A search for gravitational waves associated with the August 2006 timing glitch of the Vela pulsar

http://arxiv.org/abs/1011.1357

James Clark For The LSC
This talk: first search for GWs associated with pulsar timing glitch (and first major public outing for results):

- Pulsar glitches & gravitational radiation
- LIGO August 2006 Vela glitch search

Full details:

http://arxiv.org/abs/1011.1357

(To appear in Physical Review D soon)
Pulsar Glitches

- Occasional (for e.g., Vela I every ~2 years) sudden step increases observed in spin-frequency

- Sudden leap (drop) in spin freq (period) is followed by exponential recovery to ~pre-glitch spin on timescales of days-weeks

- Pre-glitch spin-down well modeled by Taylor expansion of frequency about reference time $\Omega_0$:

$$\Omega(t) = \Omega_0 + \dot{\Omega}t$$

- Residuals between pre-glitch spin-down model and observed pulse arrival times described by:

$$\Delta\Omega(t) = \Delta\Omega_p + \Delta\dot{\Omega}_p t + \frac{1}{2} \Delta\ddot{\Omega}_p t^2 + \sum_{i=1}^{N} \Delta\Omega_i e^{-t/\tau_i}$$

- Fitting for the recovery time-scale $\tau$ allows estimation of glitch epoch.
Pulsar Glitches & Gravitational Waves

- Mechanism is unclear but may be:
  - star-quake (crustal rearrangement)
  - internal superfluid vortex un-pinning

- Glitches & GWs:
  - superfluid vortex avalanche (short ~1ms white noise burst)
  - global oscillations (f-modes: 1-3 kHz, 50-500ms ring-downs)
  - longer emission from r-modes, internal fluid motion (hours - days)

Energy Scales

\[
\Delta E_{\text{quake}} \approx 10^{42} \text{ erg} \left( \frac{I_*}{10^{38} \text{ kg m}^2} \right) \left( \frac{\Omega}{20\pi \text{ rad s}^{-1}} \right)^2 \left( \frac{\Delta \Omega/\Omega}{10^{-6}} \right)
\]

\[
\Delta E_{\text{vortex}} \approx 10^{38} \text{ erg} \left( \frac{I_c}{10^{37} \text{ kg m}^2} \right) \left( \frac{\Omega}{20\pi \text{ rad s}^{-1}} \right)^2 \left( \frac{\Delta \Omega/\Omega}{10^{-6}} \right) \left( \frac{\Omega_{\text{lag}}/\Omega}{5 \times 10^{-4}} \right)
\]
Oscillation Model

• Assume glitch somehow excites f-mode oscillations (i.e., frequencies 1-3 kHz)

• Decompose fluid oscillations into spherical harmonics of degree $l$, order $m$.

• We’re interested in the quadrupole mode ($l=2$) with superposition of $m=-2,-1,0,+1,+2$ modes

  • $m=0$: rotational symmetry - natural connection with build-up of superfluid lag or decreasing centrifugal force

  • $|m|=1$: glitch begins at one point in star and moves out (vortex avalanche)

  • $|m|=2$: glitch inherits symmetry of magnetic dipole field

• Which, if any, dominates dictated by UNKNOWN behaviour in stellar interior
GW model

- Simplifying assumptions:
  - only a single \( m \) dominates, spin unimportant

- Plus, cross waveform polarisations:

\[
h_{+}^{2m}(t) = \begin{cases} 
  h_{2m} A_{+}^{2m} \sin[2\pi \nu_0 (t - t_0) + \delta_0] e^{-(t-t_0)/\tau_0} \text{ for } t \geq t_0, \\
  0 \text{ otherwise.}
\end{cases}
\]

\[
h_{\times}^{2m}(t) = \begin{cases} 
  h_{2m} A_{\times}^{2m} \cos[2\pi \nu_0 (t - t_0) + \delta_0] e^{-(t-t_0)/\tau_0} \text{ for } t \geq t_0, \\
  0 \text{ otherwise.}
\end{cases}
\]

- Inclination affects relative amplitudes through \( A_+, A_\times \):

- If we have inclination (and polarisation) info, we have a good handle on the intrinsic GW amplitudes

(Note that the data analysis pipeline works with power spectral densities so is insensitive to the sign of \( m \))
- Search method deploys Bayesian odds ratio as detection statistic:

\[
\mathcal{O}(+,-) = \frac{\Pr(M_+|D)}{\Pr(M_-|D)} = \frac{\Pr(M_+)}{\Pr(M_-)} \frac{\Pr(D|M_+)}{\Pr(D|M_-)}
\]

- choose between two models: detection (i.e., ring-down signal) or null-detection (Gaussian noise OR ring-down signals independent across detectors):

\[
\mathcal{O}(+,-) = \frac{\Pr(D|M_+)}{\Pr(D|T) + \Pr(D|N)}
\]

(see also poster by Prix et al on CW line veto)

- automatically rejects many instrumental transients, BUT incapable of distinguishing correlated instrumental transients

- compare on-source value to background distribution from off-source

- if on-source value > loudest off-source value, have detection candidate, meriting follow-up.

