Tuning up for Gravitational Wave Detection in Accreting Neutron Stars: a progress report

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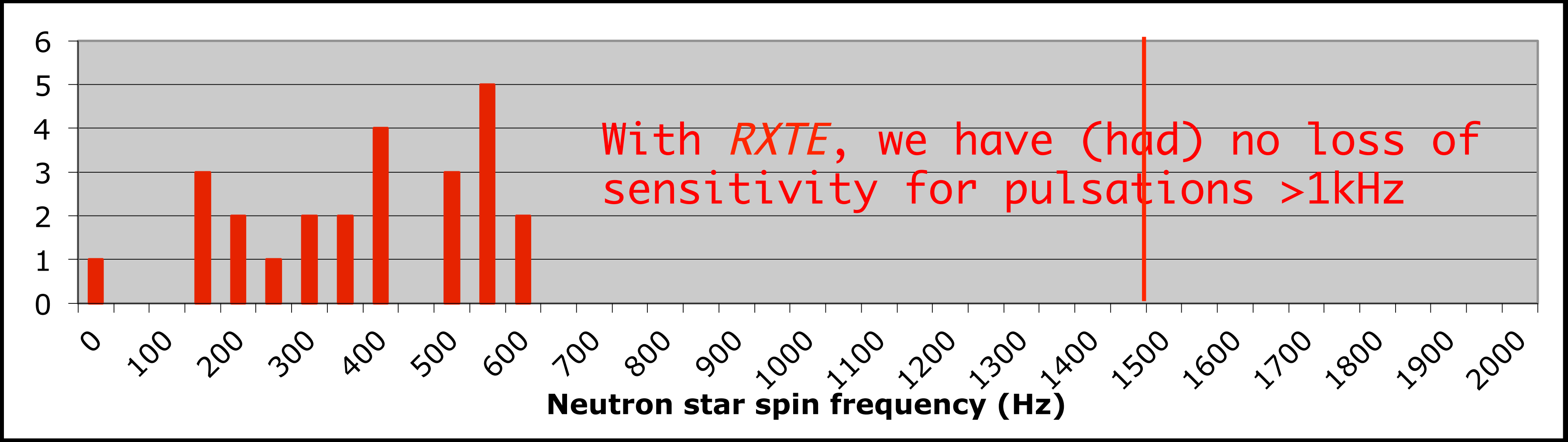
Evidence for gravitational radiation



- Spin frequencies are << breakup despite sufficient spin-up over accretion lifetime
  Chakrabarty et al. 2003, Nature 424, 42
- Several have suggested that gravitational radiation from a non-spherical neutron star might limit the maximum frequency; amplitude $\propto f^6$ Bildsten et al. 1998, ApJ 501, L89

-> detection by Advanced LIGO?

The gravitational wave strength

- A "mountain" on the neutron star will give rise to a gravitational wave strength of

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

  where F_X is the observed X-ray flux and ν_s the spin frequency (Bildsten 1998)
- We can measure the flux with satellite X-ray telescopes; the brighter the source, the greater the expected GW strength
- We can also (sometimes) measure the neutron star spin (generally to ~few Hz)

Classes of LMXBs

Type	Pulse phase?	Spin Freq?	Orbital period?	F_X
Accretion-powered millisecond pulsar (8)	Yes (while active)	Yes	Yes, Doppler modulation	Transient $<10^{-9}$ erg cm^{-2} s^{-1}
Burst oscillation/ intermittent pulsar (14)	precise)		scopy	s^{-1}
Twin kHz QPOs (e.g. Sco X-1) “Z-source”	No	1x or 2x QPO separ-ation?	Optical photometry/ spectro-scopy?	High ~10^{-8} erg cm^{-2} s^{-1}

* Note Patruno et al. 2012, ApJ 746; no need for braking via gravitational waves in MSPs

