A method for directed searches of continuous gravitational waves in advanced detector data

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Overview

- What is a continuous gravitational wave (CW)?
- CWs searches and the computational problem
- Highlights of a directed search pipeline
- Potential sources of CWs signals form Fermi and INTEGRAL
- Can we detect something in O3?
What is a Continuous Wave (CW)?

- Long-lived signals emitted by fast spinning (asymmetric) compact objects
- Expected sources in LIGO-Virgo band involve isolated neutron stars (NS) or in a binary system
- Orders of magnitude weaker than transient events from black hole and neutron star mergers

[For a CW review: Lasky 2015]
The signal

In the general case of an isolated spinning NS, non-axisymmetric with respect to the rotational axis. The GW-strain amplitude is given by:

\[
h_0 = \frac{4\pi^2 G}{c^4} \frac{I_{zz} f^2}{r} \epsilon, \quad I_{zz} : \text{moment of inertia} \quad \epsilon : \text{ellipticity} \quad (1)
\]

- The emitted frequency is proportional to the star rotational frequency and depends on the emission scenario.
- The ellipticity can be due to different mechanisms: elastic stress, strong internal magnetic fields, thermal gradients, etc. (theoretical max: \(\epsilon_{max} \sim 10^{-5} – 10^{-3}\)), depending on the EOS.

[For a CW review: Lasky 2015]
The signal modulations

A CW received at the detector is not exactly monochromatic (there is a frequency and amplitude modulation)

- there is a spin-down due to the loss of energy of the star

\[
f_0(t) = f_0 + \dot{f}_0(t - t_0) + \frac{\ddot{f}_0}{2}(t - t_0)^2 + \ldots
\]  

(2)
The signal modulations

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- due to the orbital and rotational motion of the Earth, there is a detector Doppler shift, dependent on the sky direction of the source.

\[ f(t) = \frac{1}{2\pi} \frac{d\Phi(t)}{dt} = f_0(t) \left(1 + \frac{\vec{v} \cdot \hat{n}}{c}\right), \quad \vec{v} = \vec{v}_{orb} + \vec{v}_{rot} \]
The signal modulations

A CW received at the detector is not exactly monochromatic (there is a frequency and amplitude modulation)

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\]

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\[
f(t) = \frac{1}{2\pi} \frac{d\Phi(t)}{dt} = f_0(t) \left(1 + \frac{\vec{v} \cdot \hat{n}}{c}\right), \quad \vec{v} = \vec{v}_{\text{orb}} + \vec{v}_{\text{rot}} \tag{3}
\]

- Furthermore there is a **sidereal day variation** of the phase and amplitude of the detected signal
 Correction of the signal

For a source with known rotational parameters \([f_0, \dot{f}_0, \ddot{f}_0, \ldots]\) at a given reference time:

- The **Doppler shift** can be corrected by simply multiplying the data by \(\exp(-i\phi_{dc}(t))\) where:

  \[
  \phi_{dc}(t) = 2\pi p_{\hat{n}}(t)f_0(t)
  \]

  \(p_{\hat{n}}(t)\) position of the detector projected along the source sky position \(\hat{n}\)

- While the **spin-down** phase correction is:

  \[
  \phi_{sd}(t) = 2\pi \int \dot{f}_0 \cdot (t - t_0) + \ldots dt
  \]

- Other effects like the **Einstein delay** and the **Shapiro delay** should be considered if needed
CW searches

- explore a $4 + N$ dimensional space ($\alpha, \delta, f, \dot{f} + \text{derivatives}$)
- Long integration time is needed in order to increase the Signal-to-Noise Ratio
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Directed O1:
LVC arXiv:1812.11656
15 SNR + Fomalhaut b
A method for directed searches of continuous gravitational waves in advanced detector data

CW searches

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Previous directed targets (LIGO S6): young SN remnants, the Orion Spur, Cas A, NGC 6544, LMXBs Scorpius X-1 and XTE J1751-305, the Galactic center
CW searches

- explore a $4 + N$ dimensional space ($\alpha, \delta, f, \dot{f} + \text{derivatives}$)
- Long integration time is needed in order to increase the Signal-to-Noise Ratio

Dergachev, Papa arXiv:1902.05530
The BSD-directed pipeline

1. The starting point is the Band-Sampled-Data (BSD) framework (Piccinni+ 2019)
A method for directed searches of continuous gravitational waves in advanced detector data

The BSD-directed pipeline

2. Since \((f_0, f_0')\) are unknown we partially correct the data for the Doppler in each 1 Hz band
The BSD-directed pipeline

1. BSD time series
2. Multi-Doppler corrections in sub-bands
3. Peakmaps with enhanced coherence time
4. Frequency Hough Map (HM)

Candidates followup

Candidates selection

Sum of the single HM

3. **Peakmap**: The most significant time-frequency peaks selected in the equalized spectrum (Astone+ 2005)
The BSD-directed pipeline

4. **FrequencyHough** transform maps the time frequency peaks to the source intrinsic frequency and spin-down (Astone+ 2014)
The BSD-directed pipeline

