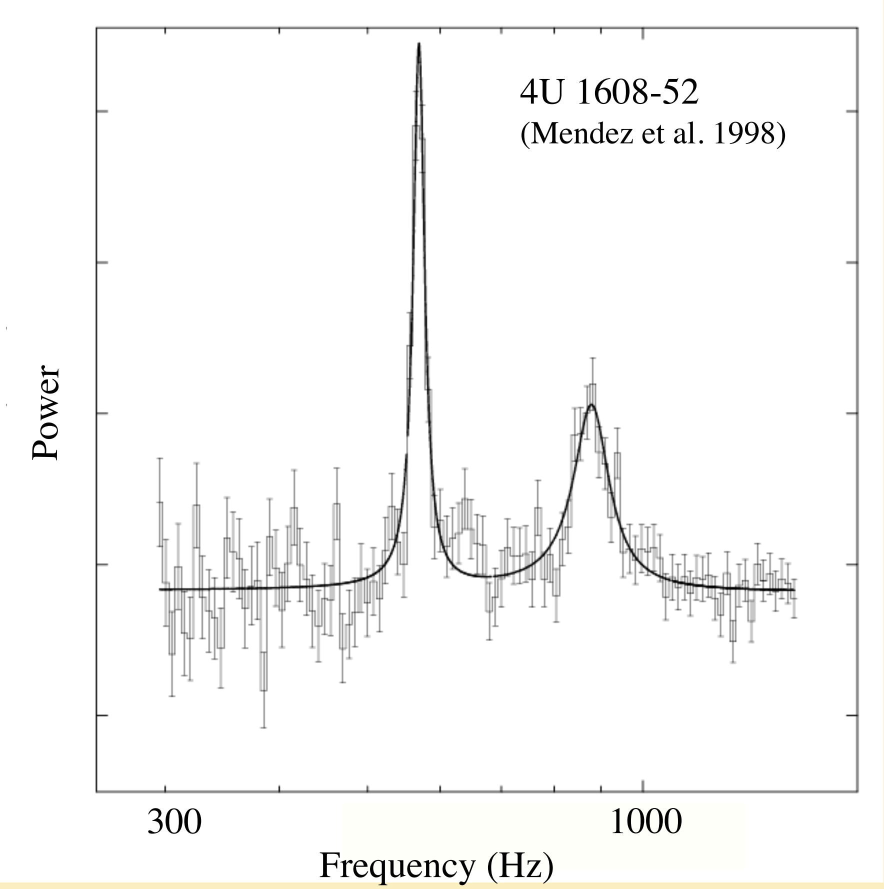


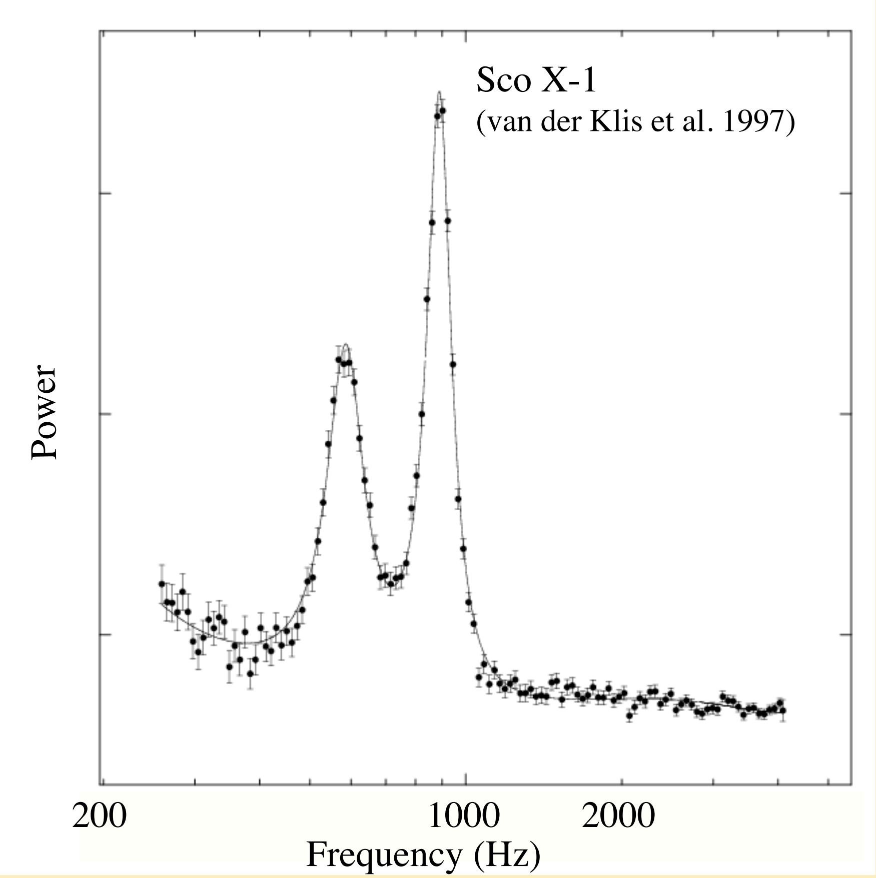
contours of oscillation power as function of time and frequency

