To Catch a Wave - Direct Searches for Gravitational Radiation

Keith Riles
University of Michigan

Shanghai Particle Physics and Cosmology Symposium
June 3-5, 2013.
What are Gravitational Waves?

- Gravitational Waves = “Ripples in space-time”
- Perturbation propagation similar to light (obeys same wave equation!)
  - Propagation speed = c
  - Two transverse polarizations - **quadrupolar**: + and x

Example:
Ring of test masses responding to wave propagating along z

Amplitude parameterized by (tiny) dimensionless strain $h$: $\Delta L \sim h(t) \times L$
Why look for Gravitational Radiation?

• Because it’s there! (presumably)

• Tests General Relativity:
  – Quadrupolar radiation? Travels at speed of light?
  – Unique probe of strong-field gravity

• Gain different view of Universe:
  – Sources cannot be obscured by dust / stellar envelopes
  – Detectable sources some of the most interesting, least understood in the Universe
  – Opens up entirely new non-electromagnetic spectrum
What makes Gravitational Waves?

- Radiation generated by quadrupolar mass movements:

\[ h_{\mu\nu} = \frac{2G}{rc^4} \frac{d^2}{dt^2} (I_{\mu\nu}) \]

(with \( I_{mn} \) = quadrupole tensor, \( r \) = source distance)

- Example: Pair of 1.4 M_{solar} neutron stars in circular orbit of radius 20 km (imminent coalescence) at orbital frequency 400 Hz gives 800 Hz radiation of amplitude:

\[ h \approx \frac{10^{-21}}{(r/15\text{Mpc})} \]
What makes Gravitational Waves?

- Compact binary inspiral: "chirps"
  - NS-NS* waveforms are well described
  - BH-BH* need better waveforms

- Supernovae / GRBs: "bursts"
  - burst signals in coincidence with signals in electromagnetic radiation / neutrinos
  - all-sky untriggered searches too

- Spinning neutron stars in our galaxy: "periodic"
  - search for observed pulsars
  - all-sky search (computing challenge)

- Cosmological Signals "stochastic background"

* NS = Neutron Star, BH = Black Hole
Gravitational Wave Detection

- Suspended Interferometers
  - Suspended mirrors in “free-fall”
  - Michelson IFO is “natural” GW detector
  - Broad-band response (~50 Hz to few kHz)
  - Waveform information (e.g., chirp reconstruction)
The GW Detector Network 2005-2010

Network increases detection confidence, allows source triangulation

LIGO Hanford

LIGO Livingston

Virgo

GEO600
LIGO strain spectral noise in 2009-2010 Science Run S6

Amplitude sensitivity ≈ (statistical scale factor) x (strain noise) / sqrt(signal duration)

10-ms transient

\[ h_{\text{sens}} \approx 10^{-21} \]

1-year pulsar emission

\[ h_{\text{sens}} \approx \text{few} \times 10^{-26} \]
Virgo’s seismic isolation allowed probing lower frequencies than initial LIGO (low-freq pulsars, BH-BH binaries)

LIGO and Virgo sensitivity comparison

Histogram of maximum distances to which a NS-NS inspiral could have been seen in S6 and Virgo VSR2/3 data runs
Searching for Gravity Waves

- **Binary Inspirals**
  - (NS-NS)
  - Spinning BH-BH merger

- **Bursts**
  - (Supernovae)

- **Continuous waves**
  - (Isolated spinning NS)
  - Accreting NS

- **Stochastic background**
  - (Cosmological, astrophysical)

**Known waveform**

**Unknown waveform**

**Short-Lived** ↔ **Long-Lived**
Searching for binary systems

Fourier transform of data time series (noise \( n \) + signal \( h \)):

\[
\tilde{x}(f) = \int_{-\infty}^{\infty} dt \ e^{-i2\pi ft} \ [x(t) = n(t) + h(t)]
\]