The most significant candidates are selected on the final HM. The total computational power needed for this search is \( \sim 100 \) CPU hours per target for a "wide" frequency/spin-down range.
Potential sources

- Sources which are likely hosting a NS are interesting candidates for our searches.
- Several potential sources are present in the astronomical catalogs like:
  - the pre-release of the 8-years Fermi-LAT point sources catalog\textsuperscript{1}
  - the IBIS-INTEGRAL soft gamma-ray source catalog (Bird+ 2016).
- most of the sources lie on the Galactic plane
- in addition to these targets the Galactic center itself is a good place to look for CW since it is likely to host several candidates (Bartels+ 2016, Lee+ 2016, Fermi-LAT coll. 2017)

\textsuperscript{1}https://fermi.gsfc.nasa.gov/ssc/data/access/lat/fl8y/
INTEGRAL catalog presents the following interesting sources: 10 SNR, 19 pulsar-like sources and 216 unidentified ones (23%) which sky distribution is shown below:
The Fermi catalog potential CW sources are:

### Identified:

<table>
<thead>
<tr>
<th>Source</th>
<th>#</th>
<th>Frequency</th>
<th>position</th>
<th>CW search</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulsar (PSR)</td>
<td>184</td>
<td>well known</td>
<td>well known</td>
<td>targeted</td>
</tr>
<tr>
<td>Pulsar Wind Nebula (PWN)</td>
<td>8</td>
<td>not known</td>
<td>known</td>
<td>directed</td>
</tr>
<tr>
<td>Supernova remnant (SNR)</td>
<td>22</td>
<td>not known</td>
<td>known</td>
<td>directed</td>
</tr>
</tbody>
</table>

### Associated: no pulsations seen yet

<table>
<thead>
<tr>
<th>Source</th>
<th>#</th>
<th>Frequency</th>
<th>position</th>
<th>CW search</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulsar (psr)</td>
<td>34</td>
<td>not well known</td>
<td>known</td>
<td>Narrow-band</td>
</tr>
<tr>
<td>Pulsar Wind Nebula (pwn)</td>
<td>11</td>
<td>not known</td>
<td>not well known</td>
<td>semi-directed</td>
</tr>
<tr>
<td>Supernova remnant (snr)</td>
<td>17</td>
<td>not known</td>
<td>not well known</td>
<td>semi-directed</td>
</tr>
<tr>
<td>Potential pwn or snr (spp)</td>
<td>96</td>
<td>not known</td>
<td>not well known</td>
<td>semi-directed</td>
</tr>
</tbody>
</table>
Fermi-LAT (2)

Unassociated: 2132 in Fermi-LAT (∼39%) we have only gamma-rays observation, no counterparts at other wavelengths
How ”good” is a target

- for a given pipeline we can have an estimate of the search sensitivity (Astone+ 2014) which is given by $h_{0\text{min}} \approx \sqrt{S_n(f)}$ (minimum detectable GW strain amplitude, $\alpha$ depends on the coherence time and peaks/candidates thresholds used)

- typically for targeted searches we can compute the indirect spin-down limit using the frequency and the spin-down parameters of a source

- for directed searches we use the age based upper limit $h_{age}$ for those sources whose age and distance is known (Wette 2008)

- a good target will have $h_{age} \geq h_{0\text{min}}$

- all these quantities can be translated in terms of the star ellipticity $\epsilon_{age}$ and $\epsilon_{min}$ (see Eq. (1))
Theoretical indirect upper limits

The sources shown in the plot are potentially detectable by our directed search pipeline since they have a theoretical indirect age based limit (among them Cas A) bigger than our search sensitivity. Other sources from the catalog were discarded because the age or the distance was unknown.

\[ h_{\text{age}} \leq \frac{1}{d} \sqrt{\frac{5G I_{zz}}{8c^3 \tau}} \]

\[ h_{0_{\text{min}}} \approx \sqrt{\frac{S_\gamma (f)}{\alpha}} \]
Theoretical indirect upper limits on the ellipticity

Since $h_0 \propto \frac{I_{zz}}{d} \epsilon f^2 \rightarrow \epsilon_{min} = \frac{c^4}{4\pi^2 G} \left( \frac{d}{I_{zz}} \right) \frac{h_{0_{min}}}{f^2}$

Curve of $\epsilon_{min}$ at 95 % C.L. for the case of LIGO and Virgo detectors with $d = 1$ kpc and 20 kpc and the 8 SNR ellipticity indirect upper limits $\epsilon_{age}$. The theoretical indirect upper limit for the star ellipticity is

$$\epsilon_{age} \leq \sqrt{\frac{5c^5}{128\pi^4 GI_{zz} \tau f^4}}$$
Conclusion

- CW could be the next surprise for GW astronomy given the enhanced sensitivity of the detectors
- In parallel, new fast and computationally robust pipelines are needed to increase the chance of detection
- Astronomical catalogs (Fermi, INTEGRAL,...) provide good targets for our directed pipelines if they beat the indirect limit
- It’s a good practice to keep track also of those sources which couldn’t beat the limit and include them as target in future searches
References

