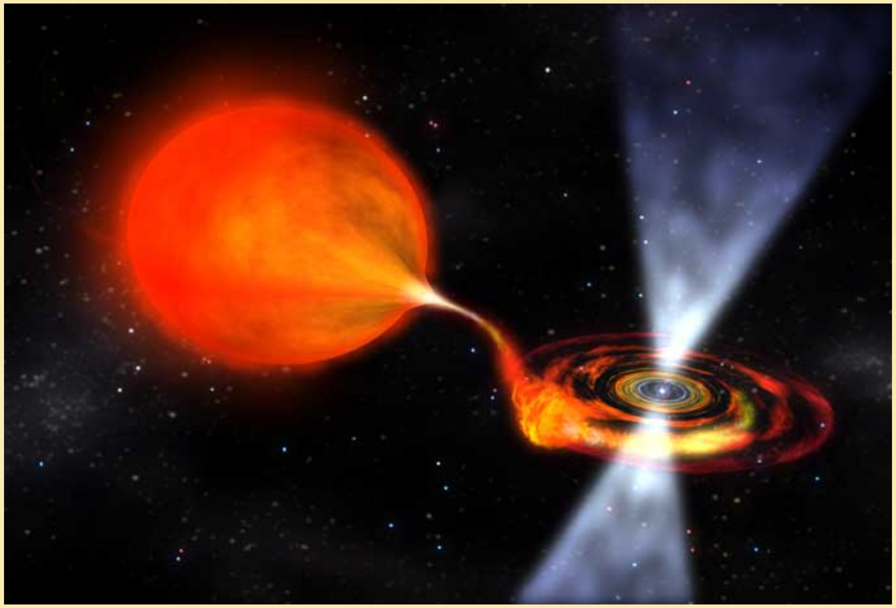
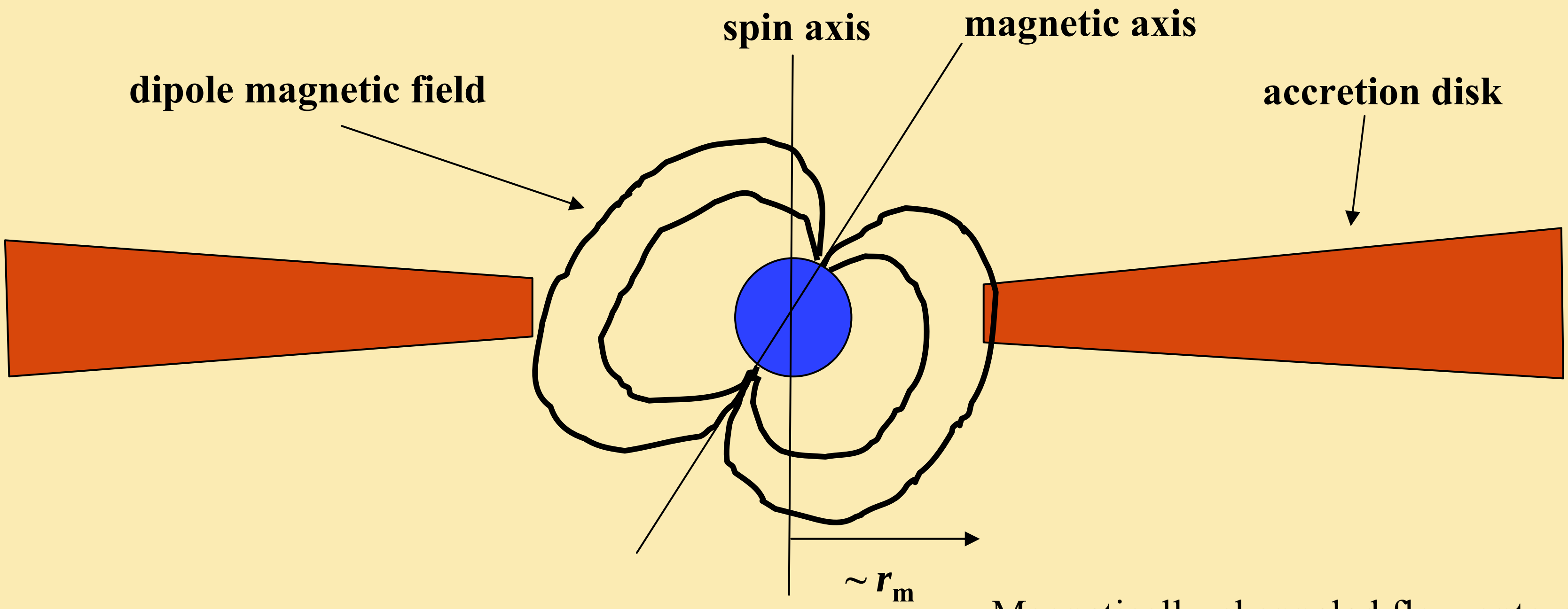
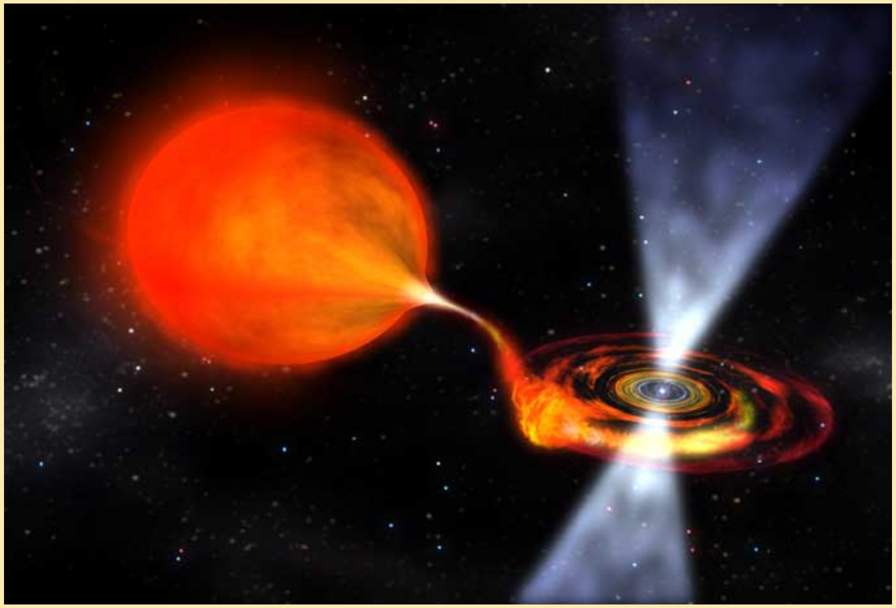


