Accreting neutron stars as gravitational wave sources

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Low-mass X-ray binaries

- ~100 LMXBs known; most are persistent or quasi-persistent, outburst/activity intervals of years
- Most neutron stars with high-mass (>1$M_{\odot}$) companions are pulsars with long spin periods; conversely, most neutron stars with low-mass binary companions do not pulse persistently
- Accreted material builds up in the accretion disk, and then is dumped onto the neutron star in transient outbursts lasting a few weeks
- With a sufficiently strong magnetic field, the accreted material lands preferentially on the magnetic poles of the star giving rise to anisotropic X-ray emission
- As with rotation-powered (radio) pulsars,

  rotation + anisotropy = pulsations

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The estimated strain

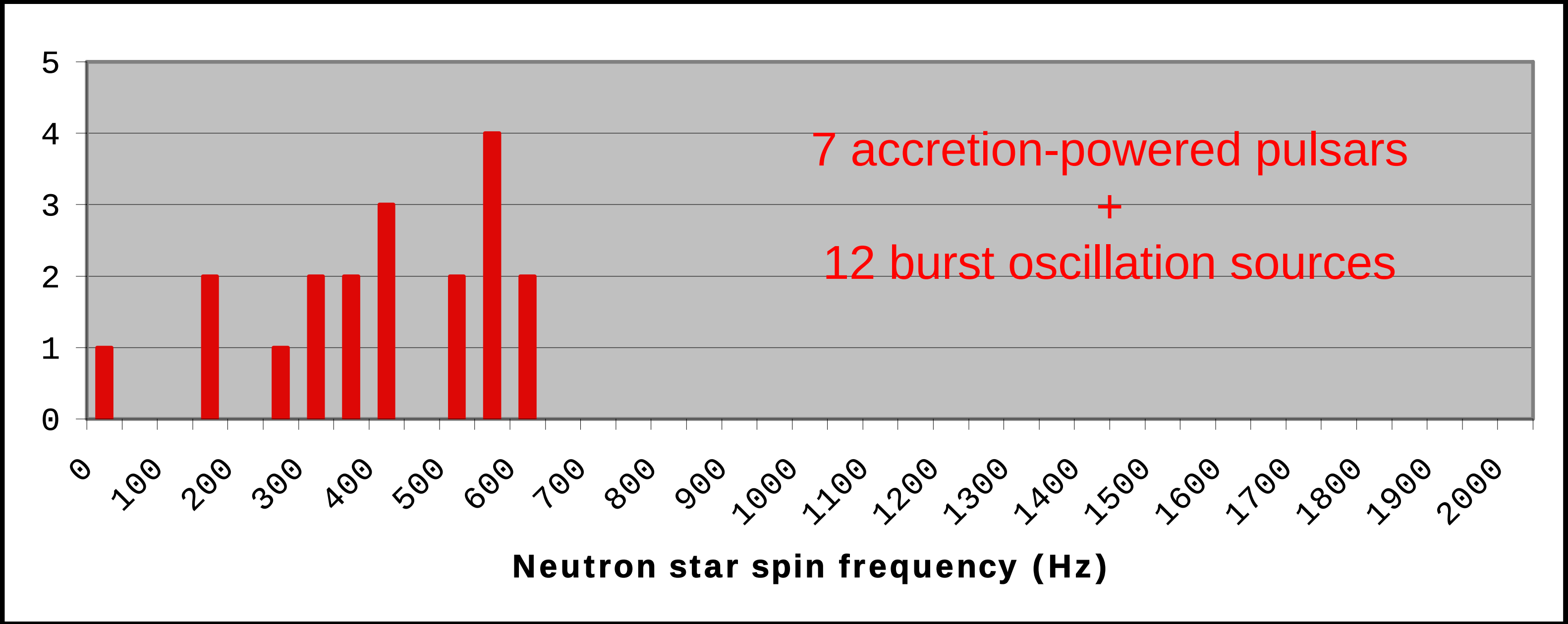
A misaligned quadrupole moment will give rise to a gravitational wave strength of (Bildsten 1998)

$$h_c \approx 4 \times 10^{-27} \frac{R_6^{3/4}}{M_{1.4}^{1/4}} \left(\frac{F_X}{10^{-8} \text{ ergs cm}^{-2} \text{ s}^{-1}} \right)^{1/2} \left(\frac{300 \text{ Hz}}{\nu_s} \right)$$

where F_X is the observed X-ray flux and ν_s is the spin frequency

- We can measure the flux with satellite X-ray telescopes; the brighter the source, the greater the GW strength
- We can also measure the neutron star spin, to varying degrees of precision

Evidence for gravitational radiation



- A Bayesian analysis suggests that the spin frequency is limited to 760 Hz (95% confidence; Chakrabarty et al. 2003)
- Several have suggested that gravitational radiation from a non-spherical neutron star might limit the maximum frequency (amplitude $\propto f^6$; e.g. Bildsten et al. 1998)

-> detection by Advanced LIGO?