- otherwise, form marginal posteriors on GW amplitude & energy to form Bayesian upper limits
A Glitch In PSR B0833 (Vela)

• 12th August 2006: large glitch observed in PSR B0833 (Vela Pulsar) by S. Buchner, C. Flanagan of Hartesbeestock Radio Astronomy Observatory (HartRAO)

• HartRAO (originally Deep Space Station 51) 26m radio telescope located ~50 km west of Johannesburg. Perform daily monitoring of Vela for glitches

• August glitch was during the fifth LSC science run (S5)

• all 3 LIGO detectors operating at design sensitivity

• only the 2 Hanford detectors have contiguous science quality data during the entire glitch epoch (L1 data suffers degradation in quality)
EM observations: orientation

- Inclination and polarisation angle of Vela is well constrained from Chandra X-ray observations
- Distance to Vela (used to estimate energy upper limits from measured GW amplitude upper limits) is well constrained by HST (293 pc)
• TEMPO2 pulsar timing software used to fit model for post-glitch phase residuals

• S. Buchner (HartRAO) dug further into radio data to provide refined estimate of glitch epoch and uncertainty:

UTC 2006-08-12 22:31:22 ±17

• We assume GW emission occurs somewhere in a 120s window around this (≈ 3-σ)
Gravitational wave search result...
August 2006 Vela Glitch: Results

- Use 161 off-source segments of 120 s to estimate background distribution of detection statistic (odds ratio)

- Estimate probability of obtaining an odds ratio greater than or equal to the value found in the on-source segment

- Probability of obtaining on-source data for no GW present = 0.92

Conclusion: no evidence for ring-down gravitational wave signal associated with Vela August 2006 Glitch
August 2006 Vela Glitch Search: Amplitude Posteriors

\[ p(h_{lm}|D, M+) \times 10^{20} \]

- \( l = 2, |m| = 0 \)
- \( l = 2, |m| = 1 \)
- \( l = 2, |m| = 2 \)

90% confidence upper limits:
- \( 1.4 \times 10^{-20} \)
- \( 1.2 \times 10^{-20} \)
- \( 6.3 \times 10^{-21} \)
August 2006 Vela Glitch Search: Energy Posteriors

\[ p(E_{lm} | D, M_+) \times 10^{-45} \]

Gravitational wave energy \( (E_{lm}) \times 10^{45} \text{ erg} \)

| \( l = 2, |m| = 0 \) | \( l = 2, |m| = 1 \) | \( l = 2, |m| = 2 \) |
|----------------|----------------|----------------|
| 5.0 \times 10^{44} | 1.3 \times 10^{45} | 6.3 \times 10^{44} |

90% confidence upper limits
August 2006 Vela Glitch: Efficacy

Determine efficacy of pipeline through software injections

- $8.3 \times 10^{-21}$
- $1.6 \times 10^{-20}$
- $1.8 \times 10^{-20}$

90% detection efficiencies
### Tabulated upper limits for different spherical harmonics

<table>
<thead>
<tr>
<th>Spherical Harmonic Indices</th>
<th>$h_{2m}^{90%}$</th>
<th>$E_{2m}^{90%}$ (erg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$l = 2, m = 0$</td>
<td>$1.4 \times 10^{-20}$</td>
<td>$5.0 \times 10^{44}$</td>
</tr>
<tr>
<td>$l = 2, m = \pm 1$</td>
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</table>

Recall most optimistic $E_{gw} \sim 10^{42}$ erg

- Notice that these appear many orders of magnitude better than comparable SGR upper limit $2.4 \times 10^{48}$ erg [Phys. Rev. Lett. 101 (2008) 211102]:
  - proximity of Vela (293 pc vs 10 kpc)
  - using orientation data to compute energy upper limits
  - Vela upper limit using average orientation & $D=10$ kpc: $1.8 \times 10^{48}$ erg
Summary

- Pulsar glitches may lead to f-mode excitation with frequencies 1-3 kHz, durations 50-500 ms

- A search for f-mode ring-down signals associated with the August 2006 Vela glitch resulted in no detection candidates but upper limits:
  - peak strain 90% confidence limits = $6.3 \times 10^{-21} - 1.4 \times 10^{-20}$
  - total GW energy 90% confidence limits = $5.0 \times 10^{44} - 6.3 \times 10^{44}$ erg

- Average sky-location, isotropic emission @ 10 kpc, we find:
  - LIGO S5 Vela glitch energy upper limit = $1.3 \times 10^{48}$ erg

- Advanced LIGO x10 improvement in strain sensitivity = x100 improvement in energy

- will begin to probe interesting ($\sim 10^{42}$ erg) energy limits for pulsar glitches

- orientation / inclination information crucial to upper limit interpretation
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