Pulsars in Low-Mass X-Ray Binaries

Deepto Chakrabarty
Massachusetts Institute of Technology

Accretion-Powered X-Ray Pulsars



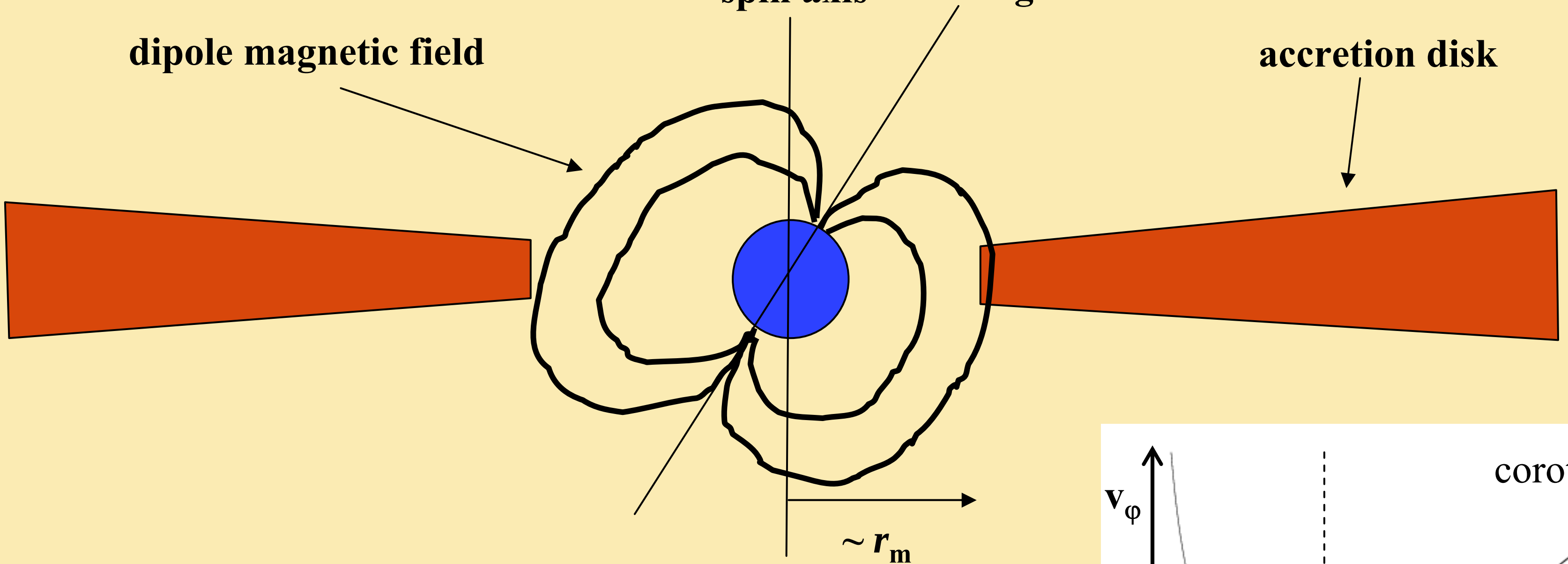


- Magnetically-channeled flow onto polar caps, hits at ~0.1c.
- Gravitational potential energy released as X-rays,

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

- 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)

Accretion Torques on X-Ray Pulsars



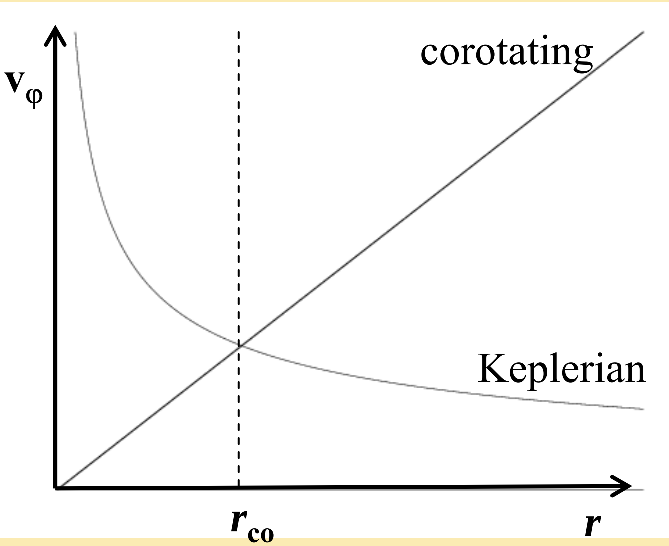
spin axis

magnetic axis

dipole magnetic field

accretion disk

$\sim \boldsymbol{r}_{\mathbf{m}}$



Important length scales:

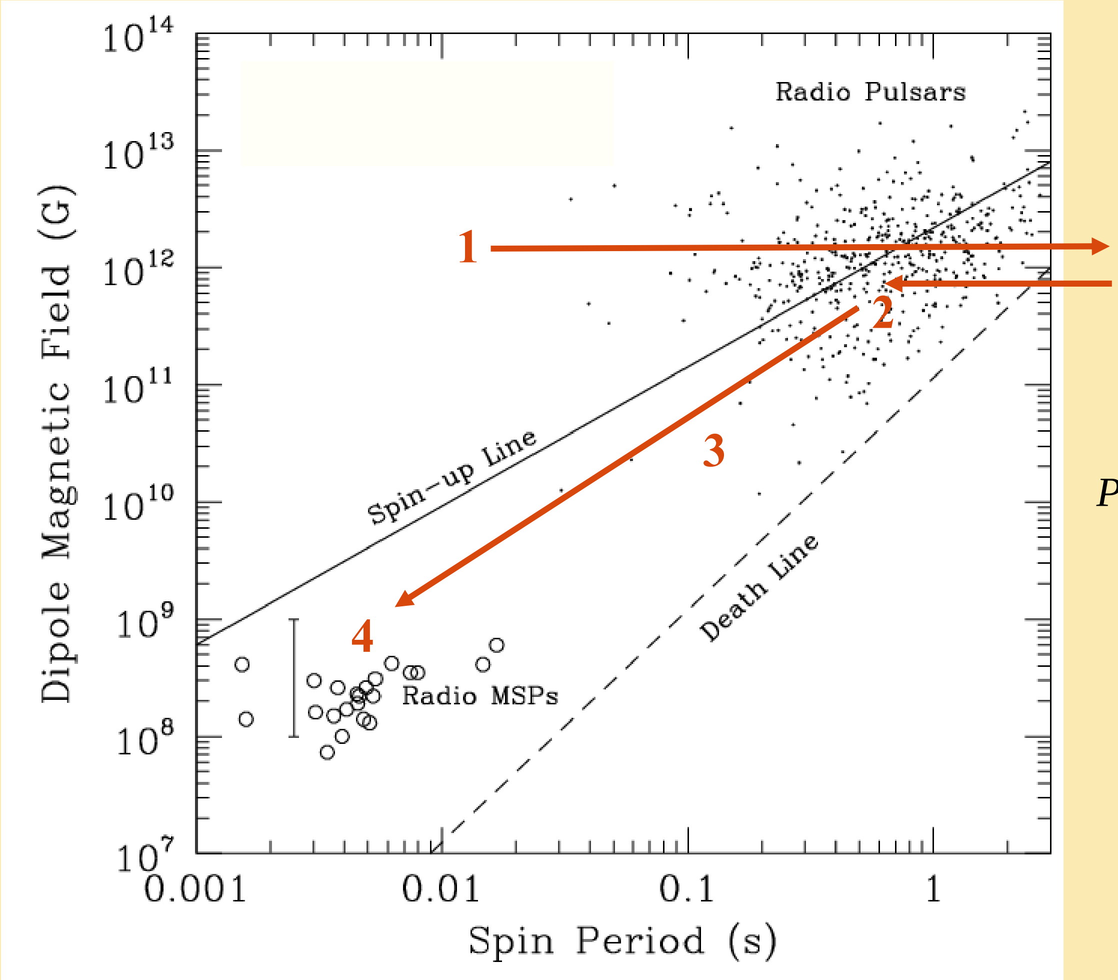
r_m = magnetospheric radius, where $\dfrac{B^2(r_m)}{8\pi} \sim \rho\, v^2(r_m)$