Critical system parameters

By analogy with e.g. searches for *electromagnetic* pulsations, optimal GW searches require knowledge of

- *Pulse phase history*, specifically where short- or long-term variations in the spin frequency (due to accretion) may be present; or at least,
- *Spin frequency* can be measured directly (pulsations, burst oscillations) or indirectly (kHz QPO peak separation)
- *Orbital period* can be determined from
  1. Doppler modulation of pulsations
  2. Optical/IR photometry or spectroscopy

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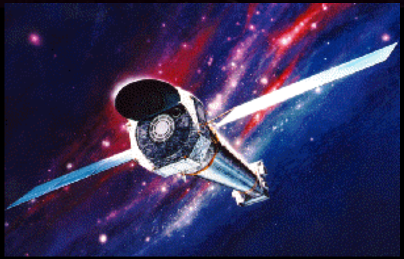
Present-day instruments



RXTE, launched 1995 (NASA) large effective area and very high timing resolution but no imaging capability [2-200 keV]

Chandra, launched 1999 (NASA), small effective area but very high spatial and spectral resolution (courtesy transmission gratings) [0.5-10 keV]

XMM-Newton, launched 1999 (ESA), moderate effective area, spatial and spectral resolution (reflection gratings) + optical monitor [0.5-10 keV]

INTEGRAL, launched 2002 (ESA), primarily gamma-ray instrument but also wide-field X-ray and optical capability [4 keV - 10 MeV]

Classes of LMXBs

Type	Pulse phase?	Spin Freq?	Orbital period?	F_X
Accretion-powered millisecond pulsar (7)	yes, X-rays (while active)	Yes	Yes, Doppler modulation	Transient $<10^{-9}$ ergs cm^{-2} s^{-1}
Burst oscillation “atoll” source (12)	Only during bursts	Yes	Optical photometry/spectro-scopy	Moderate Few 10^{-9} ergs cm^{-2} s^{-1}
Twin kHz QPOs (e.g. Sco X-1) “Z-source”	No	1x or 2x QPO separ-ation	Optical photometry/spectro-scopy	High $\sim10^{-8}$ ergs cm^{-2} s^{-1}

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Accretion-powered MSPs

Type	Pulse phase?	Spin Freq?	Orbital period?	F_X
Accretion-powered millisecond pulsar (7)	yes, X-rays (while active)	Yes	Yes, Doppler modulation	Transient $<10^{-9}$ ergs cm^{-2} s^{-1}
Burst oscillation "atoll" source (12)	Only during bursts	Yes	Optical photometry/spectro-scopy	Moderate Few 10^{-9} ergs cm^{-2} s^{-1}
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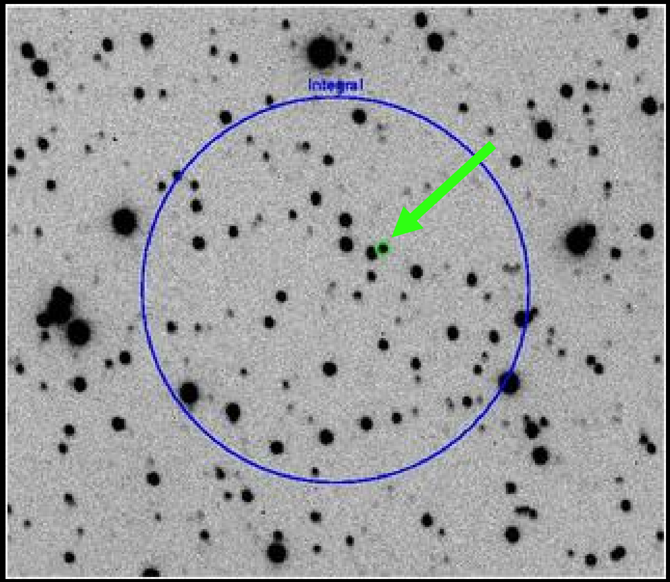
Case study: IGR J00291+5934

