CONTINUOUS WAVES FROM ROTATING NEUTRON STARS

Matthew Pitkin - University of Glasgow
DAWN Workshop

7 May 2015

LIGO G1500603
Rotating neutron stars with a non-axisymmetric deformation (a mass, or mass current, quadrupole) will emit GWs.

- ~ 160,000 “normal” and ~ 40,000 millisecond active pulsars in the Galaxy\(^1\)
- ≥ 2000 pulsars have been observed, with ~ 10% in frequency band of GW detectors

Credit: \(^1\)Lorimer, Living Rev. Relativity, 11 (2008)
Emission strength often characterised by quadrupole ellipticity $\varepsilon$, but this is uncertain within a range from $10^{-12} \lesssim \varepsilon \lesssim 10^{-5}$, maybe extending higher for hybrid/quark stars.

Credit: Andersson et al, GReGr, 43 (2011) arXiv:0912.0384
Theoretical maximum sustainable ellipticities provide upper limit, but whether these are realised in nature is unknown/unlikely. Methods of producing/sustaining ellipticities are also highly uncertain:

- mountains *locked-in* to crust following formation
- strong internal magnetic fields

We have no idea how many signal detections to expect in first years of aLIGO/AdV.

*Advocate for better modeling of neutron star deformation to enhance science case?*
What could we learn from CW gravitational wave emission\(^1\)?

- \(f_{GW} = 2f_{rot}\) star is probably a triaxial ellipsoid
- \(f_{GW} \approx 2f_{rot}\) shows components producing EM and GW emission are not completely coupled (information on crust and core coupling of star?)
- \(f_{GW} \approx f_{rot}\) precession play important role in emission
- \(f_{GW} \approx (4/3)f_{rot}\) emission from \(r\)-modes is favoured (information on interior fluid motion of star)

---

\(^1\)if accompanied by EM observation either from a known pulsar search or through follow-up of unknown sources
What could we learn from CW gravitational wave emission?

- if ellipticities are at the very high range we could potentially narrow down neutron star EOS
- multiple sources could yield information on ellipticity distributions to help constrain models of formation of deformations
  - are there different distributions for “normal” and millisecond pulsars?

But, we actually measure

\[ h \propto \frac{I_{zz} \varepsilon}{d}, \]

where \( I_{zz} \) is the moment of inertia and \( d \) is the distance, so measuring \( \varepsilon \) requires this additional information.
CONTINUOUS WAVES: SEARCHES

- **targeted searches**: fully coherent searches for known radio, X-ray and γ-ray pulsars

- **all-sky searches**: semi-coherent searches for unknown sources covering all-sky, wide frequency and frequency derivative ranges

- **directed searches**: (i.e. *searches for targets with unknown rotation rate*) coherent and semi-coherent searches using some knowledge of source (generally sky position) to perform a more sensitive search
  - supernova remnants (e.g. Cas A)
  - galactic center
  - LMXBs (e.g. Sco X–1)
Sensitivity for semi-coherent CW searches scales as

\[ h \approx \frac{C}{N^{1/4}} \sqrt[4]{\frac{S_n(f)}{T_{coh}}} \]

where \( T_{coh} \) is the coherent time, \( N \) is the number of coherent data stretches, \( S_n(f) \) is the power spectral density and \( C \) is a search dependent pre-factor.

\( C \) is proportional to the number of templates used – longer coherent times and larger parameter spaces require more templates to ensure phase coherence. Also, computational cost (for all-sky searches) scales as \( \sim T_{coh}^3 - T_{coh}^6 \).

*Best way to improve search sensitivity is to improve \( S_n(f) \)*
For all-sky and directed searches any candidate detections can be followed up using fully coherent methods to regain $T^{1/2}$ sensitivity increase

- provide better parameter estimation to constrain ellipticity
- for year long (or potentially less) integrations provides source sky position to $\sim$ arcsec precision, which greatly aids EM follow-up
Sensitivity can be improved by narrowing the parameter space (fewer templates), so input from EM observations are vital:

- targeted searches rely on EM information to provide phase evolution templates, so need to make sure we have access to latest radio, X-ray, $\gamma$-ray (new surveys, LOFAR, SKA, Fermi, ASTROSAT)
- encourage deeper searches (e.g. Einstein@home) in existing data to find more sources.
Sensitivity can be improved by narrowing the parameter space (fewer templates), so input from EM observations are vital:

- LMXB searches require huge template banks due to many source uncertainties, so narrowing these uncertainties (e.g. finding the rotation period of Sco X–1) would greatly increase sensitivity
- Directed searches could also be improved with more information, e.g. finding rotation periods of isolated X-ray sources, or neutron stars in supernova remnants

Advocate for pulsar surveys and X-ray timing with future radio and high energy observatories
For all-sky searches EM follow-up of detections enables greater physics return

- observations of pulsations gives rotational frequency and immediately narrows down the emission mechanism

But, pulsations may not be observed. We could require deeper imaging to look for faint X-ray source, or supernova remnant/pulsar wind nebula. How much telescope time would be required/could be obtained for these?

Follow-up of LMXBs may be most useful if it is coincident with further GW observations - can observe how GW and EM signals change over the same periods. This would require long term monitoring.
If we start seeing signals, and/or EM observations, and/or theory gives specifics of source parameters then we could narrow-band the detectors. However, with a detectors network *narrow-banding only one detector doesn’t help greatly* How would this effect other searches?

Credit: LIGO T0900288
How, feasible are other ways to improve sensitivity?

- Manually suppressing, or filtering, 60 Hz line from data to help with Crab? Although, the Crab is moving away from 60 Hz at a reasonable rate (currently at $\sim 59.35$ Hz and slowing down at $\sim 0.02$ Hz yr$^{-1}$!)

Unlike other searches *CW searches can make detections with a single detector.* So, if one aLIGO detector was being upgraded the other could still be used (in narrow-band mode?)
Are there things other than rotating neutron stars that we could look for?

- Search for CW emission from axions around a black hole\(^2\) (e.g. Cyg X–1, or SN1987A)
- maybe can adapt current searches for these, but there could be large signal modulation
- potential huge scientific pay-off if discovered
- Adapt searches for newly formed neutron stars following nearby supernovae
- requires searches to handle very high spin-downs and higher frequency derivatives

\(^2\)http://arxiv.org/abs/1004.3558
CONCLUSIONS

- Discovery of CW signal(s) during ADE is highly uncertain.
- Improving detector sensitivity is a guaranteed way to help CW searches.
- But, more EM input on poorly understood targets (notably Sco X–1 and Cas A) could be as valuable in improving achievable sensitivity and providing more potential sources.
- EM follow-up of detections is very important to extract physics.