r_{co} = corotation radius, where $\Omega_{kep}(r_{co}) = \Omega_{rot}$

Characteristic torque: $N_0 = \dot{M}\sqrt{GMr_{co}}$

Equilibrium spin period ($r_m \approx r_{co}$): $P_{eq} \approx 1\ \mathrm{s}\left(\dfrac{B}{10^{12}\ \mathrm{G}}\right)^{6/7}\left(\dfrac{\dot{M}}{10^{-9}\, M_{Sun}/\mathrm{yr}}\right)^{-3/7}$

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

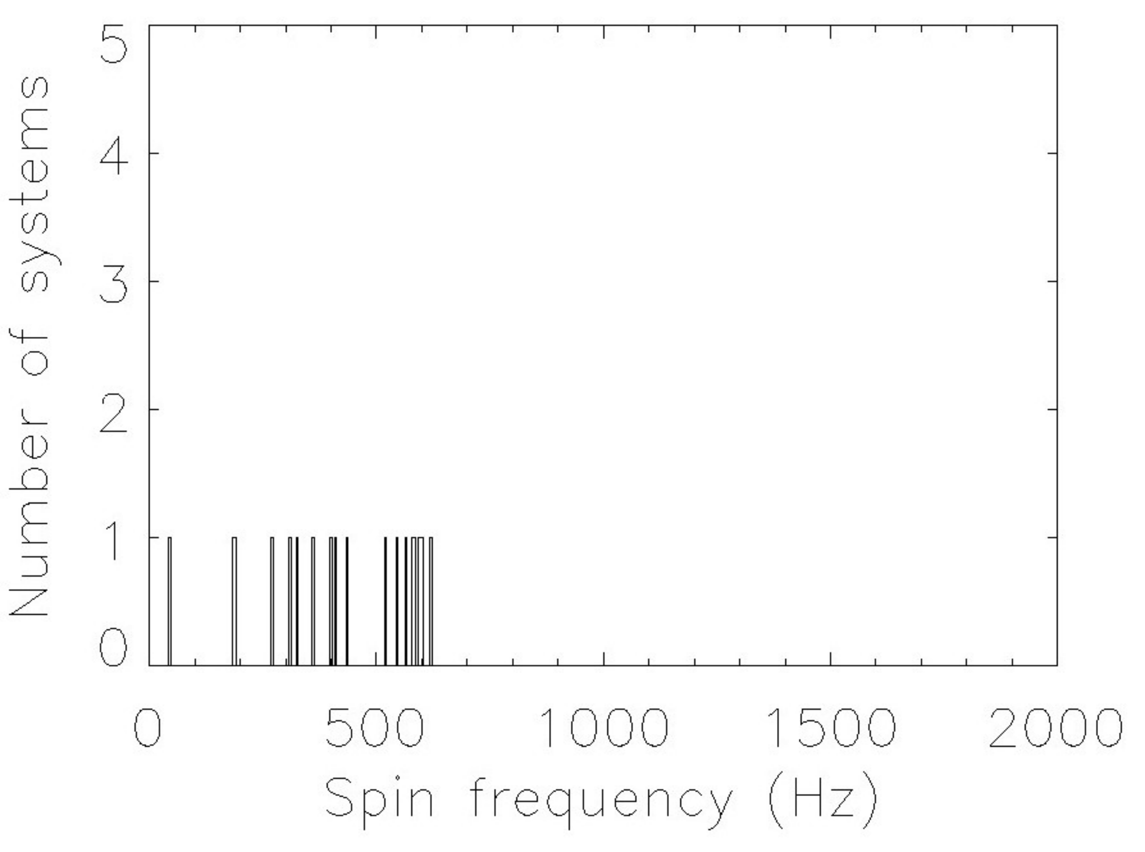
$$P_{\mathrm{eq}} \approx 1\ \mathrm{s} \left(\frac{B}{10^{12}\ \mathrm{G}}\right)^{6/7} \left(\frac{\dot{M}}{10^{-9}\ M_{\mathrm{Sun}}/\mathrm{yr}}\right)^{-3/7}$$

3. Sustained accretion (~10^{9} yr) attenuates pulsar magnetic field to B~10^{8} G, leading to equilibrium spin P~few ms (Not directly observed yet!)

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

This implies a step “3.5”: **millisecond X-ray pulsar** while accretion still active.

Distribution of Burst Oscillation Frequencies



Chakrabarty et al. 2003

- We find that $\nu_{high} < 730$ Hz (95% confidence) (exact value depends upon choice of prior)

- Recycled pulsars evidently have a maximum spin frequency that is well below the breakup frequency for most NS equations of state. Fastest known msec radio pulsar is PSR J1748-2446ad (Ter 5) at 716 Hz (Hessels et al. 2006). (Next fastest are 641, 620, 596, 578 Hz) Single population?