Prospects for detectability

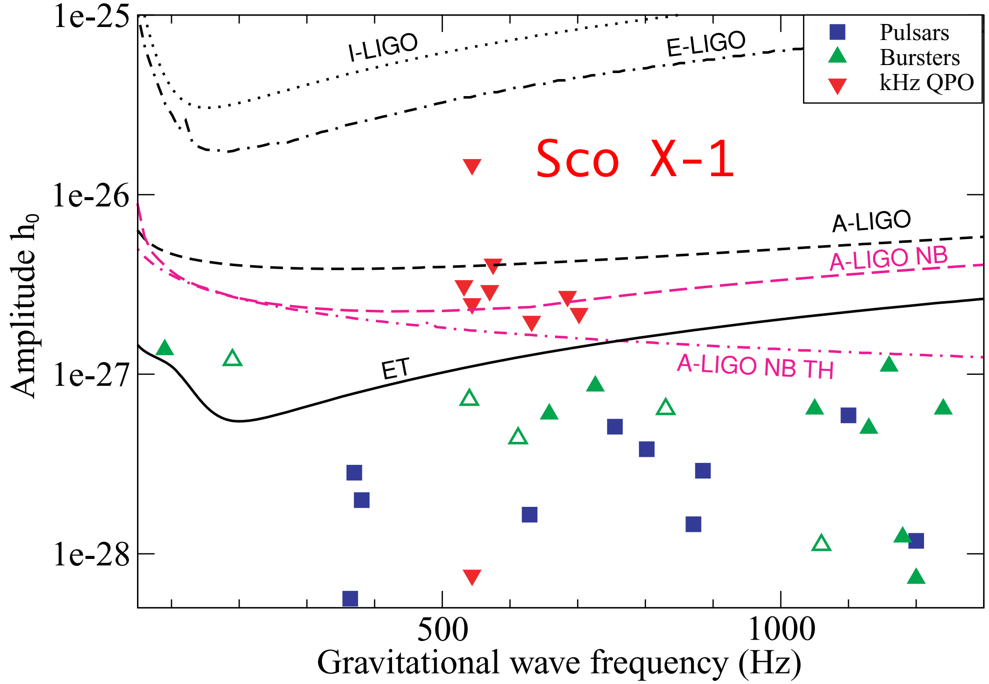


Figure 10. Effect on detectability for the mountain scenario (assuming long-term average flux and a coherent fold with $T_{obs} = 2$ yr), taking into account the effect on F_{stat} associated with the fact that $N_{temp} > 1$. Compare to the best case detectability shown in Fig. 2. As in Fig. 2, the noise curves are computed assuming $F_{stat} = 11.4$ (the single template value), but we have scaled the predicted amplitudes to reflect the fact that F_{stat} is larger. Although this is not strictly 'correct' (it is the thresholds that should move, not the predicted amplitudes) this is a useful way to visualize the impact. See the text for more details.

Even under fairly optimistic assumptions, *only* the brightest sources are likely detectable with Advanced LIGO

Watts et al. 2008, MNRAS 389, 839

Classes of LMXBs

Type	Pulse phase?	Spin Freq?	Orbital period?	F_X
Accretion-powered millisecond pulsar (8)	Yes (while active)	Yes	Yes, Doppler modulation	Transient $<10^{-9}$ ergs cm^{-2} s^{-1}
Burst oscillation/ intermittent pulsar (14)	Some-times (not precise)	Approx. (for ~20%)	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}