Define signal strength vs time (optimal filter):

\[
z(t) = 2 \int_{-\infty}^{\infty} \frac{\tilde{h}(f)\tilde{x}^*(f)}{S_n(f)} \ e^{i2\pi ft} \ df
\]

Signal-to-noise ratio:

\[
\rho(t) = \frac{|z(t)|}{\sigma}
\]

with

\[
\sigma^2 = 2 \int_{-\infty}^{\infty} \frac{|\tilde{h}(f)|^2}{S_n(f)} \ e^{i2\pi ft} \ df
\]
No evidence of (real) excess
→ Set upper limits on inspiral rate
   (# per Mpc$^3$ per year)
   vs stellar mass:

Now assume $M_{BH} \approx 10 \, M_\odot$

*Phys Rev. D85 (2012) 082002*
Searching for generic bursts (untriggered)

- Search for coincident triggers ("Coherent WaveBurst")
- Check waveform consistency among interferometers – apply vetoes
- Set a threshold for detection for low false alarm probability
- Evaluate efficiency for variety of simple generic waveforms

Parameterize strength in terms of “root sum square of h”:

$$\left(h_{\text{RSS}}\right)^2 = \int_{-\infty}^{+\infty} \left( |h_+ (t)|^2 + |h_\times (t)|^2 \right) dt$$

Efficiency

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Sine-Gaussian</td>
<td>Black Hole Ringdown</td>
<td>White Noise Burst</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$f_0$ [Hz]</th>
<th>Detection Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>2090 L</td>
<td><img src="image1.png" alt="Graph" /></td>
</tr>
<tr>
<td>2090 C</td>
<td><img src="image2.png" alt="Graph" /></td>
</tr>
<tr>
<td>2590 L</td>
<td><img src="image3.png" alt="Graph" /></td>
</tr>
<tr>
<td>2590 C</td>
<td><img src="image4.png" alt="Graph" /></td>
</tr>
</tbody>
</table>

Compliments NASA
Searching for generic bursts

No candidates found above threshold
(false alarm rate = 1 / (8 yr))
→ Set upper limits on rate vs $h_{\text{RSS}}$

Sine-Gaussians
(Q=9, varying $f_{\text{central}}$)

Phys Rev. D85 (2012) 122007
Bayesian heterodyne algorithm applied to 116 known pulsars over 23 months of LIGO data (using radio / X-ray ephemerides)

Lowest upper limit on strain:

\[ h_0 < 2.3 \times 10^{-26} \]

Lowest upper limit on ellipticity (non-axisymmetry):

\[ \varepsilon < 7 \times 10^{-8} \]

Upper limit on Crab energy loss due to GW:

2\%
Searches for **unknown** pulsars over the entire sky **computationally bound** (Doppler effects due to Earth’s motion)

→ Must make tradeoffs in sensitivity vs parameter space coverage

**“PowerFlux” approach:**

Semi-coherent, stacks (~2 years) of 30-minute, demodulated power spectra

**Astrophysical reach**
http://www.einsteinathome.org/

- GEO-600 Hannover
- LIGO Hanford
- LIGO Livingston
- Current search point
- Current search coordinates
- Known pulsars
- Known supernovae remnants

Comparable limits over larger band obtained recently with E@H

PRD87 (2013) 042001

Your computer can help too!
Searching for a stochastic background

- A primordial isotropic GW stochastic background is predicted by most cosmological theories.
- Given an energy density spectrum $W_{gw}(f)$, there is a strain power spectrum:

$$\Omega_{GW}(f) = \frac{1}{\rho_c} \frac{d\rho_{GW}(f)}{d \ln f}$$

$$S_{gw}(f) = \frac{3H_0^2}{10\pi^2} f^{-3} \Omega_{gw}(f)$$

- The signal can be searched from cross-correlations in different pairs of detectors, e.g., L1-H1.
- The farther apart the detectors, the lower the frequencies that can be searched.