References

The sensitivity of the search

\[ h_{0,\text{min}} \propto \Lambda_1 \frac{1}{N(f)^{1/4}} \sqrt{\frac{S_n(f)}{T_{coh}(f)}} \]
\[ h_{0,\text{min}} \approx \frac{4.02}{N(f)^{1/4}\theta_{thr}^{1/2}} \sqrt{\frac{S_n(f)}{T_{coh}(f)}} \left( \frac{p_0(1-p_0)}{p_1^2} \right)^{1/4} \sqrt{C R_{thr}(f) - \sqrt{2}\text{erfc}^{-1}(2\Gamma)} \]

\[ \Gamma = 95\% C.L., \; \theta_{thr} = 2.5, \; p_0 = 0.0755, \; p_1 = 0.0692, \; \text{p0 prob of selecting a noise peak} \]

\[ C R_{thr} = \sqrt{2}\text{erfc}^{-1}(2 \times N_{\text{cand}}/N_{\text{tot}}) = 6.50 \]

\[ P_{fa} = \frac{1}{N_{\text{tot}}} = \sum_{n_{if}n_{isd}} \frac{1}{n_{if}n_{isd}} = 3.98\times 10^{-11} \text{ if } N_{\text{cand}} = 1 \]

\[ h_0 = \frac{4\pi^2G I_{zz}f^2}{c^4} \frac{1}{r}\epsilon \]  

(6)
The theoretical spin-down limit

- A spinning star loses energy (spin-down)
  - Rotational energy loss: $\dot{E}_{\text{rot}} \propto I_{zz} f_{\text{rot}} \dot{f}_{\text{rot}}$
  - Gravitational energy loss: $\dot{E}_{\text{GW}} \propto I_{zz}^2 f_{\text{rot}}^6 \epsilon^2$

- We can assume that all the loss of energy of a rotating NS is caused by GW emission. In other words we assume that the observed star spin-down (the decrease of the rotation period) is due to GWs:

$$\dot{E}_{\text{rot}} = \dot{E}_{\text{GW}} \implies \epsilon_{sd} \propto \sqrt{\frac{1}{I_{zz}} \frac{|\dot{f}_{\text{rot}}|}{f_{\text{rot}}^5}}$$

(7)

From $h_0$ we can express a theoretical upper limit for the GW amplitude:

$$h_{sd} \propto \frac{1}{r} \sqrt{I_{zz} |\dot{f}_{\text{rot}}|}$$

(8)
The age based limit

If we assume that the star is spinning down with \( \dot{f} \propto f^n \) and it is spinning significantly more slowly than it was at birth, we can relate the frequency evolution to the characteristic age \( \tau \) and braking index \( n \):

\[
\tau = \frac{1}{n-1} \left( \frac{f}{-\dot{f}} \right)
\]

\[
n = \frac{f \ddot{f}}{\dot{f}^2}
\]

If the spin-down is dominated by GW from a constant mass quadrupole, then \( n = 5 \) and \( \tau \) is the true age of the star and the spindown limit becomes:

\[
h_{\text{age}} \leq \frac{1}{d} \sqrt{\frac{5GI_{zz}}{8c^3 \tau}}
\]
The Band-Sampled-Data framework

- **What has been done:** development of routines to create and manage band-limited time series (BSD), down-sampled and partially cleaned from disturbances
- **Which data:** time series is under the form of reduced-analytic signal
- **A DB of DBs:** each BSD file covers 1 month of data and 10 Hz frequency band + routines to switch to a different configuration
- **Flexibility:** optimized FFT length for a given search or step of the analysis (e.g. targeted, follow-up)
The Multi-Doppler correction

- **classical heterodyne**
  \[
  \phi_d(t) = \frac{2\pi}{c} \cdot p\hat{n}(t) \cdot f_0(t)
  \]

- **divide et impera**: the 10 Hz BSD band is divided in sub-bands

- **modified heterodyne** \((f_0(t)\text{ unknown})\)
  \[
  \phi_i(t) = \frac{2\pi}{c} \cdot p\hat{n}(t) \cdot f_i
  \]

- **corrected time series**
  \[
  y_{MD} = \sum_{i=1}^{10} y'_i(t) = \sum_{i=1}^{10} y_i(t) \cdot e^{-i\phi_i}
  \]
The peak selection

A peak is selected when the following relation holds:

\[
R(i, j) = \frac{S_{P;i}(f_j)}{S_{AR;i}(f_j)} > \theta_{thr} = 2.5
\]  

(9)

where \( S_{P;i}(f_j) \) is the square modulus of the \( i \)–th FFT, also known as periodogram, and \( S_{AR;i}(f_j) \) an auto-regressive average spectrum estimation. The ratio is computed for each \( j \)–th frequency bin of a given FFT. Each pair \((i, j)\) made by the \( i \)-th initial time of a selected FFT and the corresponding \( j \)–th frequency bin is a peak.