kHz QPOs as spin tracers

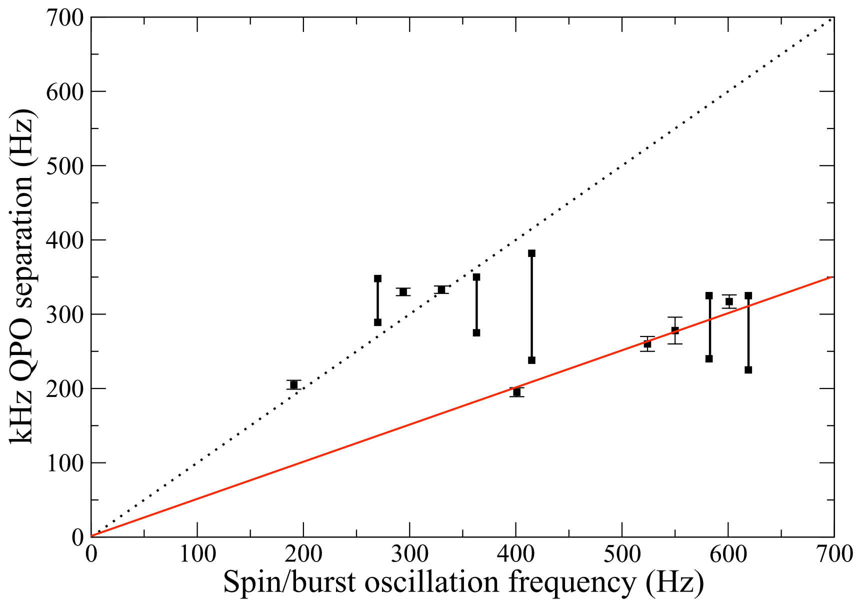


Figure 3. A comparison of twin kHz QPO separation and spin frequency or burst oscillation frequency for those sources that show both phenomena. The dotted line indicates equality of the two measures. For some objects kHz QPO separation is consistent with being constant: these are shown as single points with error bars. Note however that this may be due to poor sampling of source states. For five objects kHz QPO separation varies: these are shown as two points with a line indicating the range.

Watts et al. 2008, MNRAS 389, 839

- In sources with both kHz QPOs and pulsations/burst oscillations, the kHz QPO separation is approximately equal to the spin frequency ν or sometimes 0.5ν
- May help reduce the parameter space for GW searches (but is risky)

Search sensitivity

- The main factor affecting the gravitational wave search sensitivity is a lack of precision of the LMXB orbital parameters (Abbott et al. 2007, Phys. Rev. D., 76 082001)
- A *relatively* straightforward exercise to improve sensitivity is to make measurements of LMXB optical counterparts to improve the precision
- Our goal is maximally precise orbital phase solutions that can be maintained through to Advanced LIGO observing periods

Source selection

Source	ASM rate (count s^{-1})	bursts?	kHz QPOs?	orbital period?	optical counterpart
Sco X-1	890 ± 110		yes	18.9 hr	V818 Sco ($V = 12.2$)
GX 17+2	44 ± 5	yes	yes		candidate
Cyg X-2	38 ± 9	yes	yes	9.8 d	V1341 Cyg ($V = 14.7$)
GX 5-1	70 ± 9		yes		candidate
GX 349+2	50 ± 8		yes	22.5 hr	V1101 Sco ($V = 18.6$)
GX 340+0	29 ± 5		yes		
GX 13+1	23 ± 3			24.07 d	$K = 12$
Cir X-1*	100 ± 30	yes		16.6 d	BR Cir ($V = 21.4$)
XTE J1701-462**	24 ± 4	yes	yes?		

Table 1: Target sources for this DP, in order of decreasing observational priority. The second column gives the mean 2–10 keV intensity for the source measured by the *RXTE*/ASM; this is an approximate measure of the time-averaged source flux (and hence GW amplitude). 1 ASM count s^{-1} is approximately equivalent to an X-ray flux of $F_X = 3 \times 10^{-10}$ erg cm^{-2} s^{-1}. The third and fourth columns specify whether or not thermonuclear bursts, and kHz quasi-periodic oscillations (QPOs) have been detected. The fifth column gives the orbital period, where known, and details of the counterpart are listed in the sixth column.

* Although Cir X-1 was at this
it has been extremely faint, an
intensity returns to more typica
** XTE J1701−462 is a transie
intensity is a rough average over
unless it returns to an active state.

