Gravitational-Wave Astronomy

1060-711: Astronomical Observational Techniques and Instrumentation

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Outline

1. Gravitational-Wave Physics
   - Physical Motivation
   - Mathematical Description
   - Generation of Gravitational Waves

2. Gravitational-Wave Detectors
   - Overview
   - Details of Ground-Based Interferometers
   - Prospects for Space-Based Interferometers

3. Gravitational-Wave Astronomy
   - Gravitational Wave Sources
   - Gravitational Wave Data Analysis
   - Selected Results from First-Generation GW Detectors
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Action at a Distance

- Newtonian gravity: mass generates gravitational field
- Lines of force point towards object
Issues with Causality

- Move object; Newton says: lines point to new location
- Relativity says: can’t communicate faster than light to avoid paradoxes
- You could send me supraluminal messages via grav field
Gravitational Speed Limit

- If I’m 10 light years away, I can’t know you moved the object 6 years ago.
- Far away, gravitational field lines have to point to old location of the object.
Gravitational Shock Wave

- Sudden motion (acceleration) of object generates gravitational shock wave expanding at speed of light
Ripples in the Gravitational Field

- Move object back & forth → gravitational wave
- Same argument applies to electricity:
  - can derive magnetism as relativistic effect
  - accelerating charges generate electromagnetic waves propagating @ speed of light
Gravitational Wave from Orbiting Mass?

- Move around in a circle
- Still get grav wave pattern, but looks a bit funny
- Time to move beyond simple pseudo-Newtonian picture
Gravity + Causality = Gravitational Waves

- In Newtonian gravity, force depends on distance between objects.
- If a massive object suddenly moved, the gravitational field at a distance would change instantaneously.
- In relativity, no signal can travel faster than light. This means that time-dependent gravitational fields must propagate like light waves.

Astronomical Observational Techniques and Instrumentation
Gravitational-Wave Astronomy
Gravity as Geometry

Minkowski Spacetime:

\[ ds^2 = -c^2(dt)^2 + (dx)^2 + (dy)^2 + (dz)^2 \]

\[
= \begin{pmatrix}
  dt \\
  dx \\
  dy \\
  dz
\end{pmatrix}^T
\begin{pmatrix}
  -c^2 & 0 & 0 & 0 \\
  0 & 1 & 0 & 0 \\
  0 & 0 & 1 & 0 \\
  0 & 0 & 0 & 1
\end{pmatrix}
\begin{pmatrix}
  dt \\
  dx \\
  dy \\
  dz
\end{pmatrix}
= \eta_{\mu\nu} dx^\mu dx^\nu
\]

General Spacetime:

\[ ds^2 = \begin{pmatrix}
  dx^0 \\
  dx^1 \\
  dx^2 \\
  dx^3
\end{pmatrix}^T
\begin{pmatrix}
  g_{00} & g_{01} & g_{02} & g_{03} \\
  g_{10} & g_{11} & g_{12} & g_{13} \\
  g_{20} & g_{21} & g_{22} & g_{23} \\
  g_{30} & g_{31} & g_{32} & g_{33}
\end{pmatrix}
\begin{pmatrix}
  dx^0 \\
  dx^1 \\
  dx^2 \\
  dx^3
\end{pmatrix}
= g_{\mu\nu} dx^\mu dx^\nu
Gravitational Wave as Metric Perturbation

- For GW propagation & detection, work to 1st order in $h_{\mu\nu}$
- $h_{\mu\nu} \equiv$ difference between actual metric $g_{\mu\nu}$ & flat metric $\eta_{\mu\nu}$:

$$g_{\mu\nu} = \eta_{\mu\nu} + h_{\mu\nu}$$

($h_{\mu\nu}$ “small” in weak-field regime, e.g. for GW detection)

- Convenient choice of gauge is transverse-traceless:

$$h_{0\mu} = h_{\mu0} = 0 \quad \eta^{\nu\lambda} \frac{\partial h_{\mu\nu}}{\partial x^\lambda} = 0 \quad \eta^{\mu\nu} h_{\mu\nu} = \delta^{ij} h_{ij} = 0$$