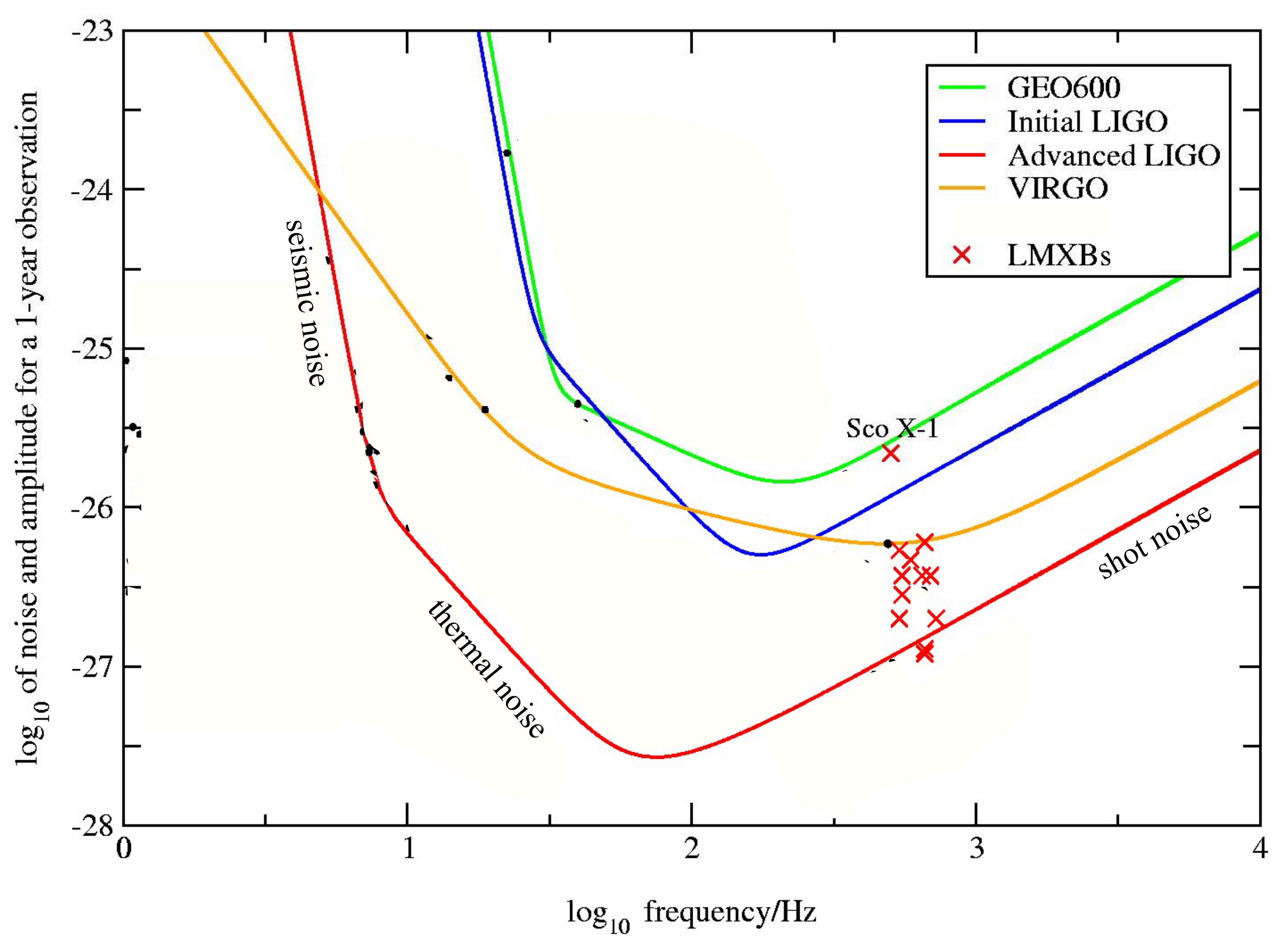
- Detailed shape of distribution still unclear. (Sharp cutoff? Pileup? Falloff?). More systems!

- Submillisecond pulsars evidently relatively rare, if they exist.

How to explain cutoff in spin distribution?

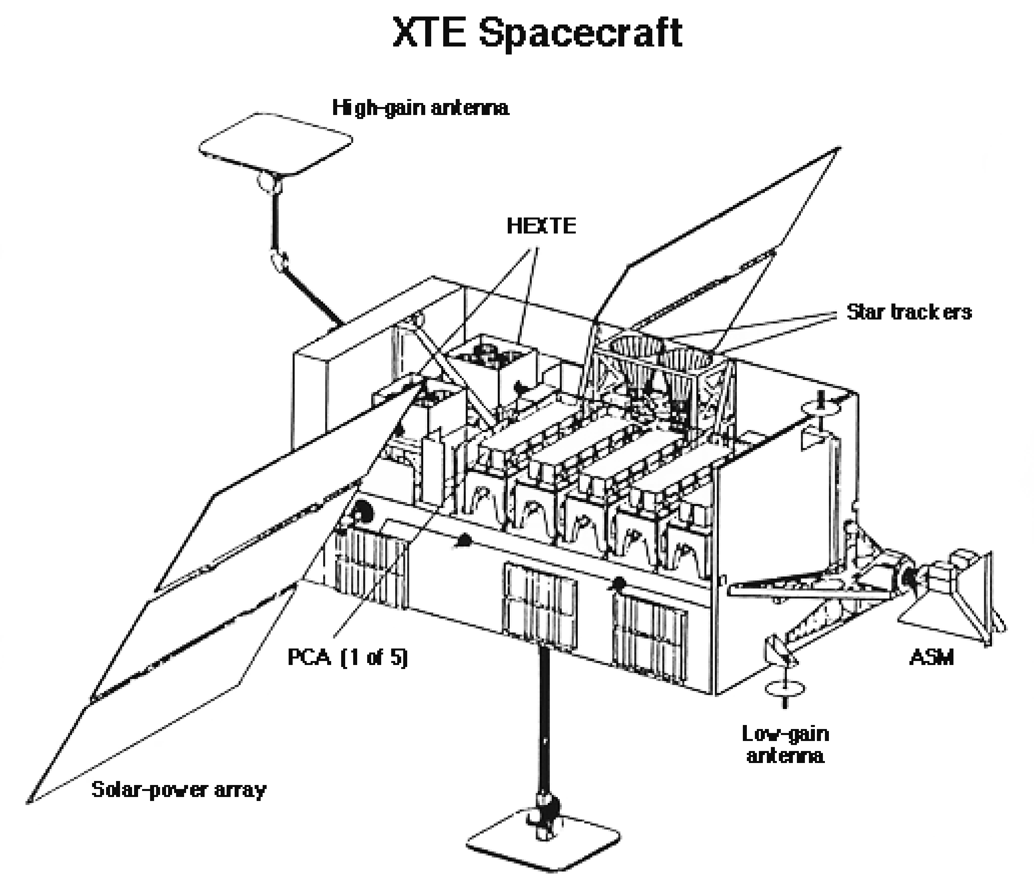
1. Equilibrium spin not yet reached?
   - Unlikely, since spin-up time scale is short compared to X-ray lifetime (but EXO 0748-676 ?)
2. Low breakup frequency for NSs?
   - Requires stiff, exotic EOS with $M<1.5\ M_\odot$ and $R\sim16$ km
3. Magnetic spin equilibrium? (e.g. Ghosh & Lamb 1979; Lamb & Yu 2005)
   - Depends on accretion rate and B. Take observed accretion rate range and apply disk-magnetosphere interaction relevant for weakly magnetic NSs (see Psaltis & Chakrabarty 1999).
   - Can reproduce spin distribution if ALL the objects have similar magnetic field $B\sim10^8$ G. However, this is inconsistent with our inference of a higher field in SAX J1808.4-3658 than in the other burst sources. (Pulsations in other 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 $h\sim10^{-26}$ for brightest LMXBs (Bildsten 2002): Advanced LIGO?
   - Use long integrations to search for persistent GW emission from pulsars