Selection criteria:

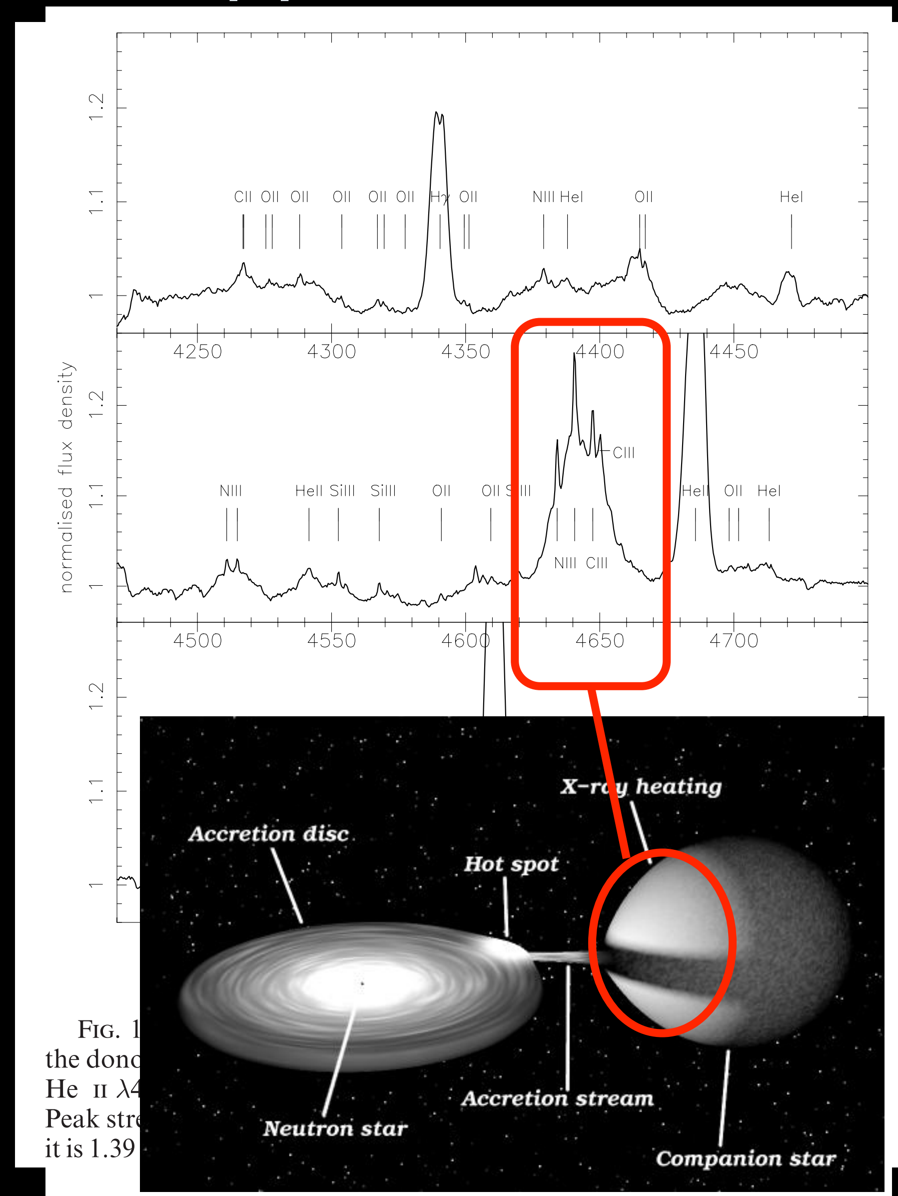
- X-ray bright
- Accessible optical counterpart

The double whammy

- Improved precision in orbital parameters also increases the detection sensitivity to X-ray pulsations, which have never been detected in the target systems
- A second stage, also exploiting the orbital solutions, is to make a search of (extensive) archival *RXTE* X-ray data for pulsations. With the improved orbital parameters and 15+ yr of *RXTE* data, we can do the most sensitive search yet
- Detection would allow us to measure the spin period; would confirm a neutron star; and give many orders of magnitude improvement in the GW search sensitivity

Observational approach

- Optical counterpart intensity and radial velocity vary with orbital phase
- Long-duration *photometric* or *spectroscopic* measurements required
- Steeghs &c pioneered use of *Bowen lines* as tracers of counterpart radial velocities