In this gauge:
- Test particles w/constant coördinate are freely falling
- Vacuum Einstein eqns $\implies$ wave equation for $\{h_{ij}\}$:

$$\left( - \frac{1}{c^2} \frac{\partial^2}{\partial t^2} + \nabla^2 \right) h_{ij} = 0$$
Far from source, GW looks like plane wave prop along $\vec{k}$

TT conditions mean, in convenient basis,

$$\{k_i\} \equiv k = \begin{pmatrix} 0 \\ 0 \\ 1 \end{pmatrix} \quad \{h_{ij}\} \equiv h = \begin{pmatrix} h_+ & h_x & 0 \\ h_x & -h_+ & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

where $h_+ \left( t - \frac{x^3}{c} \right)$ and $h_x \left( t - \frac{x^3}{c} \right)$ are components in “plus” and “cross” polarization states

More generally

$$\vec{h} = h_+ \left( t - \frac{\vec{k} \cdot \vec{r}}{c} \right) \vec{e}_+ + h_x \left( t - \frac{\vec{k} \cdot \vec{r}}{c} \right) \vec{e}_x$$
wave propagating along $\vec{k}$; construct $\vec{e}_+,$ $\vec{e}_\times$ from $\perp$ unit vectors $\vec{l}$ & $\vec{m}$:

$$\vec{e}_+ = \vec{l} \otimes \vec{l} - \vec{m} \otimes \vec{m} \quad \vec{e}_\times = \vec{l} \otimes \vec{m} + \vec{m} \otimes \vec{l}$$
Effects of Gravitational Wave

Fluctuating geom changes distances btwn particles in free-fall:

<table>
<thead>
<tr>
<th>Plus (+) Polarization</th>
<th>Cross (×) Polarization</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image" alt="Plus Polarization" /></td>
<td><img src="image" alt="Cross Polarization" /></td>
</tr>
</tbody>
</table>
"Electric Dipole"? No, "dipole moment" $\int \vec{r} \, dm \propto \text{ctr of mass}$

COM can’t oscillate (also no negative “charge” in GR)

"Magnetic Dipole"? No, "mag moment"

$\frac{1}{2} \int \vec{r} \times \vec{v} \, dm \propto \text{spin}$, another conserved quantity

"Electric Quadrupole"? Yes! In TT gauge,

$$h_{ij}(t) = \frac{2G}{c^4 d} \mathcal{P}_{TT}^{\vec{k}k\ell} \tau_{i j}^{\vec{k}k\ell}(t - d/c)$$

in terms of mass quadrupole moment

$$\tau_{i j} = \int \left( r_i r_j - \delta_{i j} \frac{r^2}{3} \right) \, dm$$
Quadrupole Radiation From Rotating/Orbiting System

- Equatorial moments of inertia $I_1, I_2$
- Orbital/rotational ang vel $\Omega$
- GW frequency $f_{gw} = \frac{2\Omega}{2\pi}$
- Since $\ddot{I} \sim (2\Omega)^2 |I_1 - I_2|$, 

$$
\leftrightarrow h = \frac{4G\Omega^2(I_1 - I_2)}{c^4d} \left( \hat{e}_+ \frac{1 + \cos^2 \iota}{2} \cos 2\Omega t + \hat{e}_x \cos \iota \sin 2\Omega t \right)
$$

- For binary system w/masses $m_1, m_2$ and separation $r$,

$$
I_1 = 0 \quad \text{and} \quad I_2 = \mu r^2
$$

where $\mu = \frac{m_1m_2}{m_1+m_2} = \frac{m_1m_2}{M}$ is the reduced mass
Total mass $M = m_1 + m_2$; reduced mass $\mu = \frac{m_1 m_2}{M}$; orbital freq $\Omega$

- Amplitude is $h_0 = \frac{4G\Omega^2 \mu r^2}{c^4 d}$

- Kepler’s 3rd law: $GM = r^3 \Omega^2 \implies r^2 = (GM\Omega^{-2})^{2/3}$

- $h_0 = \frac{4G^{5/3} M^{2/3} \mu \Omega^{2/3}}{c^4 d} = \frac{4(GM_c)^{5/3} \Omega^{2/3}}{c^4 d}$

where $M_c = M \eta^{3/5}$ is chirp mass & $\eta = \frac{\mu}{M}$ is symm mass ratio

