Spin and Orbital Evolution of the Accreting Millisecond Pulsar SAX J1808.4-3658: Implications for Gravitational Wave Searches

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Featuring Ph.D. thesis work of Jacob M. Hartman at MIT.


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Life History of Pulsars: Spin and Magnetic Evolution

1. Pulsars born with $B \sim 10^{12} \text{ G}$, $P \sim 20 \text{ ms}$. 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

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

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

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.
• 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)
“Bona Fide” Accretion-Powered Millisecond X-Ray Pulsars

Can measure spin and orbital parameters.

10 known examples, generally all X-ray transients with low mass accretion rates.
• 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 (but see Galloway talk for complication....). Cannot continuously monitor spin and orbital evolution in these systems.

X-Ray Sources: Persistent versus Transient
Nuclear-Powered Millisecond X-Ray Pulsars (X-Ray Burst Oscillations)

- 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.
• We find that $v_{\text{high}} < 730$ 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 $\sim 3\sigma$). 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 (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 $B \sim 10^8\ G$. 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 $h \sim 10^{-26}$ 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)
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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,

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

where we have scaled to an accretion rate typical for X-ray transient outbursts. Assuming steady accretion, this corresponds to a decoherence time of

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

Note that in the X-ray transients, there is only a significant accretion torque during the (short) outbursts. It would be interesting to know how the spin evolves during X-ray quiescence, when accretion is shut off.
Can we study the spin evolution of individual millisecond X-ray pulsars?

- In principle, accretion-powered millisecond pulsars ideal targets. Pulse timing during weeks-long active outburst allows precise measurement of spin and orbital parameters.

- Spin frequency derivatives have been measured during outbursts of several systems.

- **Complication:** Some millisecond X-ray pulsars subject to substantial pulse shape variability, both systematic and stochastic. This can potentially mimic spin evolution! (Hartman et al. 2007)

- **Consolation:** Not all millisecond X-ray pulsars have strong pulse shape noise, so accretion torque study during outburst is possible for some sources -- but only during active accretion. Spin derivatives of order $\sim 10^{-14}$ Hz/s have been measured (Galloway et al. 2002; Burderi et al. 2006, 2007; Papitto et al. 2007; Riggio et al. 2007)

- For sources with multiple outbursts, can also study long-term spin and orbital evolution by using outbursts spaced over several years. Best case is SAX J1808.4-3658, which has been observed in 1998, 2000, 2002, and 2005.
Long-Term Spin-down of the Accretion-Powered Millisecond Pulsar SAX J1808.4-3658

This spin-down cannot be due to accretion torques during outbursts, based on spin derivative limits during outbursts. The torque is occurring between outbursts, when there is no accretion.

Magnetic dipole spin-down?

- In the absence of accretion, this should always be present at some level.
- Requires $B < 1.5 \times 10^8$ G for consistency with measured spindown. For comparison, presence of accretion-powered pulsations over observed outburst flux range implies $B$ in range $(0.4 - 12) \times 10^8$ G

Magnetic propeller spin-down?

- Consistent with long-term mass transfer

Gravitational wave spin-down?

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

Note that magnetic dipole spin-down with expected field strength easily explains data -- gravitational wave torque not required for this 401 Hz system. However, given $\Omega^5$ torque dependence, GWs could easily still play an important role at $\sim 700$ Hz. It would be nice to repeat measurement for a faster rotator.
Orbital Evolution of the Accretion-Powered Millisecond Pulsar SAX J1808.4-3658

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

- 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: “black widow” radio pulsars which are ablating their low-mass companions through intense particle irradiation. At least 2 of these systems have large, varying orbital period derivatives that are quasi-cyclic on decade timescale (Arzoumanian et al. 1994; Doroshenko et al. 2001).

- There is some optical evidence that SAX J1808.4-3658 may be an active radio pulsar during X-ray quiescence (Burderi et al. 2003; Campana et al. 2004). If so, then it may be a black widow system as well. It will be interesting to monitor orbital evolution further, look for quasi-cyclic sign changes in derivative.

- 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). This may complicate long GW integrations.
Summary

• Issues of importance for gravitational wave community:
  • Short-term spin evolution of millisecond X-ray pulsars during transient outbursts appears modest
  • Long-term spin evolution of SAX J1808.4-3658 is very modest, consistent with magnetic dipole spindown. Gravitational wave torque evidently unimportant for 400 Hz rotator.
  • 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

References:
  (arXiv:0708.0211)