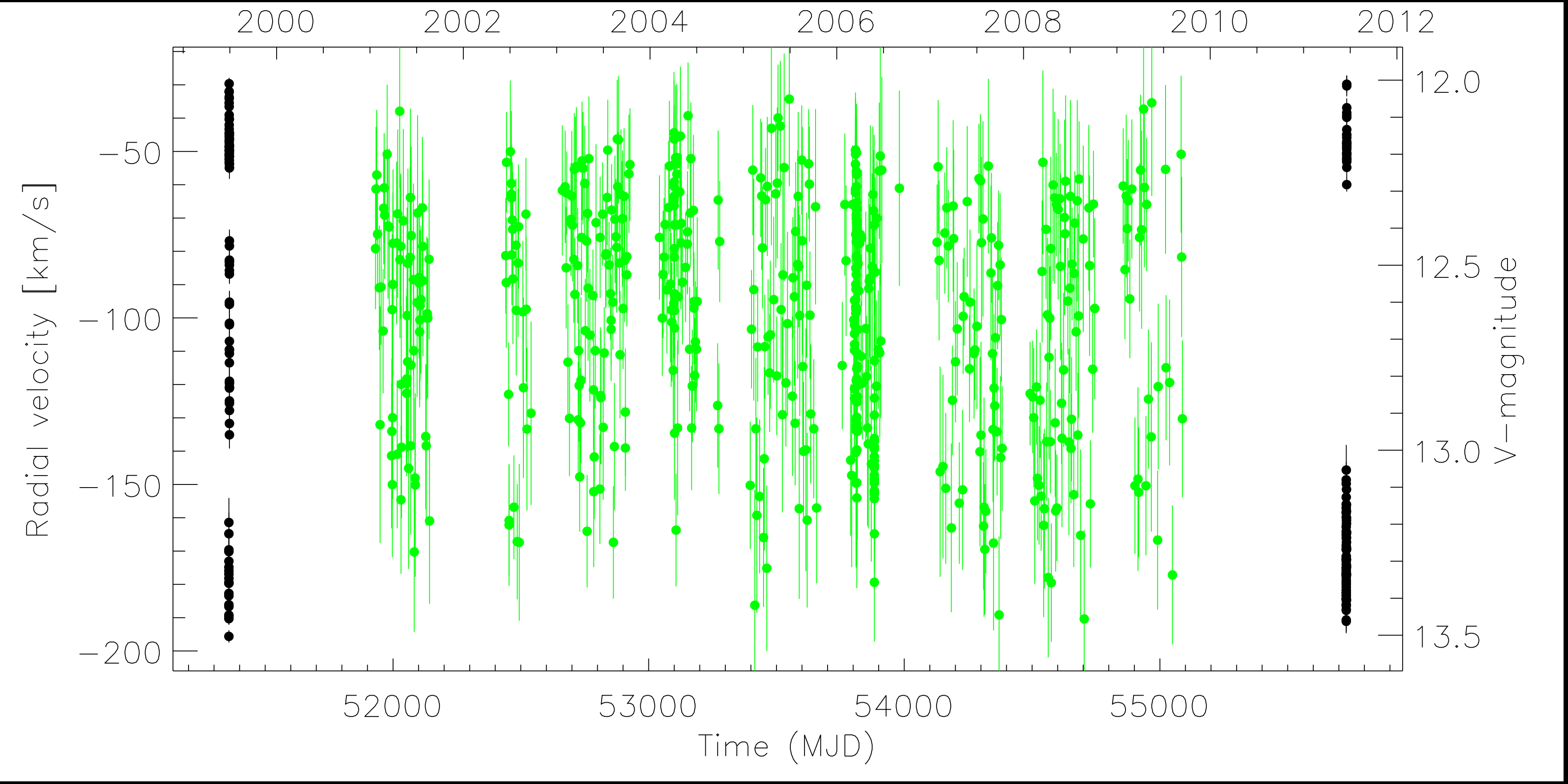
Candidate #1: Sco X-1

- Literature orbital period is based on photometric observations going back >100 years! Gottlieb et al. 1975, ApJ 195, L33
- Most recent ephemeris from spectroscopic measurements in 1999 Steeghs et al. 2002, 568, 273
- A reported alias with a slightly longer period (0.78901 d instead of 0.787313 d) due to the seasonality of photometric observations Vanderlinde et al. 2003, PASP 115, 739