- Orbit will evolve due to GW emission (radiation reaction): energy lost, $r$ dec., $\Omega$ inc., $h_0$ inc.: “chirp”

- Quasicircular assumption breaks down when $r_{isco} \approx 6GM/c^2$ near “innermost stable circular orbit” (ISCO); orbital freq @ ISCO is $\Omega_{isco} \approx \sqrt{\frac{GM}{r_{isco}^3}} = \frac{c^3}{6^{3/2} GM}$

- Modelling final merger accurately requires numerical simulations like those done in RIT CCRG
Some Sources of Gravitational Waves

Band: ground, space, pulsar timing

- Binary coalescence (inspiral+merger+ringdown):
  - Supermassive BH binary
  - extreme mass ratio (stellar mass + SMBH)
  - Stellar mass BH and/or neutron star

- Galactic white dwarf binary orbit (continuous source)

- Rotating neutron star (pulsar, LMXB, etc)

- Supernova, SGR

- Cosmological background
  - (primordial, phase transitions, cosmic superstrings, etc)

- SMBH flyby
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Methods for Measuring Gravitational Waves

- Cosmic Microwave Background Perturbations \( (f_{gw} \sim H_0 \sim 10^{-18} \text{ Hz}) \)
- Pulsar Timing Arrays \( (10^{-9} \text{ Hz} \lesssim f_{gw} \lesssim 10^{-7} \text{ Hz}) \)
- Laser Interferometers
  - Space-Based \( (10^{-3} \text{ Hz} \lesssim f_{gw} \lesssim 10^{-1} \text{ Hz}) \)
  - Ground-Based \( (10^1 \text{ Hz} \lesssim f_{gw} \lesssim 10^3 \text{ Hz}) \)
- Resonant-Mass Detectors (narrowband, \( f_{gw} \sim 10^3 \text{ Hz} \))

Note, observable GW freq cover 20 orders of magnitude, similar to EM radiation, but the frequencies are much lower \( (10^3 \text{ Hz} \lesssim f_{em} \lesssim 10^{23} \text{ Hz}) \)
The Gravitational-Wave Spectrum

http://www.tapir.caltech.edu/~teviet/Waves/
Rogues’ Gallery of Ground-Based Interferometers

LIGO Hanford (Wash.)

GEO-600 (Germany)

LIGO Livingston (La.)

Virgo (Italy)
Initial Gravitational Wave Detector Network

- “1st generation” ground-based interferometric GW detectors (kilometer scale):
  - TAMA 300 (Tokyo, Japan) first online, late 90s; now offline
  - LSC detectors conducting science runs since 2002
    - LIGO Hanford (4km H1 & 2km H2)
    - LIGO Livingston (4km L1)
    - GEO-600 (600m G1)
  - Virgo (3km V1) started science runs in 2007
  - LSC-Virgo long joint runs @ design sensitivity 2005-2010
- LIGO and Virgo being upgraded to 2nd generation “advanced” detectors (10× improvement in sensitivity)
- GEO-600 remains operational in “astrowatch” mode in case there’s a nearby supernova
Advanced Gravitational Wave Detector Network

“2nd generation” ground-based interferometric GW detectors:
- Adv LIGO expected to take science data from 2014 or 2015
  4km detectors in Livingston, La. & Hanford, Wa.
- Advanced Virgo should be on comparable timescale
- KAGRA (cryogenic detector in Kamioka mine, Japan) uses 2.5-generation technology
- Third advanced LIGO detector (4km) may be installed in India, taking data c.2019+
  Big payoff for sky localization via tringulation

Planning for 3rd generation already underway:
- Einstein Telescope in Europe
- USA 3G plans still under development
  (RIT CCRG involved in astrophysics planning)
Initial/enhanced LIGO was a power-recycled Fabry-Pérot Michelson interferometer

Advanced LIGO will be a dual-recycled Fabry-Pérot Michelson interferometer

Basic idea: use interferometry to measure changes in difference of arm lengths to detect $h \lesssim 10^{-20}$
Gravitational-Wave Physics
Gravitational-Wave Detectors
Gravitational-Wave Astronomy