X-ray burst count rate

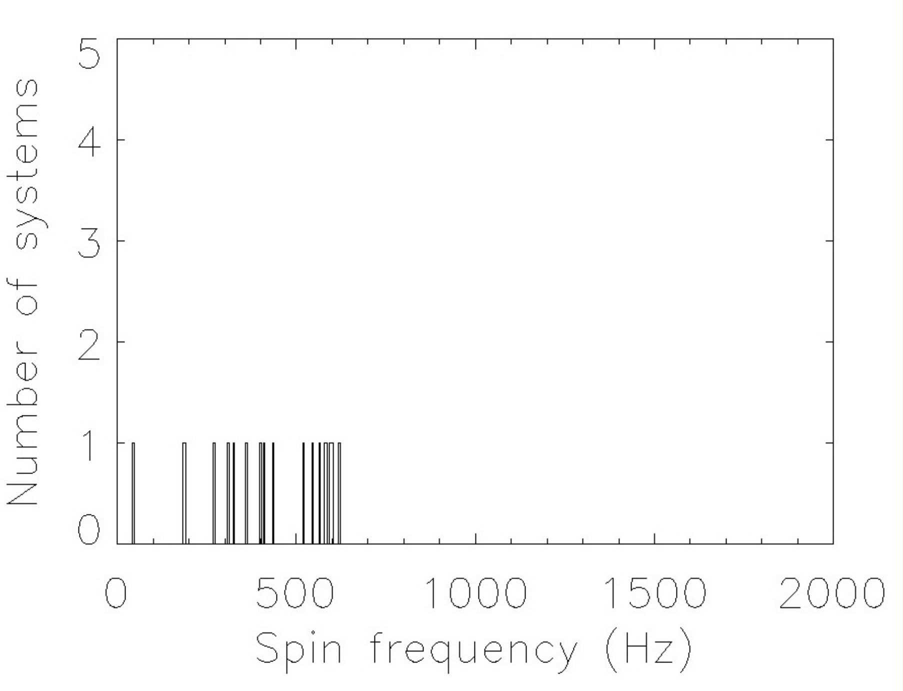
Kilohertz quasi-periodic oscillations (kHz QPOs)

- QPO pairs with roughly constant frequency separation (~300 Hz). QPO frequencies drift by hundreds of Hz as X-ray flux changes (200-1200 Hz). Separation frequency ($\Delta\nu$) is a characteristic of a given source
- Separation frequency $\approx \nu_{spin}$ or $\approx (\nu_{spin}/2)$ for cases where spin known (Fast vs Slow). Not usable as a precise spin tracer, but may give clue to spin range. However, connection to spin has recently been challenged as a statistical artifact (Mendez & Belloni 2007).
- Seen in over 20 LMXBs. Believed to originate in accretion disk. Mechanism?





Distribution of Neutron Star Spins in Low-Mass X-Ray Binaries



Chakrabarty 2005

- We find that $\nu_{high} < 730$ Hz (95% confidence) (Chakrabarty et al. 2003)

- Recycled pulsars evidently have a maximum spin frequency that is well below the breakup frequency for most NS equations of state. Fastest known radio pulsar is PSR J1748-2446ad (Ter 5) at 716 Hz.