- Discovered 2004 December 2 with IBIS/ISGRI and JEM-X aboard *INTEGRAL* (Eckert et al., ATel #352; see also Shaw et al. ‘05)
- *R*~17.4 optical counterpart (Fox et al., ATel #354). Rapidly fading with e-folding time 5.7 d (Bikmaev et al., ATel #395)
- IR magnitudes J=16.8, H=16.8, K=16.1 (Steeghs et al., ATel #363); IR excess compared to disk model?
- Spectroscopic observations show weak He & Hα lines (Roelofs et al., ATel #356)
- Fading radio counterpart <1mJy @ 5, 15 GHz (ATels #355, 361, 364)



Pulse timing with *RXTE*: f_0 = 598.89 Hz

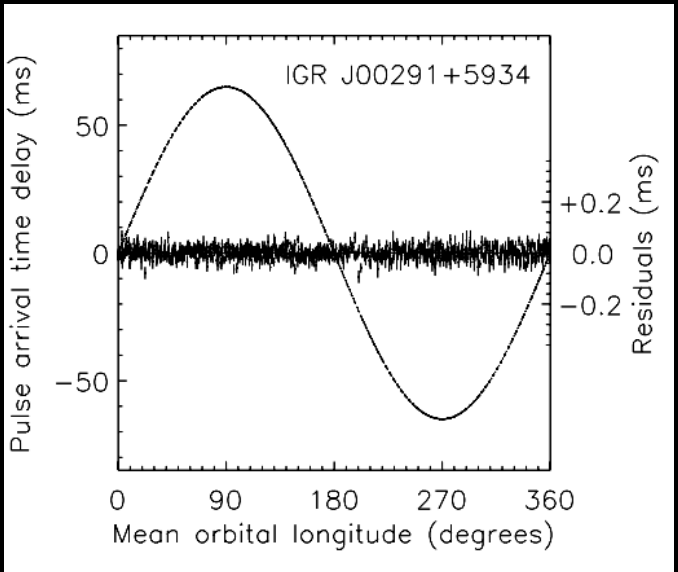
Fastest accretion-powered pulsar (Marquardt et al. 2004, ATel #353, 360)

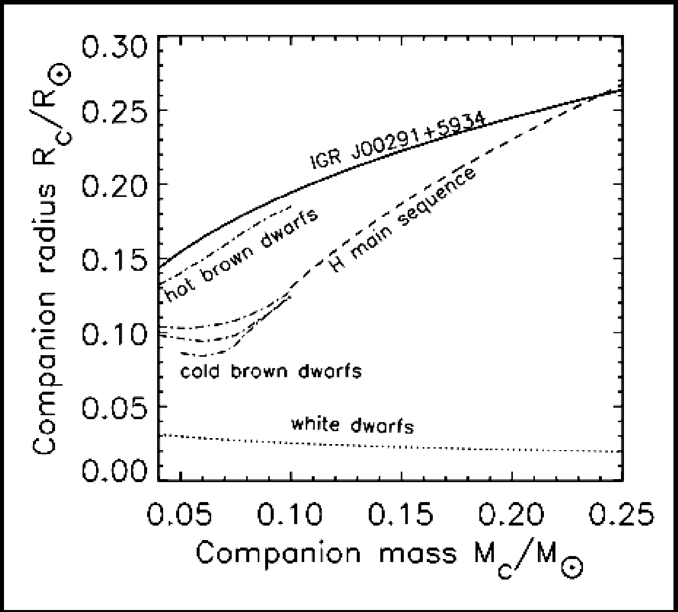
… but not the fastest spinning neutron star (641 Hz)

Pulse phase fitting results:

- P_{orb}=2.46 hr
- $a_X \sin i$ = 65.0 lt-ms
- Mass fn. $f_X = 2.8\times10^{-5}\,M_\odot$
- Mass donor is likely a brown dwarf ($M>0.039\,M_\odot$) heated by low-level X-ray emission during quiescence