Overview
Ground-Based IFOs
Space-Based IFOs

Michelson Interferometer

\[ w/\lambda_{\text{laser}} \sim 10^{-6} \text{ m} \& L \sim 10^3 \text{ m} \]

would need to measure

\[ \delta L \sim 10^{-11} \lambda_{\text{laser}} \]

to detect \( h \sim 10^{-20} \)
Increase “effective length” of arms by keeping light in resonance within FP cavities; finesse $\sim 200$ amplifies signal
Lengths tuned to keep antisym port dark; power recycling mirror recovers light & sends it back into IFO
Advanced LIGO/Virgo will also have signal recycling mirror (technology tested by GEO) to decouple noise sources
Have to keep FP cavities locked; don’t literally let mirrors move in response to GW (& environment); feedback loop keeps IFO in resonance; “GW channel” derived from applied control signal.
Sources of Noise in Initial LIGO

![Graph showing the sensitive region for gravitational wave detection](graph.png)

- **SUSPENSION THERMAL**: Thermal noise from the suspension system.
- **RADIATION PRESSURE**: Pressure from distant light sources.
- **GRAVITY GRADIENT**: Gravity gradient effects.
- **TEST MASS THERMAL**: Thermal noise from the test masses.
- **RESIDUAL GAS, 10^-6 TORR H_2**: Noise from residual gas at 10^-6 Torr.
- **STRAY LIGHT**: Light scattered from outside the instrument.
- **RESIDUAL GAS, 10^-9 TORR H_2**: Noise from residual gas at 10^-9 Torr.

The shaded area represents the sensitive region where gravitational waves can be detected above the noise background.
Initial Detector Sensitivities

Representative Noise Spectral Density Curves During S5 and VSR1

- H1 (range = 34.1Mpc)
- L1 (range = 33.1Mpc)
- H2 (range = 15.3Mpc)
- V1 (range = 7.7Mpc)

See arXiv:1003.2481
“Enhanced” Detector Sensitivities

Representative Spectra for LIGO/Virgo Detectors in S6/VSR2-3

Amplitude Spectral Density ($1/\sqrt{Hz}$)

Frequency (Hz)

See arXiv:1203.2674
Advanced Detector Expectations

Advanced LIGO

See arXiv:1304.0670
Advanced Detector Expectations

See arXiv:1304.0670
The Saga of Space-Based GW Detectors
The Saga of Space-Based GW Detectors

- LISA (Laser Interferometer Space Antenna) originally proposed in 1993 for 2011 launch; designed to detect mHz GWs from SMBH, galactic WD binaries, EMRIs, etc
- Planned as joint NASA/ESA mission
- Never got funding wedge; dropped by NASA in 2011
- ESA considered “NGO” (LISA-lite) for L-class mission; recently opted for JUICE (moons of Jupiter mission)
- LISA/NGO consistently rated high on science by NASA/ESA, but concerns about practicalities
- LISA Pathfinder Mission flies 2014, to demonstrate technology
- Next ESA L-class mission will be selected in 2015; could fly mid-2020s
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At freqs relevant to ground-based detectors (10s-1000s of Hz), natural division of sources according to nature of signal

<table>
<thead>
<tr>
<th></th>
<th>modelled</th>
<th>unmodelled</th>
</tr>
</thead>
<tbody>
<tr>
<td>long</td>
<td><strong>Periodic Sources</strong> (e.g., Rotating Neutron Star)</td>
<td><strong>Stochastic Background</strong> (Cosmological or Astrophysical)</td>
</tr>
<tr>
<td>short</td>
<td><strong>Binary Coalescence</strong> (Black Holes, Neutron Stars)</td>
<td><strong>Bursts</strong> (Supernova, short BH Merger, etc.)</td>
</tr>
</tbody>
</table>
Data Analysis Techniques

- **Periodic**: Waveform well-modelled & long-lived
  Sky position via **Doppler modulation**

- **Stochastic**: Cross-correlate detector outputs
  → Signal-to-noise improves with time

