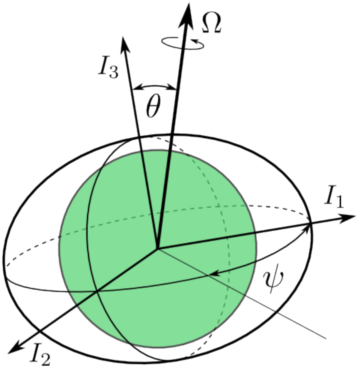
Continuous GWs from pulsars in ET MDC

Michał Bejger, Tomasz Bulik, Marek Cieślar & Andrzej Królak



6th Einstein Telescope Symposium, LMA-CNRS Lyon, 19-20.11.14

Outline

- Astrophysical sources of the periodic GW signal,
- Current upper limits from LIGO and Virgo,
- Adding pulsars to the ET MDC project:
  - Generation of the `.gwf` frames,
  - Full-scale MDC with narrowband data.

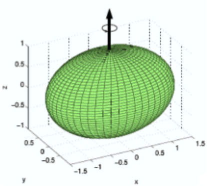
Continuous GWs from rotating neutron stars

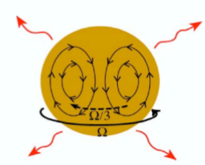
Time-varying quadrupole moment needed:

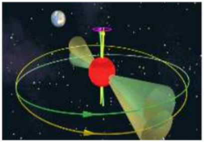
- ⋆ Mountains (supported by elastic and/or magnetic stresses in the NS crust and/or core),
- ⋆ Oscillations (r-modes)
- ⋆ Free precession,
- ⋆ Accretion from the companion (deformations, thermal gradients, magnetic fields).

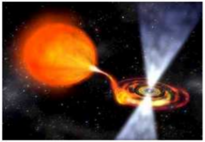
Main characteristics of such GWs:

- ⋆ periodic, $f_{\mathrm{GW}} \propto f_{\mathrm{rot}}$,
- ⋆ long-lived, $T > T_{\mathrm{obs}}$.

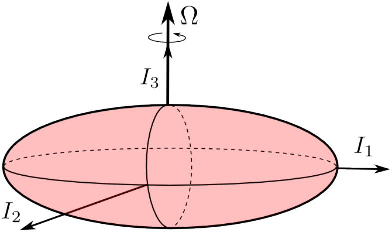








GW from NSs models: triaxial star



$\star$ Triaxial ellipsoid rotating about one of the principal directions of the moment of inertia tensor

$\star$ $\Omega_{gw} = 2\Omega$

2 GW degrees of freedom (wave polarizations):

$$h_+ = 2(\Omega^2/r)\Delta I_{21}$$
$$(1+\cos^2\iota)\cos(2\Omega t + \Phi_{gw})$$

$$h_\times = 4(\Omega^2/r)\Delta I_{21}\cos\iota\sin(2\Omega t + \Phi_{gw})$$

Parameters of the problem:

- $\star$ Spin frequency Ω
- $\star$ Orientation of spin axis, ι and ϕ
- $\star$ Amplitude $h_0 \propto (\Omega^2/r)\Delta I_{21}$
- $\star$ Phase Φ_{gw}

Estimated GW amplitude

Using the quadrupole formula, the GW amplitude is estimated as follows:

$$h_0 = \frac{16\pi^2 G}{c^4} \frac{I\epsilon f^2}{d}$$

$$= 4 \times 10^{-25} \left(\frac{\epsilon}{10^{-6}}\right) \left(\frac{I}{10^{45}\ \mathrm{g\ cm^2}}\right) \left(\frac{f}{100\ \mathrm{Hz}}\right)^2 \left(\frac{100\ \mathrm{pc}}{d}\right)$$

where $\epsilon = (I_1 - I_2)/I$, I - moment of inertia along the principal axis of its tensor, d - distance

Theoretical predictions for maximal possible deformations:

- ⋆ "Normal matter", $\epsilon \leq 10^{-6} - 10^{-7}$ (Ushomirsky, Cutler & Bildsten 2000, Johnson-McDaniel & Owen 2012)
- ⋆ Quark matter, $\epsilon \leq 10^{-4} - 10^{-5}$ (Owen 2005, Johnson-McDaniel & Owen 2012)