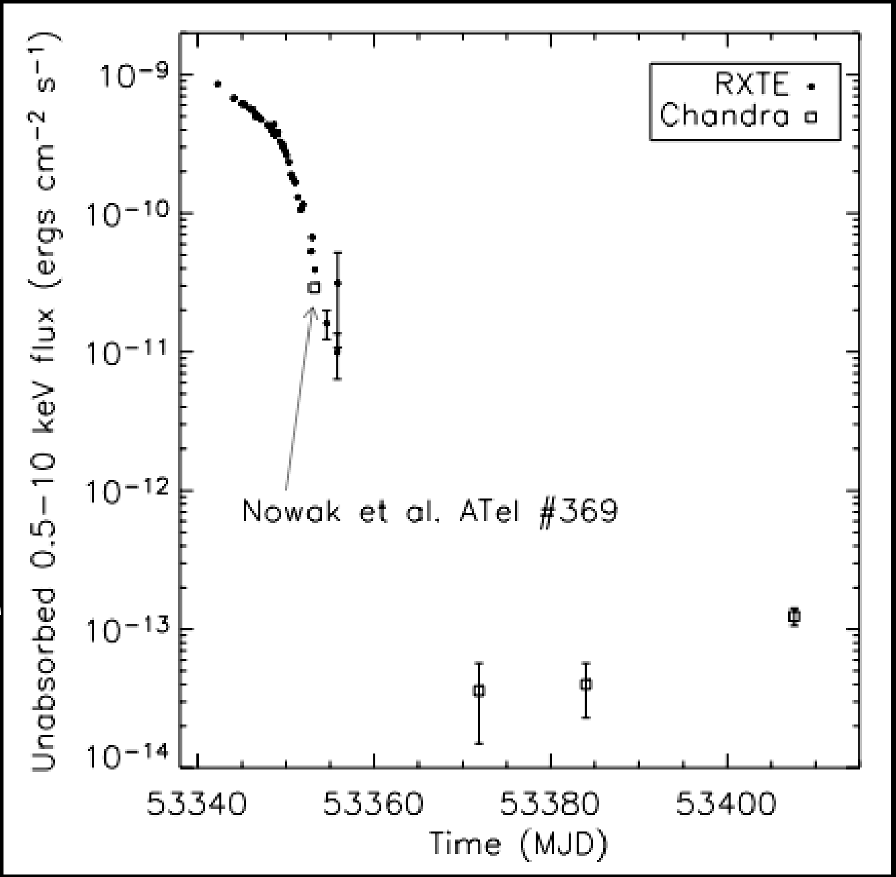
(Galloway et al. 2005, ApJ 622, 45L)





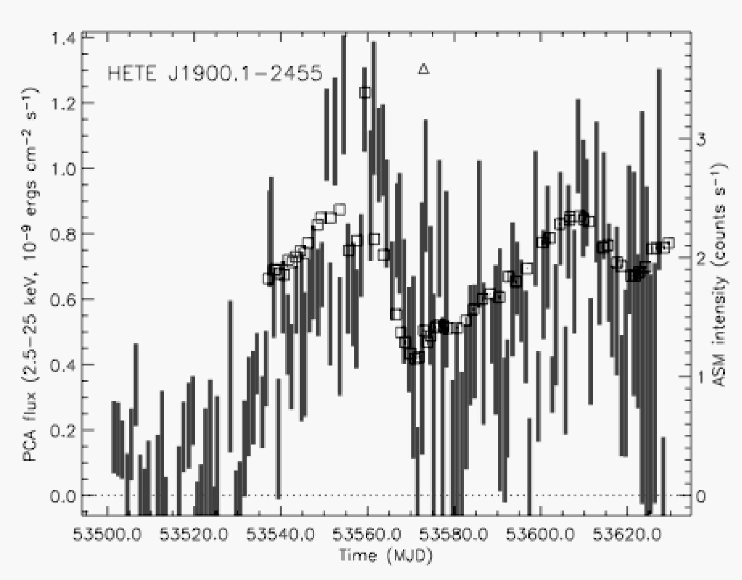
Followup observations by *RXTE* & *Chandra*

- Initial X-ray flux e-folding time 8.5 d, later 1.68 d
- Variable in quiescence (Jonker et al. 2005, astro-ph/0505120)
- X-ray brightness contrast between activity and quiescence $>10^4$



Two previous outbursts detected retro-actively by *RXTE*/ASM; recurrence time 3 yr

Breaking news: HETE J1900.1-2455



- A thermonuclear burst from this source detected by the *HETE-2* satellite June 2005 (ATel #516)
- Subsequent PCA observations revealed 377.3 Hz pulsations and Doppler variations from an 83.3 min orbit (ATel #523, 538; Kaaret et al., in prep.)