- **Bursts**: Signal unmodelled
  → Look for unusual features & **coherence** between detectors
  Recent searches include **GRB triggers**

- **Inspiral**: Signal well modelled (at least early)
  → **Matched Filtering**
Template Waveforms for Binary Coalescence

- Inspiralling binaries produce well-modelled GW signals;
- Search with pattern-match filter
- Compact object binary coalescence consists of inspiral / plunge / merger / ringdown

Cartoon by Kip Thorne
Template Waveforms for Binary Coalescence

- Inspiralling binaries produce well-modelled GW signals; Search with pattern-match filter
- Compact object binary coalescence consists of inspiral / plunge / merger / ringdown

Compact object binary coalescence consists of inspiral / plunge / merger / ringdown.

For first part of inspiral, orbits not too relativistic can expand in powers of $\frac{v}{c} \rightarrow$ post-Newtonian methods. Can estimate orb vel from Kepler’s 3rd law: $v \approx (\pi GMf)^{1/3}$

- **Low Mass** $\rightarrow$ plunge @ high freq
  $1.4M_\odot/1.4M_\odot$ NS/NS binary has $v \approx 0.3c$ @ 800 Hz; PN OK in LIGO band
- **High Mass** $\rightarrow$ plunge @ low freq
  $10M_\odot/10M_\odot$ BH/BH binary has $v \approx 0.4c$ @ 200 Hz; merges in LIGO band

Different template families used for different mass ranges.
Matched Filtering GW Data

- Match-filtered signal-to-noise ratio measures how well template “fits” data: \( \rho \sim \int df \frac{x^*(f)h(f)}{S_n(f)} \)
- Time series for each set of param (e.g., \( m_1 \) & \( m_2 \)) values
- Lay out parameter choices in template bank to get good overlap w/possible signals
Continuous Waves: Searching for Known Pulsars

- **Phase params** (rotation, sky pos [& binary params]) known
  Pulsar ephemerides (timing) detail phase evolution
- Can search over **amplitude params** ($h_0, \iota, \psi, \phi_0$);
  search cost **NOT** driven by observing time
- Different options for **amplitude parameters**:
  - Maximize likelihood analytically ($\mathcal{F}$-statistic)
  - Marginalize likelihood numerically ($\mathcal{B}$-statistic)
  - Get posterior prob distribution w/Markov-Chain Monte Carlo
  - Use astro observations to constrain spin orientation ($\iota$ & $\psi$)
- Spindown produces **indirect upper limit**
  - GW emission above limit $\rightarrow$ more spindown than seen
  - Pulsars w/rapid spindown have “more room” for GW
  - LIGO/Virgo have surpassed spindown limit for Crab & Vela
LMXB: compact object (neutron star or black hole) in binary orbit with companion star
If NS, accretion from companion provides “hot spot”; rotating non-axisymmetric NS emits gravitational waves
Bildsten *ApJL* 501, L89 (1998) suggested GW spindown may balance accretion spinup; GW strength can be estimated from X-ray flux
Torque balance would give $\approx$ constant GW freq
Signal at solar system modulated by binary orbit
Brightest LMXB: Scorpius X-1

Scorpius X-1
- $1.4M_\odot$ NS w/ $0.4M_\odot$ companion
- unknown params are $f_0$, $a \sin i$, orbital phase

LSC/Virgo searches for Sco X-1:
- Coherent $\mathcal{F}$-stat search w/ 6 hr of S2 data
  Abbott et al (LSC) *PRD* 76, 082001 (2007)
- Directed stochastic ("radiometer") search (unmodelled)
  Abbott et al (LSC) *PRD* 76, 082003 (2007)
  Abbott et al (LSC) *PRD* 107, 271102 (2011)

Proposed directed search methods:
- Look for comb of lines produced by orbital modulation
  Messenger & Woan, *CQG* 24, 469 (2007)
- Cross-correlation specialized to periodic signal
  Dhurandhar et al *PRD* 77, 082001 (2008)