Related quantity, $m = l = 2$ mass quadrupole moment:

- ⋆ $Q_{22} \propto I\epsilon$

Spin-down limit for known pulsars

Limit on h_0, assuming that all rotational energy is lost in GWs:

- ⋆ Change of rotational energy: $E_{\rm rot} = 2\pi^2 I f^2,\ \dot{E}_{\rm rot} \propto I f \dot{f}$
- ⋆ GW luminosity: $\dot{E}_{\rm GW} \propto \epsilon^2 I^2 f^6$

$$\dot{E}_{\rm GW} = \dot{E}_{\rm rot} \quad \rightarrow \quad h_{\rm sd} = \frac{1}{d}\sqrt{\frac{5GI}{2c^3}\frac{|\dot{f}\,|}{f}} =$$

$$= 8 \times 10^{-24}\sqrt{\left(\frac{I}{10^{45}\ {\rm g\ cm}^2}\right)\left(\frac{|\dot{f}\,|}{10^{-10}\ {\rm Hz/s}}\right)\left(\frac{100\ {\rm Hz}}{f}\right)\left(\frac{100\ {\rm pc}}{d}\right)}\,.$$

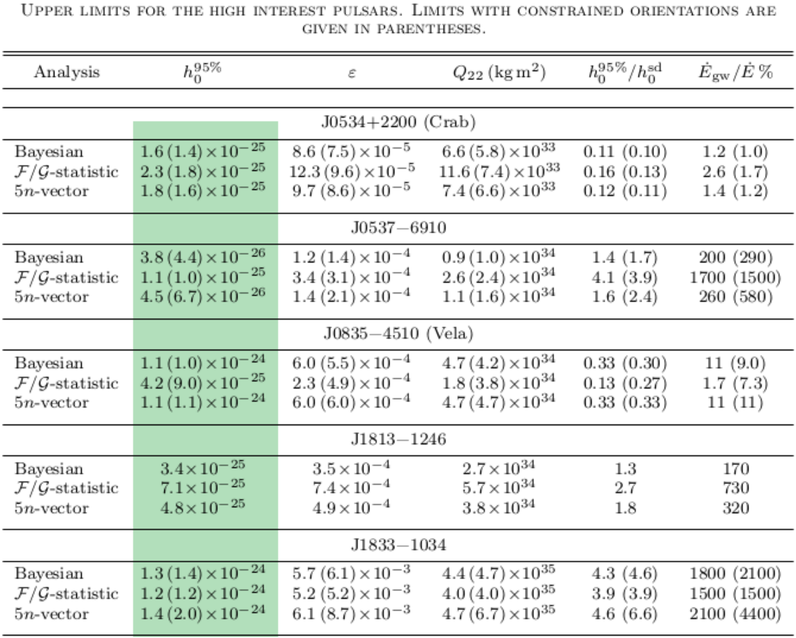
$h_0 \leq h_{\rm sd} \rightarrow$ **upper limit on the deformation ϵ:**

$$\epsilon_{\rm sd} = 2 \times 10^{-5}\sqrt{\left(\frac{10^{45}\ {\rm g\ cm}^2}{I}\right)\left(\frac{100\ {\rm Hz}}{f}\right)^5\left(\frac{|\dot{f}\,|}{10^{-10}\ {\rm Hz/s}}\right)}.$$

or

$$\epsilon_{\rm sd} = 0.2\left(\frac{h_{\rm sd}}{10^{-24}}\right) f^{-2} I_{45}^{-1} d_{kpc}$$

Current limits (J. Aasi et al., 2014 ApJ **785** 119)



UPPER LIMITS FOR THE HIGH INTEREST PULSARS. LIMITS WITH CONSTRAINED ORIENTATIONS ARE GIVEN IN PARENTHESES.