Sensitivity of Current and Future Gravitational Wave Observatories



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

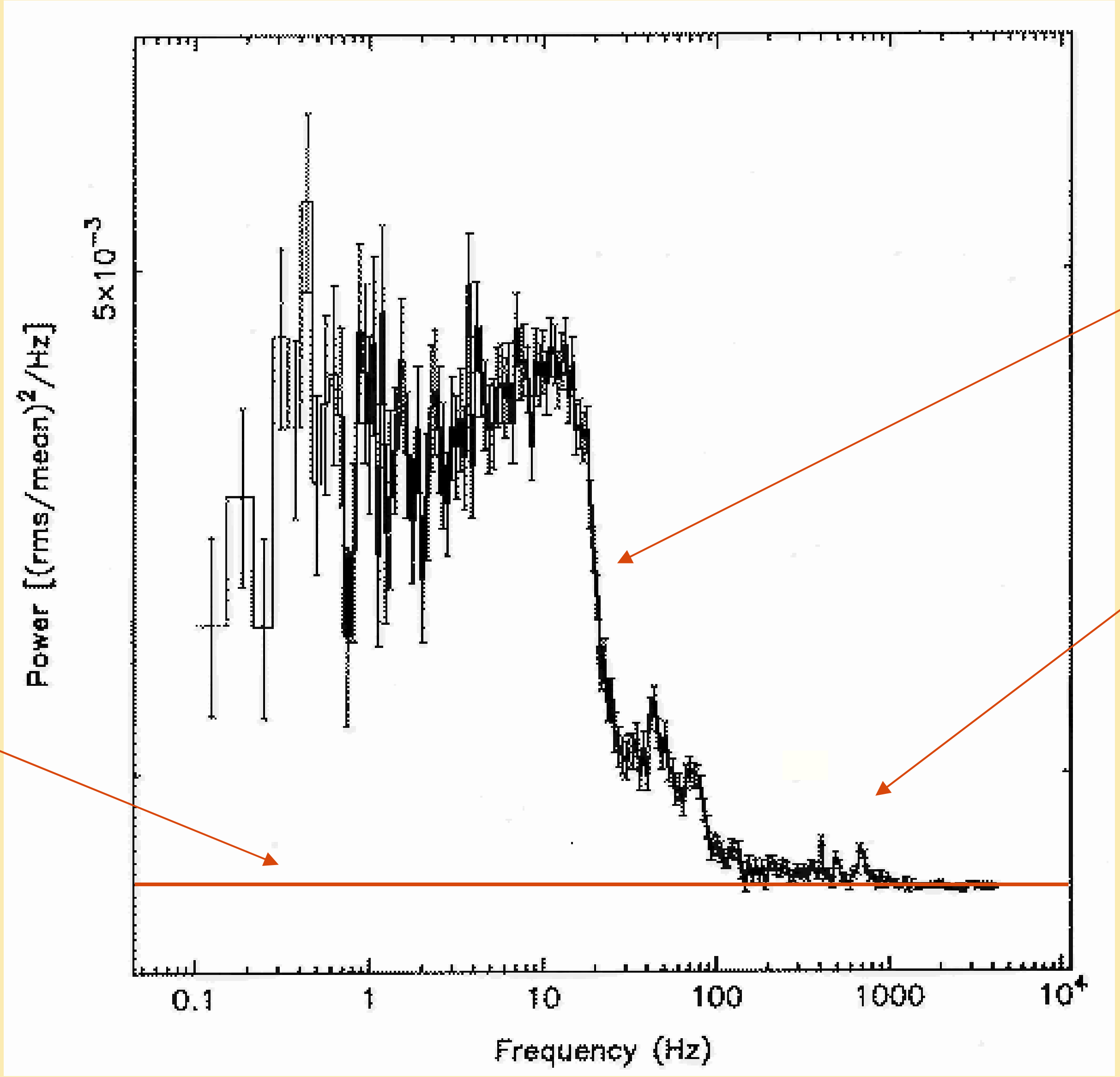
NASA Rossi X-Ray Timing Explorer (RXTE)



- Named for Prof. Bruno Rossi (1905-1993) of MIT
- Launched Dec. 1995, will operate until at least Feb 2009
- 6000 cm^2 proportional counter array (PCA), 2-60 keV, μs time resolution
- HEXTE (high-energy instrument), 20-200 keV
- Small area all-sky monitor (ASM) for activity alerts
- Rapid repointing possible (X-ray transients)

Example of X-ray timing with RXTE:

Power spectrum of X-ray count rate from SAX J1808.4-3658



Red noise

Millisecond variability

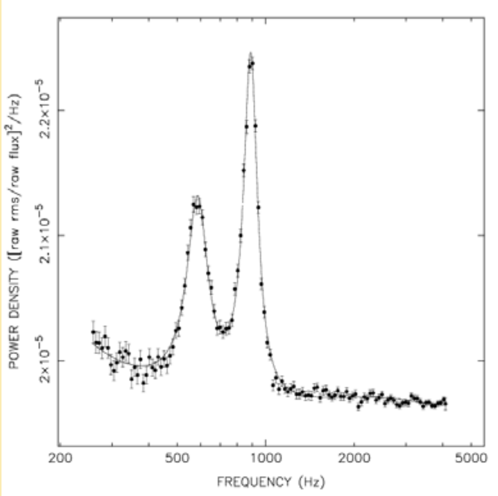
Poisson level

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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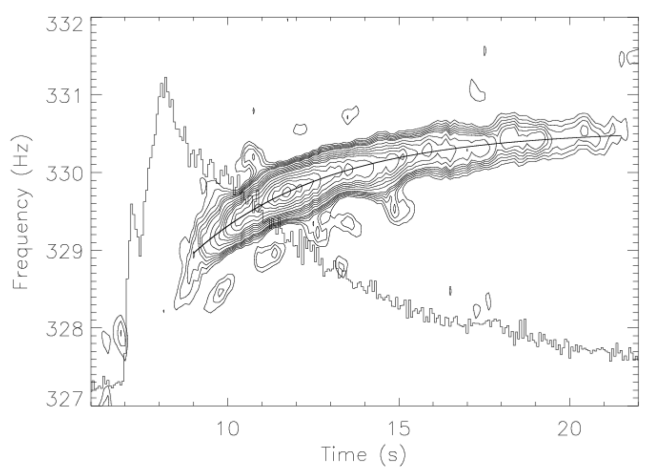