- Source is *still active*, >100 d after the outburst commenced. This is by far the longest active period of any of the millisecond pulsars
- Pulsations detected only intermittently since a bright flare early in the outburst; at times this source is *indistinguishable from a faint, non-pulsing LMXB*
- While the inferred Mdot is rather low at only ~2% M_{Edd}, if it remains active it will be the highest of the accretion-powered pulsars

“Atoll” sources

Type	Pulse phase?	Spin Freq?	Orbital period?	F_X
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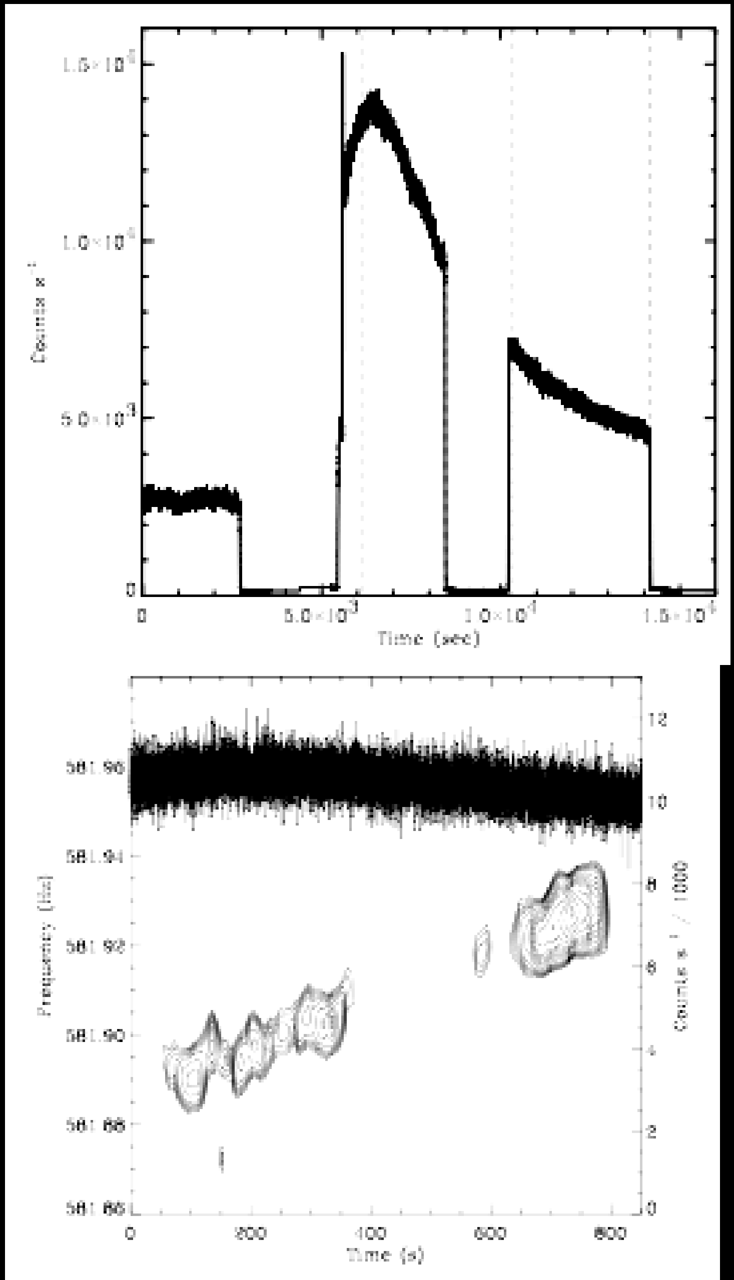
A “nuclear-powered” pulsar



- 4U 1636-536 is a well-known thermonuclear burst source with 581 Hz burst oscillations
- Observed frequency drifts by a few % during the burst; with recurrence times of hours, no hope of tracking phase inbetween
- Modulation consistent with orbital Doppler shifts, most notably during a superburst observed by *RXTE* (Strohmayer et al. 2002)