- Detailed shape of distribution still unclear. (Sharp cutoff? Pileup? Falloff?) Need more systems!

- Submillisecond pulsars evidently relatively rare, if they exist.

- Recent report of 1122 Hz burst oscillation in XTE J1739-285 (Kaaret et al. 2007), but statistical significance questionable (actual significance is only ~3σ). Remains an interesting candidate.

How to explain cutoff in spin distribution?

1. Equilibrium spin not yet reached?
   - Unlikely, since spin-up time scale is short compared to X-ray lifetime

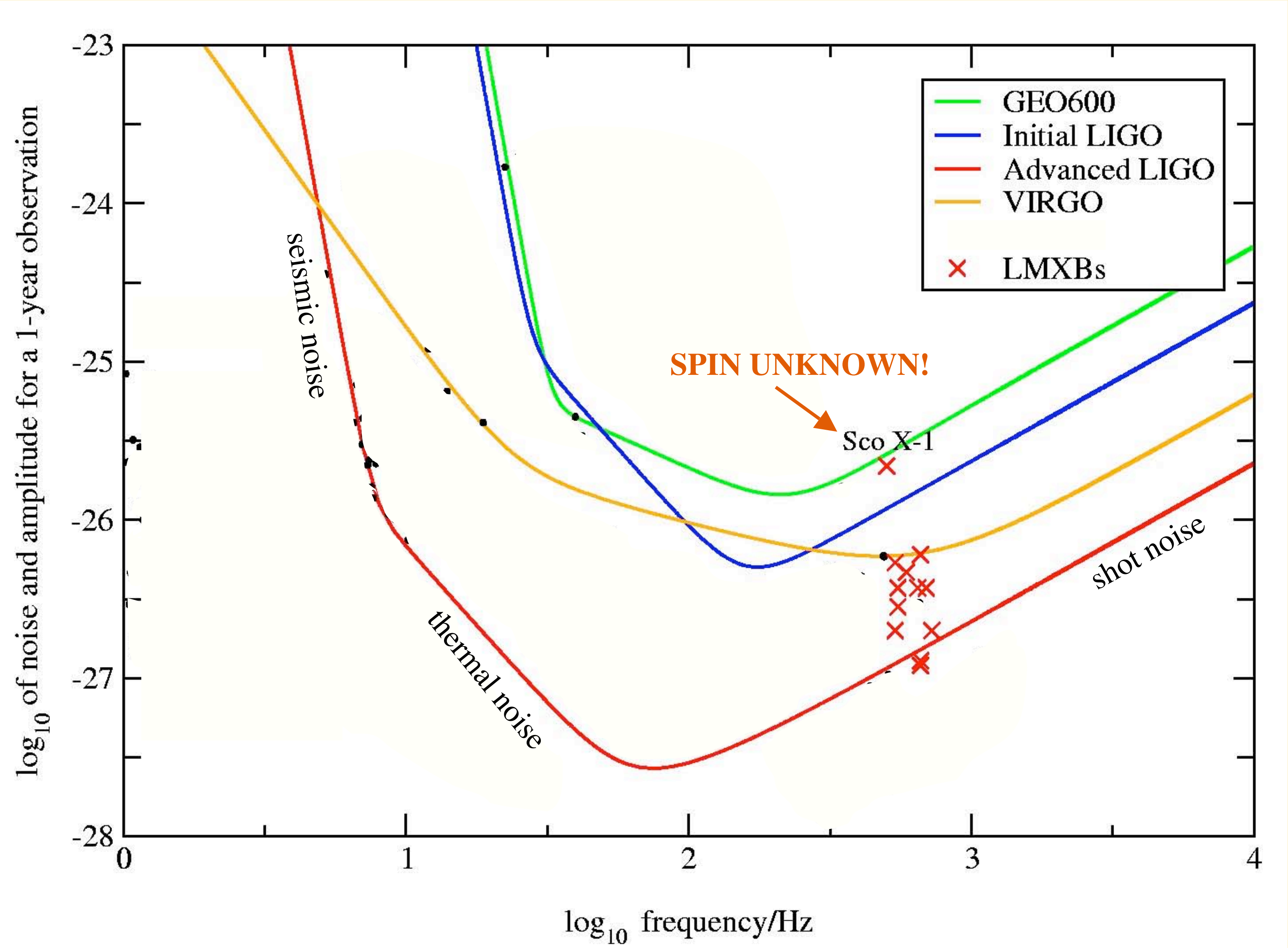
2. Low breakup frequency for NSs?
   - Most NS equations of state are inconsistent with this idea.