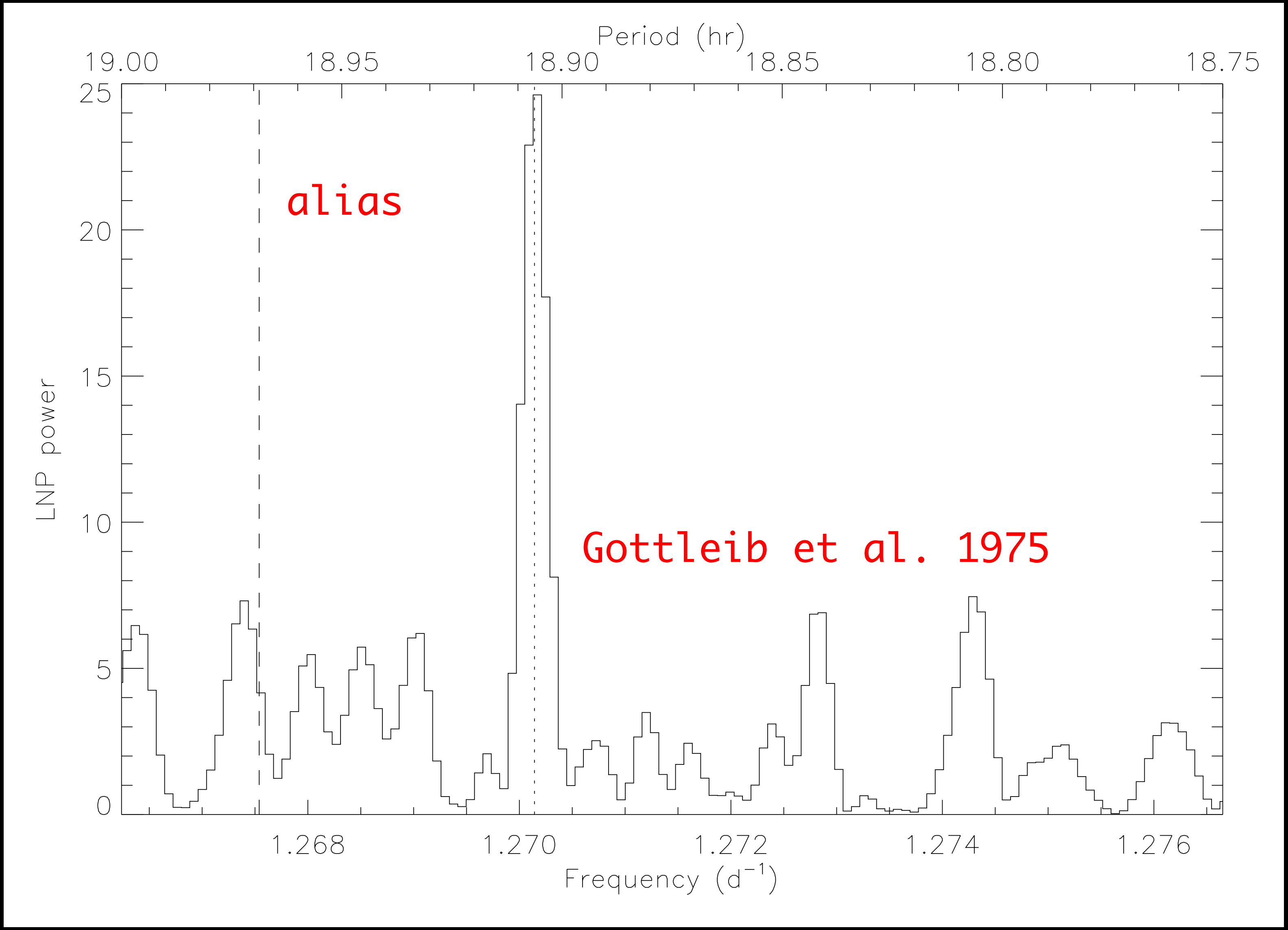
Parameter	value
P_{orb}	0.787313(1) d
T_0	2451358.568(3) HJD
K_2	77.2(4) km s^{-1}

