Gravitational waves from binary mergers

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Workshop on Massive Stars, MN

Personal opinions
Not speaking on behalf of LIGO or Virgo
Why gravitational waves & binaries?

• Context and provocations: binary evolution

• New window on universe

• Applications
  – Electromagnetic counterparts
  – Measuring the merging binary
  – Nuclear matter and the “cosmological collider”

• What to expect
Detections likely soon


Galactic NS-NS : ~ few mergers/Myr


LIGO range : ~200 Mpc (conservative 1-ifo)

→ 10-ish /yr NS-NS mergers
Population synthesis

• Outline of (typical) evolution:
  – Evolve and **expand**
  – Mass transfer (perhaps)
  – Supernovae #1
  – Mass transfer (perhaps)
  – Supernovae #2

Formation of Hulse-Taylor (B1913+16)
Voss and Tauris 2003

Movie: [John Rowe](#)
Interaction needed

- **Mass transfer:**
  Small orbit -> MT essential
  GW radiation “fast” (< 10 Gyr) only for tight orbits
  Example: Hulse-Taylor PSR
  \[ \tau_{gw} \approx 0.3\text{Gyr} \]
  \[ a \approx 2.7R_\odot \ll O(10^3R_\odot) \approx R_{giar} \]

  **Kicks on BHs:** (assumed) Weak/suppressed
  [fallback]
  Common envelope ~ needed
  \[ \ldots + \text{avoid merger as stars} \]

  BH-BH binaries **barely merge** – long delays

Formation of Hulse-Taylor (B1913+16)
Voss and Tauris 2003
First estimate

Synthetic galactic population

Table 1

<table>
<thead>
<tr>
<th>Type</th>
<th>$Z_\odot$ (100%)</th>
<th>0.1 $Z_\odot$ (100%)</th>
<th>$Z_\odot + 0.1 Z_\odot$ (50% + 50%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NS-NS</td>
<td>40.8 (14.4)</td>
<td>41.3 (3.3)</td>
<td>41.1 (8.9)</td>
</tr>
<tr>
<td>BH-NS</td>
<td>3.2 (0.01)</td>
<td>12.1 (7.0)</td>
<td>7.7 (3.5)</td>
</tr>
<tr>
<td>BH-BH</td>
<td>1.5 (0.002)</td>
<td>84.2 (6.1)</td>
<td>42.9 (3.1)</td>
</tr>
<tr>
<td>TOTAL</td>
<td>45.5 (14.4)</td>
<td>138 (16.4)</td>
<td>91.7 (15.4)</td>
</tr>
</tbody>
</table>

Belczynski et al 2010 [arxiv:1004.0386]
Low metallicity contribution

Event rate versus metallicity

All low Z star formation (ever) important?

Previous estimates

Abadie, CQG 27 3001

Dominik et al in prep
Really? Let nature decide…

<table>
<thead>
<tr>
<th>Model</th>
<th>NS-NS</th>
<th>BH-NS</th>
<th>BH-BH</th>
</tr>
</thead>
<tbody>
<tr>
<td>S</td>
<td>3.9 (1.3)</td>
<td>9.7 (5.1)</td>
<td>7993.4 (518.7)</td>
</tr>
<tr>
<td>V5</td>
<td>3.9 (1.3)</td>
<td>9.4 (4.8)</td>
<td>8057.8 (533.7)</td>
</tr>
<tr>
<td>V6</td>
<td>3.9 (1.3)</td>
<td>9.3 (4.7)</td>
<td>8041.7 (523.6)</td>
</tr>
<tr>
<td>V7</td>
<td>5.0 (1.5)</td>
<td>14.8 (8.3)</td>
<td>8130.1 (574.2)</td>
</tr>
<tr>
<td>V8</td>
<td>3.9 (1.3)</td>
<td>1.2 (0.3)</td>
<td>172.2 (14.0)</td>
</tr>
<tr>
<td>V9</td>
<td>3.9 (1.3)</td>
<td>11.8 (6.7)</td>
<td>8363.6 (654.9)</td>
</tr>
<tr>
<td>V10</td>
<td>5.2 (1.7)</td>
<td>5.7 (4.9)</td>
<td>7762.7 (487.0)</td>
</tr>
<tr>
<td>V11</td>
<td>3.9 (1.1)</td>
<td>10.5 (6.3)</td>
<td>12434.4 (888.1)</td>
</tr>
<tr>
<td>V12</td>
<td>11.7 (0.8)</td>
<td>7.6 (5.8)</td>
<td>8754.6 (275.3)</td>
</tr>
<tr>
<td>V13</td>
<td>3.7 (0.9)</td>
<td>76.9 (62.1)</td>
<td>1709.6 (966.1)</td>
</tr>
</tbody>
</table>

Belczynski and Dominik 2012 (1208.0358)
mixture: 50% solar, 50% 0.1 solar
Why gravitational waves & binaries?