3. Magnetic spin equilibrium? (e.g. Ghosh & Lamb 1979; Lamb & Yu 2005)
   - Possible, but requires narrow range of magnetic field strengths. Why no pulsations in most sources?

4. Accretion torque balanced by gravitational radiation? (Wagoner 1984; Bildsten 1998)
   - Gravitational wave torque $\propto \Omega^5$, from any of several models:
     - r-mode instability (Wagoner 1984; Andersson et al. 1999)
     - Accretion-induced crustal quadrupole (Bildsten 1998; Ushomirsky et al. 2000)
     - Large (internal) toroidal magnetic fields (Cutler 2002)
     - Magnetically confined "mountains" (Melatos & Payne 2005)
   - Strain of $h \sim 10^{-26}$ for brightest LMXBs (Bildsten 1998). Use long integrations with Advanced LIGO/VIRGO to search for persistent GW emission from these systems? (How good a timing ephemeris is needed? Are contemporaneous X-ray measurements required?)

Sensitivity of Current and Future Gravitational Wave Observatories (old plot)

(my apologies for not having more recent sensitivity curves for Advanced LIGO/VIRGO)



Adapted from D. Ian Jones (2002, *Class. Quant. Grav.*, **19**, 1255)
University of Southampton, UK

What do we know about the spin frequency evolution?

This will affect the ability to do long integrations for pulsar GW searches.

- For a pure accretion torque (no other torque contribution) near magnetic spin equilibrium,

$$\dot{\nu} = 4 \times 10^{-14} \left(\frac{\dot{M}}{0.01\, \dot{M}_{\rm Edd}} \right) \left(\frac{\nu}{600\ {\rm Hz}} \right)^{-1/3}\ {\rm Hz\ s^{-1}}$$

where we have scaled to an accretion rate typical for X-ray transient outbursts.

Assuming steady accretion, this corresponds to a decoherence time of

$$\tau = \frac{1}{\sqrt{\dot{\nu}}} \approx 60 \left(\frac{\dot{M}}{0.01\, \dot{M}_{\rm Edd}} \right)^{-1/2} \left(\frac{\nu}{600\ {\rm Hz}} \right)^{-1/6}\ {\rm days}$$