“Z” sources

Type	Pulse phase?	Spin Freq?	Orbital period?	F_X
Accretion-powered millisecond pulsar (7)	yes, X-rays (while active)	Yes	Yes, Doppler modulation	Transient $<10^{-9}$ ergs cm^{-2} s^{-1}
Burst oscillation “atoll” source (12)	Only during bursts	Yes	Optical photometry/spectro-scopy	Moderate Few 10^{-9} ergs cm^{-2} s^{-1}
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Sco X-1

- Brightest persistent X-ray source in the sky
- 800 & 1100Hz quasi-periodic oscillations detected by *RXTE* in 1996 (van der Klis et al, 1997)
- Twin QPO peak separation in the lower-Mdot “atoll” sources is typically 1x or 2x the burst oscillation frequency…
- … which we know, from studies of millisecond pulsars, very likely is the spin frequency of the neutron star…
- … suggesting that the spin frequency of the neutron star in Sco X-1 is ~300 or ~600 Hz

Coordinated LIGO-RXTE observations?

Summary and future prospects

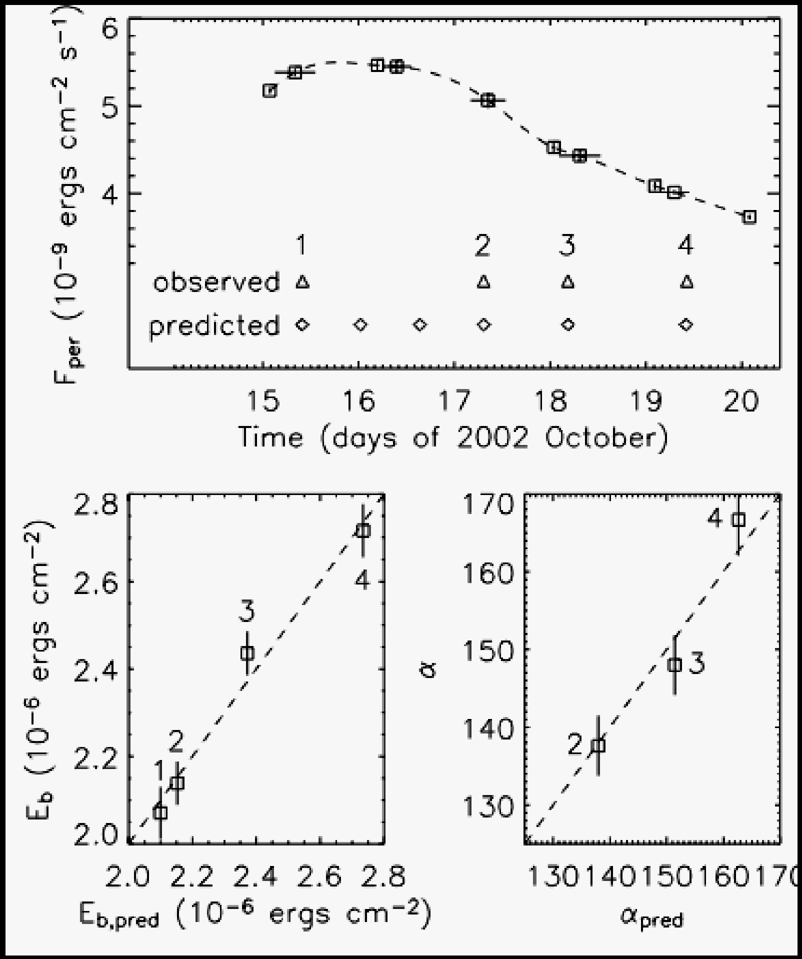
- Accretion-powered millisecond pulsars are by far the fastest-growing subclass of these sources
- Can precisely track pulse phase and frequency over the (typically) two-week outburst period

BUT

- Time-averaged M-dot is very low (bad for GW) AND infrequent transient activity
- HETE J1900.1-2455 gives us hope that in the future new “quasi-persistent” sources may appear
- Burst oscillation sources are generally higher M-dot, but can’t track phase as well (and some orbital periods are unknown)
- Z-sources like Sco X-1 are by far the brightest, but also the sources about which the least is known

Need to weigh the relative benefits of high Mdot with knowledge of the system parameters for assessing detection probability

Distance to SAX J1808.4-3658



- First accretion-powered millisecond pulsar discovered; spin frequency 401 Hz
- Four bursts observed during the 2002 October outburst
- Comparison with ignition models allows us to constrain the distance to a previously unheard-of precision:

  3.40 ± 0.02 kpc

New & interesting behaviour