Promising source for Advanced Detectors
Searching for Unknown NSs: Einstein@Home

Semicoherent methods needed to handle phase param space; Increase computing resources by enlisting volunteers
Distributed using BOINC & run as screensaver

http://www.einsteinathome.org/
Searching for a Stochastic Background

- Noisy data from GW Detector:
  \[ x(t) = n(t) + h(t) = n(t) + \hat{h}(t) : \bar{d} \]

- Look for correlations between detectors

  \[
  \langle x_1 x_2 \rangle = \overbrace{\langle n_1 n_2 \rangle}^{\text{avgto0}} + \overbrace{\langle n_1 h_2 \rangle}^{\text{avgto0}} + \overbrace{\langle h_1 n_2 \rangle}^{\text{avgto0}} + \langle h_1 h_2 \rangle
  \]

- Expected cross-correlation (frequency domain)

  \[
  \langle \tilde{x}_1^*(f) \tilde{x}_2(f') \rangle = \langle \tilde{h}_1^*(f) \tilde{h}_2(f') \rangle = \overleftrightarrow{d_1} : \langle \tilde{h}_1^*(f) \otimes \tilde{h}_2(f') \rangle : \overleftrightarrow{d_2}
  \]

- For stochastic backgrounds

  \[
  \langle \tilde{h}_1^*(f) \tilde{h}_2(f') \rangle = \delta(f - f') \gamma_{12}(f) \frac{S_{gw}(f)}{2}
  \]

  \[ S_{gw}(f) \] encodes spectrum; \[ \gamma_{12}(f) \] encodes geometry
Initial LIGO/Virgo Highlights

- GRB070201 (and GRB051103)
- Crab and Vela spindown
- BBN bound
- Blind Injections
GRB070201

- 2007 Feb 1: short GRB whose error box overlapped spiral arm of M31 (770 kpc away)
- LHO 4 km & 2 km detectors operating & sensitive to CBC out to 35.7 & 15.3 Mpc
- No GW seen; rule out CBC progenitor in M31 w/ > 99% conf

Crab Pulsar Upper Limit

- Pulsar in Crab Nebula
- Created by SN 1054
- \( \sim 2 \text{ kpc} \) away
- \( f_{\text{rot}} = 29.7 \text{ Hz} \)
- \( f_{\text{gw}} = 59.4 \text{ Hz} \)

Image credit: Hubble/Chandra

- Initial LIGO (S5) upper limit beats spindown limit
- No more than 2% of spindown energy loss can be in GW
Initial Virgo Targets the Vela Pulsar

S6/VSR2 Best Strain Sensitivities (PRELIM)

- LIGO Hanford 4km Detector
- LIGO Livingston 4km Detector
- Virgo 3km Detector
- Initial LIGO Design (4km)
- Initial Virgo Design

Amplitude Spectral Density (strain/√Hz)

Frequency (Hz)

Vela Crab
Vela Pulsar Upper Limit

- Pulsar in Vela SN remnant
- Created $\sim 12,000$ years ago
- $\sim 300$ pc away
- $f_{\text{rot}} = 11.2$ Hz
- $f_{\text{gw}} = 22.4$ Hz

Image credit: Chandra

- GW frequency below initial LIGO “seismic wall”
- Virgo has better low-frequency sensitivity
- VSR2 upper limit beats spindown limit
- No more than 10% of spindown energy loss can be in GW

Isotropic Stochastic Background Limit

S5 limit $\Omega_{gw}(f) < 6.9 \times 10^{-6} \left( \frac{72 \text{ km/s/Mpc}}{H_0} \right)^2$

Enhanced LIGO Recovers “Blind Injection”

http://www.ligo.org/science/GW100916/
Summary

Gravitational waves predicted by GR; energetic but couple weakly to matter

Generated by rapidly changing mass quadrupole moments, e.g., compact object binaries, rotating NSs, supernovae . . .

Current state-of-the-art GW detectors: ground-based interferometers, sensitive at $10^1 - 10^3$ Hz. Initial detectors have set upper limits; advanced detectors should make detections

Ground-based detectors part of GW spectrum analogous to EM spectrum; multi-wavelength GW observations include space-based detectors (planned, $10^{-3} - 10^{-1}$ Hz) & pulsar timing arrays (operating, $10^{-9} - 10^{-7}$ Hz)