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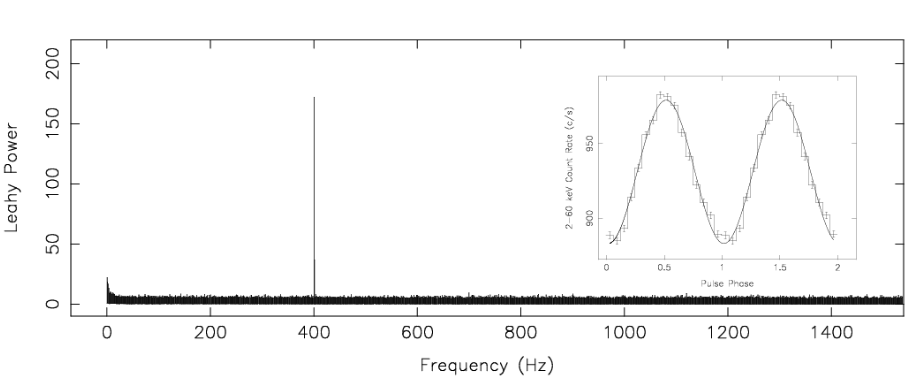
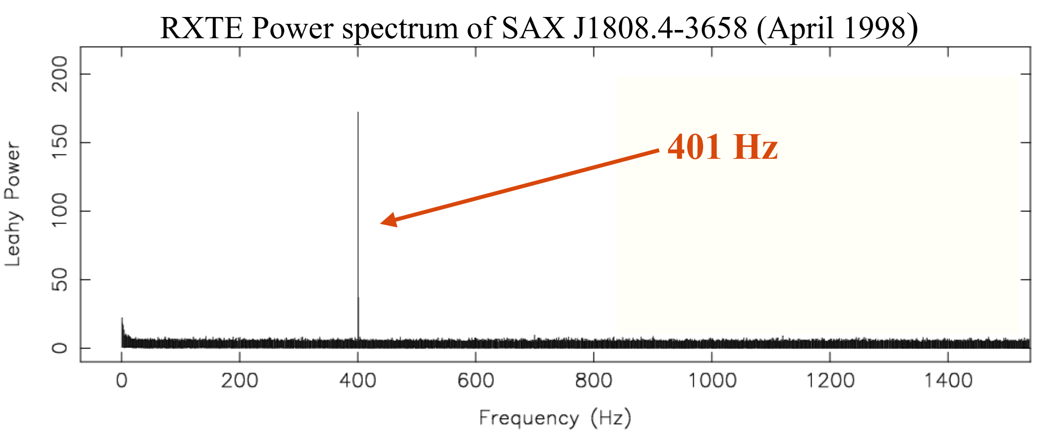
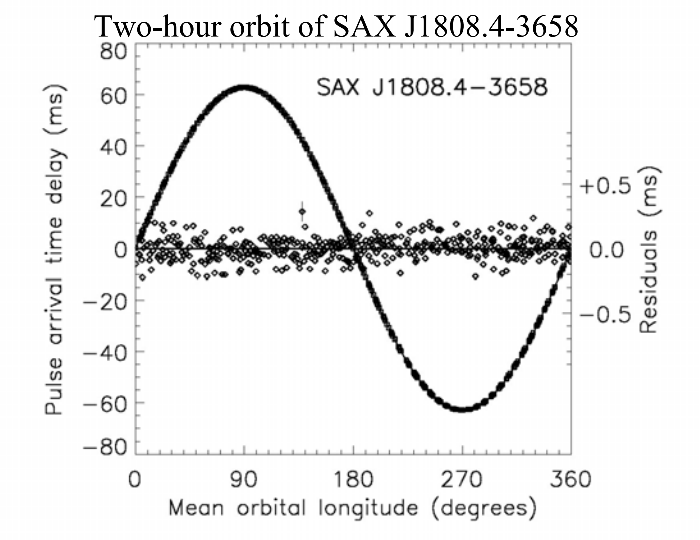


“Bona Fide” Accretion-Powered Millisecond X-Ray Pulsars



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

- Discovered with *Rossi X-Ray Timing Explorer (RXTE)* in 1998, 17 years after first msec radio pulsar.
- Persistent, coherent millisecond pulsations in non-burst emission. Doppler-modulated by binary motion.
- Long-term coherence of pulsations conclusively establishes link to rotation of neutron star.
- Confirms prediction that low-mass X-ray binaries contain rapidly rotating NSs with msec spins.
- 7 sources known, all are X-ray transients (~weeks duration) in highly compact binaries.
- Pulsed amplitude ~5%, well above non-detection limits in other LMXBs. Why not detected in (most) other systems?

Accretion-Powered Millisecond Pulsars

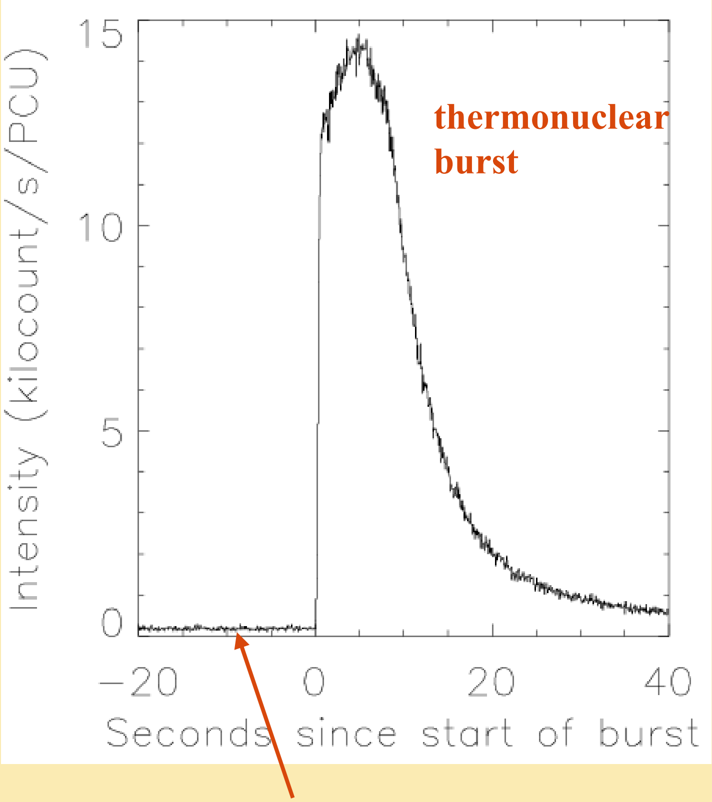
Year	Object	ν_{spin}	P_{orb}	Long.	Lat.
1998	SAX J1808.4-3658	401 Hz	2.01 hr	355º	–8º
2002	XTE J1751-305	435 Hz	0.71 hr	359º	–2º
2002	XTE J0929-314	185 Hz	0.73 hr	260º	+14º
2003	XTE J1807-294	191 Hz	0.68 hr	2º	–4º
2003	XTE J1814-338	314 Hz	4.27 hr	359º	–8º
2004	IGR J00291+5934	599 Hz	2.46 hr	120º	–4º
2005	HETE J1900.1-2455	377 Hz	1.39 hr	11º	–13º

- About half of the pulsars are in ultracompact binaries with nearly *identical* binary periods.