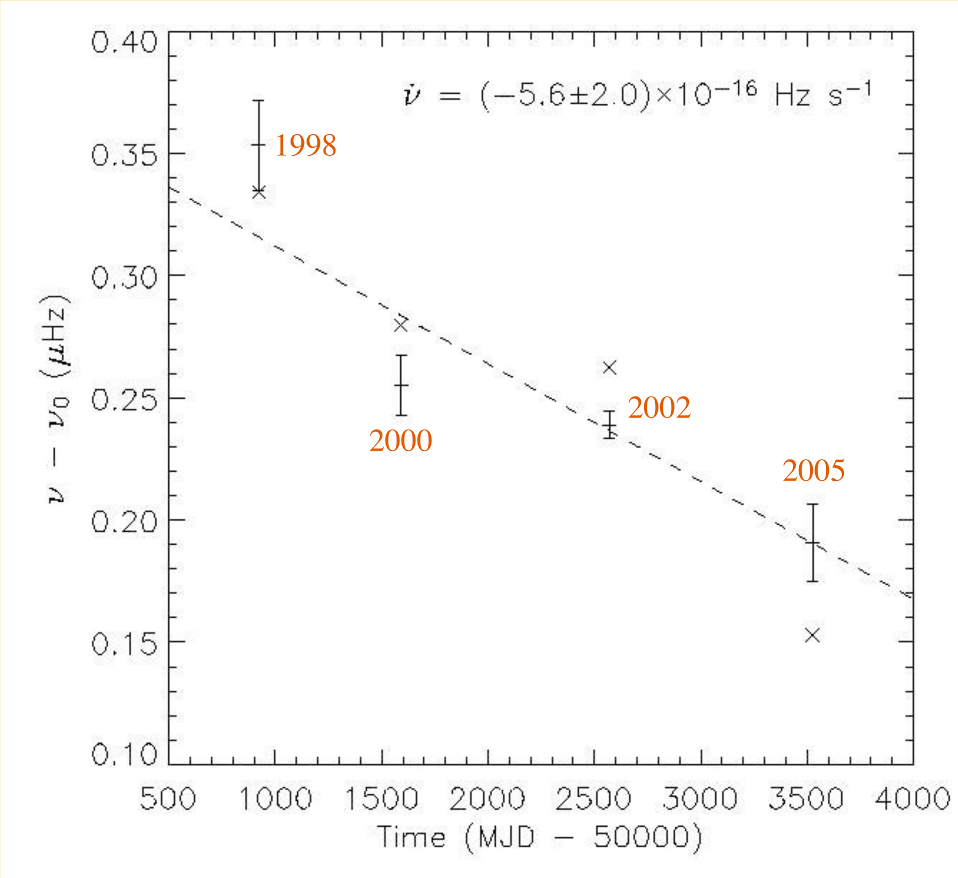
For Sco X-1 (the brightest persistent X-ray binary), the mean accretion rate is ~50% Eddington, corresponding to a decoherence time of only ~10 days. This will complicate long integrations.

- Note that in the X-ray transients, there is only a significant accretion torque during the (short) outbursts. Thus, the decoherence time may be considerably longer for these systems.
- It would be interesting to know how the spin evolves during X-ray quiescence, when accretion is shut off.

Long-Term Spindown of the Accretion-Powered Millisecond Pulsar SAX J1808.4-3658

This spindown is not due to accretion torques during outbursts, but is occurring between outbursts. The decoherence time is ~1 year, which is good news for long integrations.

Hartman et al. (2007)



Magnetic dipole spindown?

- In the absence of accretion, this should always be present at some level.
- Requires surface dipole field $B < 1.5\times10^8$ G for consistency with measured spindown
- For comparison, presence of accretion-powered pulsations over observed outburst flux range implies B in range $(0.4 - 12)\times10^8$ G

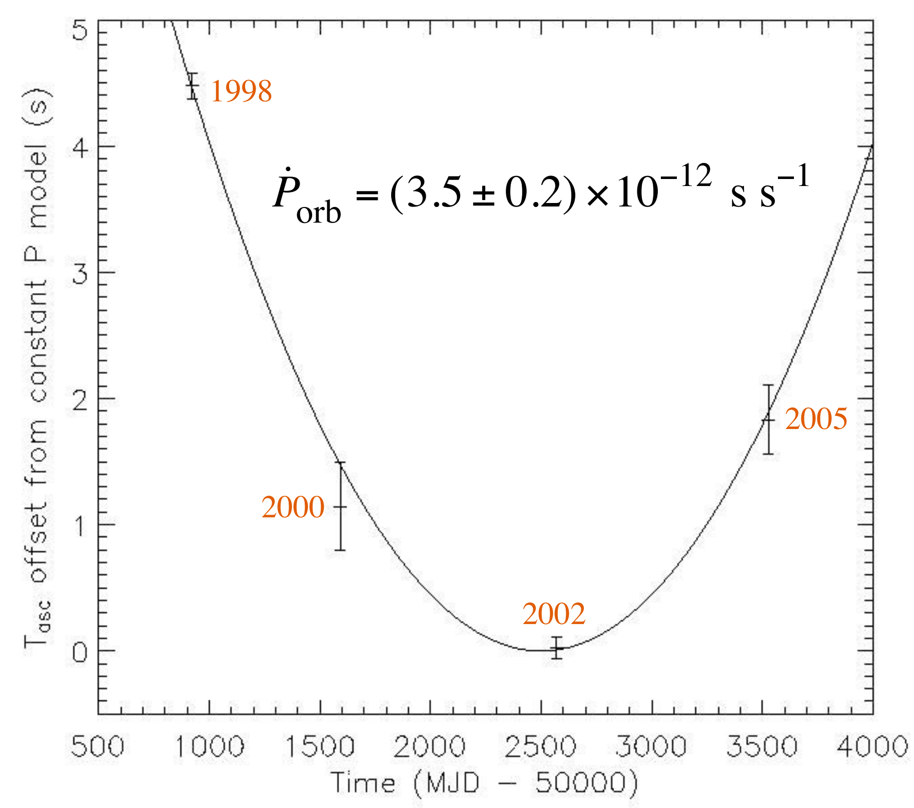
Gravitational wave spindown?