New data

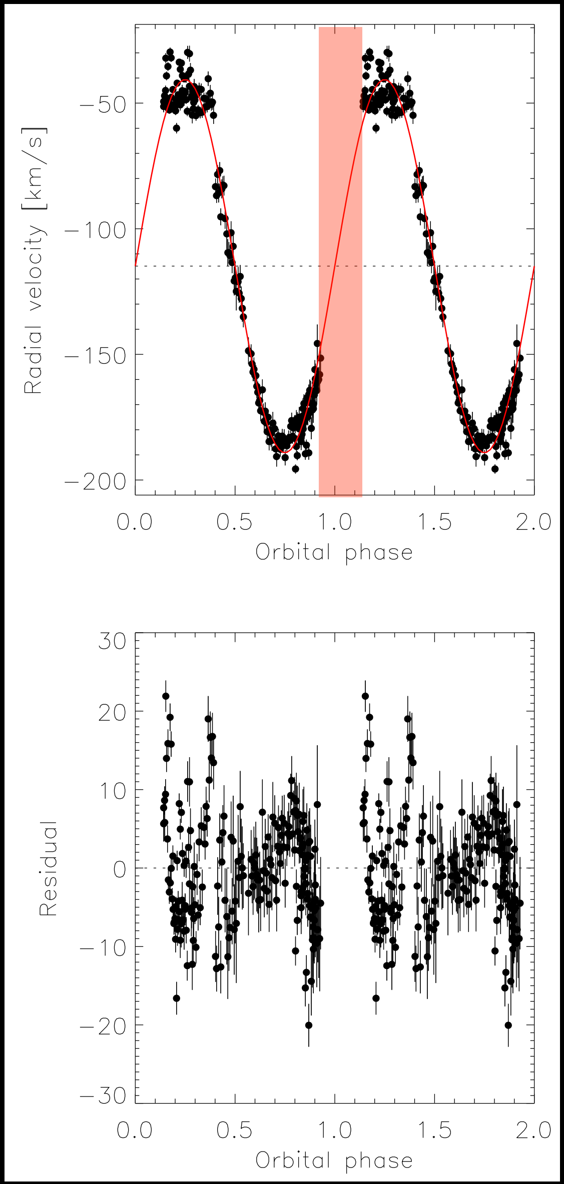
- Photometric data from All-sky Automated Survey (ASAS) http://www.astrouw.edu.pl/asas
- New epoch of optical spectroscopy (Jun 2011)