Analysis	$h_0^{95\%}$	ε	Q_{22} (kg m^2)	$h_0^{95\%}/h_0^{\rm sd}$	$\dot{E}_{\rm gw}/\dot{E}$ %
J0534+2200 (Crab)					
Bayesian	$1.6\,(1.4)\times10^{-25}$	$8.6\,(7.5)\times10^{-5}$	$6.6\,(5.8)\times10^{33}$	0.11 (0.10)	1.2 (1.0)
$\mathcal{F}/\mathcal{G}$-statistic	$2.3\,(1.8)\times10^{-25}$	$12.3\,(9.6)\times10^{-5}$	$11.6\,(7.4)\times10^{33}$	0.16 (0.13)	2.6 (1.7)
$5n$-vector	$1.8\,(1.6)\times10^{-25}$	$9.7\,(8.6)\times10^{-5}$	$7.4\,(6.6)\times10^{33}$	0.12 (0.11)	1.4 (1.2)
J0537−6910					
Bayesian	$3.8\,(4.4)\times10^{-26}$	$1.2\,(1.4)\times10^{-4}$	$0.9\,(1.0)\times10^{34}$	1.4 (1.7)	200 (290)
$\mathcal{F}/\mathcal{G}$-statistic	$1.1\,(1.0)\times10^{-25}$	$3.4\,(3.1)\times10^{-4}$	$2.6\,(2.4)\times10^{34}$	4.1 (3.9)	1700 (1500)
$5n$-vector	$4.5\,(6.7)\times10^{-26}$	$1.4\,(2.1)\times10^{-4}$	$1.1\,(1.6)\times10^{34}$	1.6 (2.4)	260 (580)
J0835−4510 (Vela)					
Bayesian	$1.1\,(1.0)\times10^{-24}$	$6.0\,(5.5)\times10^{-4}$	$4.7\,(4.2)\times10^{34}$	0.33 (0.30)	11 (9.0)
$\mathcal{F}/\mathcal{G}$-statistic	$4.2\,(9.0)\times10^{-25}$	$2.3\,(4.9)\times10^{-4}$	$1.8\,(3.8)\times10^{34}$	0.13 (0.27)	1.7 (7.3)
$5n$-vector	$1.1\,(1.1)\times10^{-24}$	$6.0\,(6.0)\times10^{-4}$	$4.7\,(4.7)\times10^{34}$	0.33 (0.33)	11 (11)
J1813−1246					
Bayesian	3.4×10^{-25}	3.5×10^{-4}	2.7×10^{34}	1.3	170
$\mathcal{F}/\mathcal{G}$-statistic	7.1×10^{-25}	7.4×10^{-4}	5.7×10^{34}	2.7	730
$5n$-vector	4.8×10^{-25}	4.9×10^{-4}	3.8×10^{34}	1.8	320
J1833−1034					
Bayesian	$1.3\,(1.4)\times10^{-24}$	$5.7\,(6.1)\times10^{-3}$	$4.4\,(4.7)\times10^{35}$	4.3 (4.6)	1800 (2100)
$\mathcal{F}/\mathcal{G}$-statistic	$1.2\,(1.2)\times10^{-24}$	$5.2\,(5.2)\times10^{-3}$	$4.0\,(4.0)\times10^{35}$	3.9 (3.9)	1500 (1500)
$5n$-vector	$1.4\,(2.0)\times10^{-24}$	$6.1\,(8.7)\times10^{-3}$	$4.7\,(6.7)\times10^{35}$	4.6 (6.6)	2100 (4400)

CW additions to ET MDC code: `CW_Pulsar_Inject()`

```
/* Add continues wave from pulsars */
if(cw_pulsar_inject_flag) {
  REAL8TimeSeries *pulsar_cw[numDetectors];

  for(j=0;j<numDetectors;j++) {
    pulsar_cw[j]=CW_Pulsar_Inject(gpsStartTime,rate,Tseg,&(det[j]));

    for(k=0;k<segLength;k++)
      series[j]->data->data[k] += pulsar_cw[j]->data->data[k];

    XLALDestroyREAL8TimeSeries(pulsar_cw[j]);

  }

}
```

New function `CW_Pulsar_Inject()` is defined in `Pulsars/CWPulsarInject.c` (header `Pulsars/CWPulsarInject.h`)

CW additions to ET MDC code: `CW_Pulsar_Inject()`

- We use the approach of `./lalapps/src/pulsar/Injections/sw_inj_frames.c` used in CW LIGO-Virgo MDC,
- generate the signals with `XLALGeneratePulsarSignal`, use everything that is needed from `lalsuite`,
- add signals together, finally add everything to the `.gwf` frame,
- new switch `-pulsarcw` in `Mdc_ET` main file.