- Requires mass quadrupole moment $Q < 4.4\times10^{36}$ g cm^2 (= 10^{-8} I) for consistency with measured spindown

Note that magnetic dipole spindown with *expected* field strength easily explains data -- gravitational wave torque not required for this 401 Hz system. (However, given Ω^5 torque dependence, GWs could easily still play an important role at ~700 Hz. Measure for faster system?) Might expect X-ray pulsars to become active radio pulsars during X-ray quiescence -- continuous monitoring?

Orbital Evolution of the Accretion-Powered Millisecond Pulsar SAX J1808.4-3658

Hartman et al. 2007. (also Di Salvo et al. 2007)



$$\dot{P}_{\text{orb}} = (3.5 \pm 0.2) \times 10^{-12}\ \text{s s}^{-1}$$

- We expect orbital period to evolve on a 3 Gyr timescale due to mass transfer and angular momentum losses. Measured value is an order of magnitude faster! Explanation not clear.

- Interesting comparison: Some “black widow” radio pulsar binaries have large, varying orbital period derivatives that are quasi-cyclic on decade timescale (Arzoumanian et al. 1994; Doroshenko et al. 2001). Many similarities to this system.

- Unexpectedly large orbital period derivatives have been measured in other low-mass X-ray binaries as well (4U 1820-30, EXO 0748-676, 4U 1822-371).

- Large (and possibly variable) orbital period evolution will complicate long integrations for gravitational wave searches.

Prospects for Contemporaneous X-ray Timing in the Advance LIGO/VIRGO Era

- RXTE, operating since 1995, is currently scheduled to be shut off in mid-2009. This schedule will be revisited during the upcoming NASA Senior Review in March 2008.

- No other currently operating X-ray missions are capable of providing millisecond X-ray timing measurements of accreting neutron stars.

- India plans to launch ASTROSAT, a mission which includes X-ray timing and monitoring capability comparable to RXTE. Currently projected for 2009 launch, although schedule has evidently been slipping at roughly 1 yr/yr.

- Planned ESA mission XEUS will include X-ray timing capability. However, mission is not optimized for bright sources or rapid response to transients, so utility for providing regular pulsar monitoring unclear. Currently projected for 2018 launch.

- A NASA mission concept study for an RXTE follow-up mission has recently been proposed by MIT, NASA/GSFC, and NRL. The Advanced X-ray Timing Array (AXTAR) would have an order of magnitude better sensitivity than RXTE and would remain optimized for rapid follow-up of bright X-ray transients with submillisecond timing. Any such mission is a decade away.

The propsects for X-ray timing in the near-term future are very uncertain.

Summary

- Accreting neutron stars in low-mass X-ray binaries are attractive candidates for GW searches. Although their predicted GW strain is weak, they are continuous sources.
- There is X-ray evidence that pulsars with ~700 Hz spin may be the most promising targets. Gravitational wave emission is demonstrably not significant at 400 Hz.
- The most luminous LMXBs do not have precisely known spin or orbital parameters.
- The most luminous LMXB (Sco X-1) has a decoherence time of only ~10 days.
- The X-ray transient millisecond pulsars have decoherence times of order ~1 year.
- Orbital evolution of LMXBs may be significant and variable.
- The most luminous LMXBs do not have precisely known spins or orbits
- Continuous X-ray timing of most LMXBs not possible
- Long-term programmatic prospects for X-ray timing are uncertain

Recent reference:

- Hartman et al. 2008, ApJ, in press (arXiv:0708.0211)