$h(f) = S_{gw}^{1/2}(f) = 5.6 \times 10^{-22} h_{100} \sqrt{\Omega_0} \left( \frac{100\text{Hz}}{f} \right)^{3/2} \text{Hz}^{1/2}$
Published H1-L1 Bayesian 90% UL:

\[ \Omega_{90\%} = 6.9 \times 10^{-6} \text{ (40-170 Hz)} \]

Will return to this
Binary coalescence:
• Low-mass inspirals (primordial black holes)
• High-mass inspirals
• Spinning black holes
• Ringdown of final black hole (merger final state)

Gravitational Wave transients coincident with
• Gamma Ray Bursts
• Soft Gamma Repeaters
• Magnetar flares
• High Energy Neutrinos

Continuous gravitational waves from
• Vela (low-frequency pulsar)
• Cassiopea A (isolated neutron star)
• Scorpius X-1 (low-mass X-ray binary)

Anisotropic stochastic gravitational radiation
(including from galactic center, Sco X-1, Supernova 1987A)
Advanced LIGO

Increased laser power:

10 W → 200 W

Improved shot noise (high freq)

Increased test mass:

10 kg → 40 kg

Compensates increased radiation pressure noise

Higher-Q test mass:

Fused silica with better optical coatings

Lower internal thermal noise in band
Advanced LIGO

New suspensions:

Single $\rightarrow$ Quadruple pendulum

Lower suspensions thermal noise in bandwidth

Improved seismic isolation:

Passive $\rightarrow$ Active

Lowers seismic “wall” to $\sim$10 Hz
Neutron Star Binaries:
Average range ~ 200 Mpc
Most likely rate ~ 40/year

The science from the first 3 hours of Advanced LIGO should be comparable to 1 year of initial LIGO

But that sensitivity will not be achieved instantly...

Advanced LIGO

arXiv: 1304.0670
The GW Detector Network~2020

- Advanced LIGO Hanford
- Advanced Virgo
- GEO600
- LIGO-India
- KAGRA

- Advanced LIGO Livingston
Alternate Path to Direct GW Detection

Pulsar Timing Arrays

If our galactic neighborhood is bathed in very-long-wavelength GW radiation, the timing pulses received from distant pulsars may be distorted in a quadrupolar spatial pattern.

Detectable statistically from an ensemble of stable pulsars

→ Look for correlations in timing residuals after fitting to pulse model.
Pulsar Timing Arrays

Three radio astronomy consortia:
• Parkes PTA (Australia)
• European PTA
• NanoGrav (N. America)

Joint analysis planned as part of International Pulsar Timing Array (PPTA+EPTA+NanoGrav = IPTA)
NanoGrav Pulsar Timing Residuals [µs]

J0030+0451
J0613−0200
J1012+5307
J1455−3330
J1600−3053
J1640+2224
J1643−1224
J1713+0747
J1744−1134
J1853+1308
B1855+09
J1909−3744
J1910+1256
J1918−0642
B1953+29
J2145−0750
J2317+1439

Courtesy: David Nice
Pulsar Timing Arrays

Sensitive to gravitational waves at extremely low frequencies (~10 nHz)

Most likely source – stochastic background from incoherent superposition of many distant supermassive black hole inspirals

But detecting a single “nearby” CW source is possible too

Challenge:
Separating stochastic GW background from experimental noise

Best solution:
Find more millisecond pulsars!
→ Intense hunt ongoing
Summary

Bottom line:

No GW signal detected yet 😞

But

• Not all initial LIGO/Virgo searches completed
• Advanced LIGO / Virgo will bring major sensitivity improvements with orders of magnitude increase in expected event rates

First LIGO/Virgo discovery likely in next 3-5 years

• Depends on commissioning progress
  – unexpected technical obstacles are the worry
• Also depends on Nature’s kindness

Wild Card: PTAs may see first glimpse of ~nHz GWs on same time scale!

New field of astronomy will open soon – exciting era ahead!