- All of these are low-luminosity transients with low mass-accretion rates. Why no persistent sources?

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

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



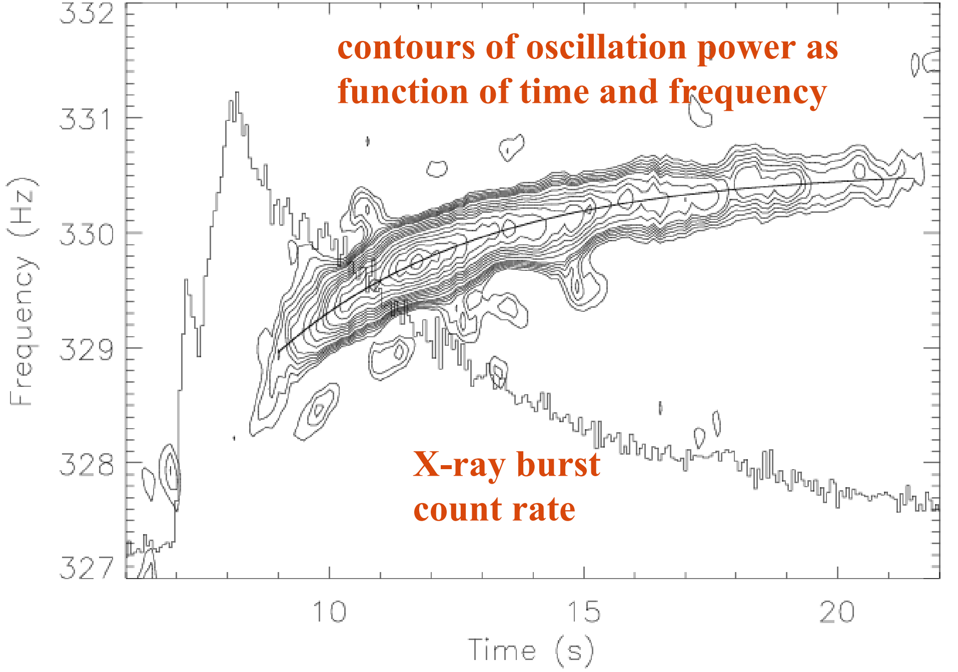
thermonuclear burst

quiescent emission due to accretion

- Thermonuclear X-ray burst phenomenon known since 1970s.
- Burst oscillations discovered with *RXTE* (Strohmayer et al. 1996).
- Nearly coherent millisecond oscillations during thermonuclear X-ray bursts (270-619 Hz). More than 100 examples in over 10 sources, most also with kHz QPOs.
- Frequency drifts by several Hz over a few seconds, with asymptotic maximum at spin frequency. Frequency drift interpreted as angular momentum conservation in a decoupled burning layer on neutron star surface. (Strohmayer; Cumming & Bildsten)

- Amplitude evolution in burst rise interpreted as spreading hot spot on rotating NS surface. (Strohmayer et al.)
- Oscillations in burst tail not yet understood.
- "Superburst" oscillations in 4U 1636-53 (Strohmayer & Markwardt)

4U 1702-43 (Strohmayer & Markwardt 1999)



contours of oscillation power as function of time and frequency

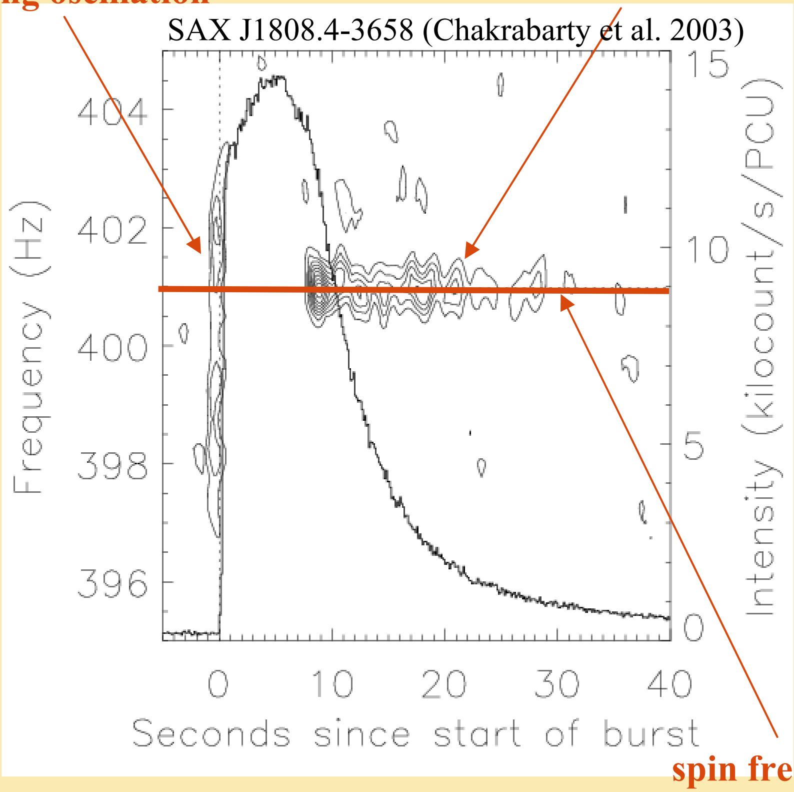
X-ray burst count rate

Nuclear-Powered Millisecond Pulsars

EXO 0748-676	45 Hz
4U 1916-05	270 Hz
XTE J1814-338 (*)	314 Hz
4U 1702-429	330 Hz
4U 1728-34	363 Hz
SAX J1808.4-3658 (*)	401 Hz
SAX J1748.9-2021	410 Hz
KS 1731-26	524 Hz
A1744-361	530 Hz
Aql X-1	549 Hz
X1658-298	567 Hz
4U 1636-53	581 Hz
X1743-29	589 Hz
SAX J1750.8-2900	601 Hz
4U 1608-52	619 Hz