Confirming the Gottlieb et al. P_{orb}



Improving the P_{orb} precision

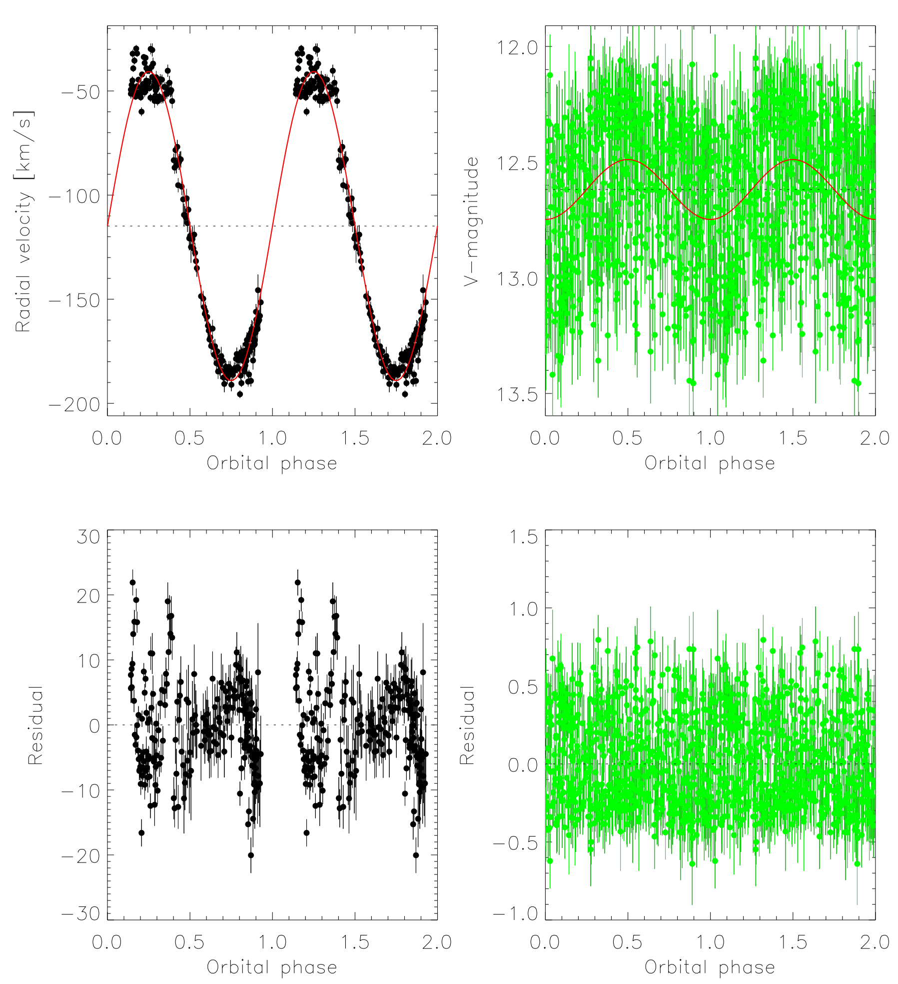


- Radial velocities from Bowen blend measurements are subject to *systematic uncertainties* due to weakness of lines around phase 0 (inferior conjunction)
- We screen the data to remove measurements with weak lines
- Can measure orbital phase to ~0.003 d (Steeghs et al. 2002)
- Over 6030 orbital cycles expect $\sigma P_{orb} \approx 7\times10^{-7}$ d
- Fits give

$$P_{orb} = 0.7873127 \pm 0.0000007 \text{ d}$$

Combined fits

- Joint fit of photometric and spectriscopic data yields the best precision on the parameters of interest
- Overall factor of ≈4 improvement in precision



Parameter	literature	this work	unit
P_{orb}	0.787313(1)	0.7873127(5)	d
T_0	2451358.568(3)	2451358.5769(13)	HJD
K_2	77.2(4)	74.3(7)	km s^{-1}

Conclusions & prospects

- Demonstrated feasibility of the program
- Still need to measure $a_X \sin i$, via Doppler tomography; expect (perhaps) another factor of ~2 improvement
- In Sco X-1, long-term P_{orb} (T_0) precision limited by
  - finite timespan
  - systematic uncertainties in radial velocities
- Likely can get these to a few by 10^{-7} (10^{-3}) days, respectively, for aLIGO searches; need to assess what that does for searches
- Apart from more data, modelling of the emission region is a (high-overhead) option

Recommended candidate #2: Cyg X-2

- A known burst source with an accessible optical counterpart
- Joint fits to archival data going back to 1975 with contemporary measurements provides improvements in system parameters:

Param	literature	Joint fits	Plus 2011a observations
P_{orb} (sec)	26	6	4
$a_X \sin i$ (lt-sec)	1.6	(0.9)	
T_0 (min)	43	16	13

Conclusions & prospects

- Our initial observations (over the next few months) will allow us to accurately estimate the likely precision we can reach by the AdvLIGO epoch
- We need to determine whether this is “good enough”, i.e. what is the best search strategy given the likely system parameter precision we can achieve
- Once our initial best-set of parameters are available, we will carry out X-ray pulsation searches (and perhaps also searches of in-hand LIGO data?)