Input from TEMPO-style `.par` files (stored in `input/pulsars.par/`):

```
PSRJ  J0534+2200
RAJ 05:34:31.97232
DECJ  22:00:52.069
PMRA  10.0661
PMDEC 2.5501
F0  29.74654212201602
F1  -3.719908752949545e-10
PEPOCH  55197
EPHEM DE405
psi -0.65215
phi0  2.7792
cosiota -0.24438
h0  1.e-27
```

`LAL`

MDC ET links to `LAL` libraries:

- Information about the detector from `LAL`:
  `lal/packages/tools/src/CreateDetector.c`
  `lal/packages/tools/include/LALDetectors.h`
- In order to produce time series - for example with `lalapps_heterodyne_pulsar` small changes has to be made in `lalpulsar/src/SFTutils.c` (currently it doesn't know about ET channels, `E1:STRAIN`, etc.).

We have prepared a patch.

Narrowband MDC: Crab pulsar example

A simpler way (especially for initial tests) to simulate the date is to generate a narrowband signal directly and add it to the simulated ET noise.

Example: in the narrow band, generate noise with Gaussian distribution with zero mean and variance

$$\sigma = \frac{A_h(f_{GW})}{\sqrt{2\,dt}}$$

where $A_h(f_{GW})$ is the amplitude spectral density of ET at pulsar GW frequency.

- ⋆ For Gaussian noise → upper limit (5% false alarm, 95% confidence) for GW signal from Crab (i.e., targeted search, pulsar with known position) for 1 yr observation by a single ET detector is

$$h_{UL} = 1.5 \times 10^{-27}.$$

Narrowband MDC: Crab pulsar example

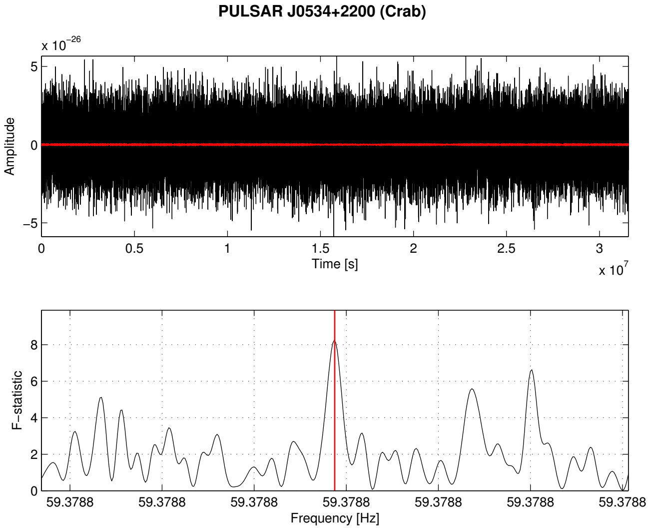
We have added the GW signal from Crab with amplitude h_{UL} to the simulated ET noise.

We then detect it with 0.25% false alarm probability and we estimate the 4 parmeters: h_0, phase ϕ_0, and polarisation angles ψ and ι.

Parameter estimation errors:

Parameter	Error (% or rad.)	Error in σs (Fisher matrix)
h_0[%]	8.9774	0.27021
ϕ_0 [*rad*]	0.12961	0.72511
ψ [*rad*]	0.095673	0.52306
cos(ι) [*rad*]	0.18879	1.0977

Narrowband MDC: Crab pulsar example



Upper panel: show data and added signal (red). *Lower panel*: array of the F-statistic values for the narrow band (black), and true signal frequency (red vertical line).

Summary

- ⋆ We are ready (± testing) to add pulsars to the ET `.gwfs`,
- ⋆ MDC focused on astrophysical question - use narrowband approach to save computing time?
  - ⋆ Known pulsars catalogue (ATNF, Fermi, . . .),
  - ⋆ Population synthesis for pulsars' background,
- ⋆ Study pulsars' distribution using GW and EM observations,
- ⋆ Production code for an all-sky search & analysis from a network of detectors (L1, H1, V1 and E1, E2, E3) is now ready,
- ⋆ Go beyond simple quadrupole radiation: 1f/2f (superfluid NS interior model Jones 2010, data analysis method by Bejger & Królak 2014), r-modes, EM-GW offset etc.