(*) = also an accretion-powered pulsar

- 15 sources known. These systems include both persistent and transient LMXBs spanning a range of orbital periods and luminosities, showing that rapid spins are a common feature of NS/LMXBs.
- 2 of these are also accretion-powered pulsars, conclusively establishing that burst oscillations trace the NS spin. (Chakrabarty et al. 2003; Strohmayer et al. 2003).



drifting oscillation

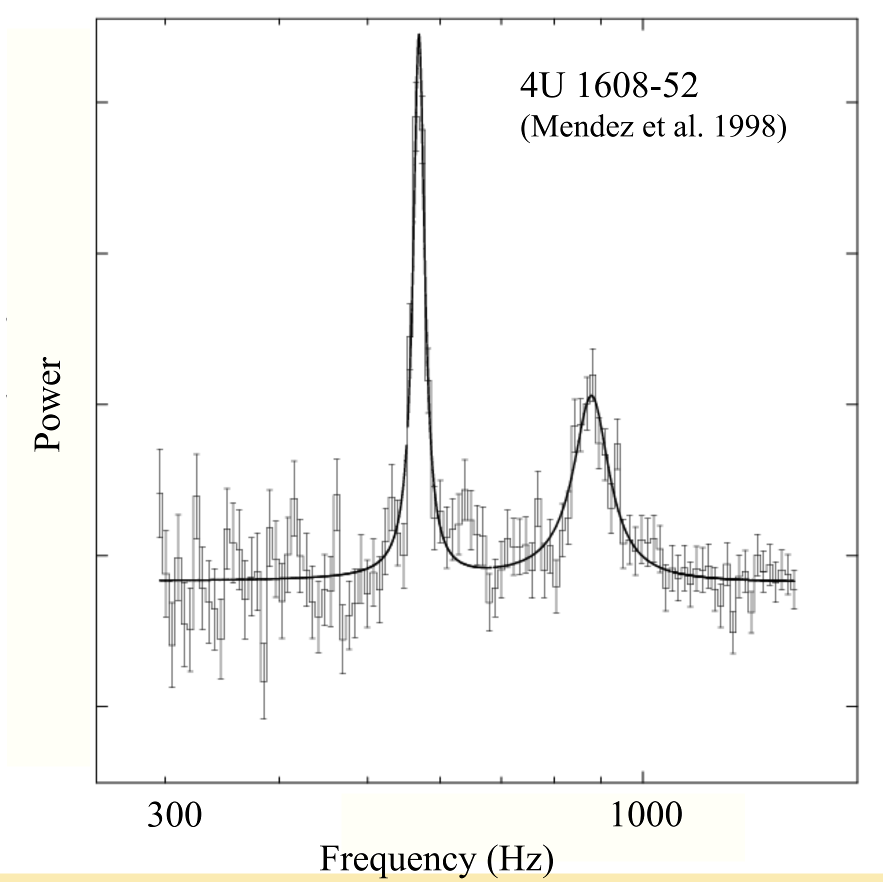
burst tail oscillation

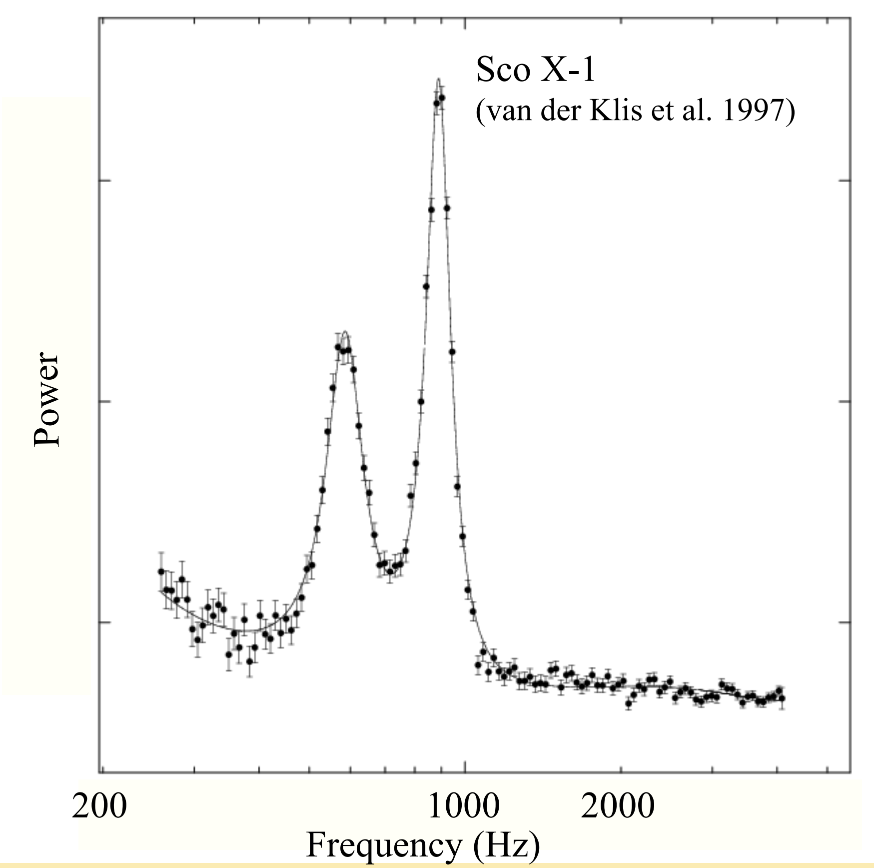
SAX J1808.4-3658 (Chakrabarty et al. 2003)

spin frequency

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)
- Particular 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)
- Seen in over 20 LMXBs. Believed to originate in accretion disk. Mechanism?





What do we know about the spin frequency evolution?

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

$$\dot{\nu} = 4\times10^{-12}\left(\frac{\dot{M}}{\dot{M}_{\mathrm{Edd}}}\right)\left(\frac{\nu}{600\ \mathrm{Hz}}\right)^{-1/3}\ \mathrm{Hz\ s^{-1}}$$

This corresponds to a decoherence time of

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

This time scale is many months long for millisecond X-ray pulsars like SAX J1808.4-3658. Note that in the X-ray transients, there is only a significant torque during the (short) outbursts. The long-term average mass accretion rate is generally well below the Eddington rate in these systems.

What is known about orbital evolution?

In SAX J1808.4-3658, an orbital period derivative is measured:

$$\dot{P}_{\mathrm{orb}} = 3.3\times10^{-12}$$

$$\frac{\dot{P}_{\mathrm{orb}}}{P_{\mathrm{orb}}} = 1.62\times10^{-8}\ \mathrm{yr^{-1}}$$

Summary

- Issues of importance for gravitational wave community:
    - 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
    - Spin evolution of millisecond X-ray pulsars appears to be modest

References:

- Chakrabarty et al. 2003, *Nature*, **424**, 42
- Chakrabarty 2005, astro-ph/0408004