• New window on universe

• Applications
  – Electromagnetic counterparts
  – Measuring the merging binary
  – Nuclear matter

• What to expect
Binary merger dynamics

- Inspiral
  - NS
  - BH
  - ≤ 1 kHz

- Merger
  - 1 – 3 kHz

- Hypermassive NS
  - M\text{binary} ≥ 3 M\text{⊙}
  - M\text{NS1} ≠ M\text{NS2}
  - M\text{binary} ≤ M_{\text{NS, max}}

- Accretion
  - Stable
  - BH
  - NS

- Ringdown
  - 5 – 6 kHz
  - 6.5 – 7 kHz

- Tidal disruption
  - BH
  - NS

- Plunge

- Very short lived HMNS

- M\text{NS1} = M\text{NS2}

- R_{\text{tidal}} ≥ R_{\text{ISCO}}
Merger dynamics

\[ \frac{m_1}{m_2} = 4 \]
\[ a_1 = a_2 = 0.6 \]

ROS et al. 1209.3712
Merger signal

**Time-frequency**

[Graph showing time-frequency analysis with a curve and labels: $M \omega (\chi = 0.5)$ and Fit to $M \omega$.]

**Strain vs frequency**

[Graph showing strain vs frequency with various regions labeled: effectively point-particle, tidal effects, Initial LIGO, Advanced LIGO, Einstein Telescope, post merger, NS-NS, BH-BH.]

**Strain vs time**

[Graph showing strain vs time with labeled frequencies and distances: $f_{GW} = 405$ Hz, $a = 57.1$ km.]

Beaming and modulation
Polarization changes

• Experiments see one line of sight
  **Measure** $R,L$
  …if sensitive to both linear polarizations

• Polarization changes over time

![Diagram showing polarization changes over time](image-url)

- **Right handed**
- **Left handed**

Log amplitude vs time/M
Detectors

Prior experience

1203.2674
Initial LIGO, inspiral
Detection and range

Search for model

Unmodeled
Smaller, algorithm dependent range
Detection and range

Search for model

Equal mass
Why gravitational waves & binaries?

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Electromagnetic counterparts

Goals:

- Host galaxy/progenitors?
  - Typical host?
  - Age, Z of population?
  - Position vs host?

- Engine energetics
  - GRB = “collider”
    - GW : input
    - EM : output

Common for SN, GRBs (Fruchter talk)
Electromagnetic counterparts

Strong EM source (short GRBs)

Rate of events: debated

Here’s one way:
- Fraction of EM GRB rate
  [simplifies beaming,L,…]
- BH-NS: possible >~ 1/yr
- NS-NS:
  Sensitive to prior (# faint?)
  Estimate ~ few % of blind rate

Metzger and Berger 2012
Yunes, ROS et al 2010
Chen and Holz 2012; Kelly et al 2012; Petrillo and Dietz
Abadie et al 2012 [1205.2216]
In prep: Dietz et al; Nissanke et al
Electromagnetic counterparts

Here’s another
- Start with (beamed) GRB event rate/volume
- Correct for beaming

Belczynski, ROS et al 2007

Chen and Holz 2012
Also: Coward et al 2011; Petrillo and Dietz 2012 (102.0804)
Electromagnetic counterparts

Here’s another
- Extrapolate existing LIGO search (S6 short GRB: 1206.2216)
  90% upper limits on population
**Electromagnetic counterparts**

**GW-triggered EM followup**
- Faint, isotropic event?
- GW localize poorly
  - 10s-100s deg$^2$
- Cover out to 200 Mpc?
  - **Mansi = ok**

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Fairhurst, KITP 2012
Fairhurst 2009
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• What to expect
Properties of the binary at merger

Why?

Mass distributions probe supernova physics

One initial-final relation (with fallback)


Properties of the binary at merger

Why?

Mass distributions probe supernova physics

Another initial-final relation
(with fallback)

Ugliano et al 2012
Properties of the binary at merger

Why?

BH mass distributions probe
mass loss rate
binary interactions
Z distribution
Properties of the binary at merger

Why?

BH spin distributions probe
J transport in rotating stars
Binarity (spinup, stripping)

Properties of the binary at merger

How

- "Chirp" -> "chirp" mass

\[ M_c = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}} \]

- "Exact" at low mass

\[ m_1 + m_2 \ll 30 M_\odot \]

\[ \Delta M_{c,90\%} \lesssim 0.1 M_\odot (M_c/3)^{8/3} \]
Properties of the binary at merger

Distribution predictions

Data from Dominik et al 2012 (V1A)
Constraint methods: ROS (1209.3712); Mandel (0912.5531); Bulik et al 2003; Farr et al 2011 (1011.1495); Pejcha et al 2012
Properties of the binary at merger

Distribution predictions

Significant variability
Easy to distinguish…
if enough events

Dominik et al 2012  (arXiv:1202.4901)
**Properties of the binary at merger**

**Bad news: Mass ratio**

\[ \eta = \frac{m_1 m_2}{(m_1 + m_2)^2} \]

- \( \eta = 1/4 \)  
- \( \eta \gtrsim 0.1 \)  
- \( \eta \gtrsim 0.22 \)  
- \( \Delta \eta_{90\%} \approx (0.02 - 0.1) \)

**Very strong signal**

**Typical signal**

Cutler and Flanagan 1994

Cho et al 2012 1209.4494 + in prep
Properties of the binary at merger

**Spin**: spin-orbit

Bad

Orbit duration: many factors

= spin↑ or mass↓
Properties of the binary at merger

**Spin**

Bad: Orbit duration degeneracy

Good: **Precession** modulates
Spin encoded **geometrically**

\[ \Delta \chi_{90\%} \approx 0.1 \]  
BH-NS

Brown, Lundgren, ROS (1209.3712)
Cho et al 2012 1209.4494 + in prep
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Nuclear matter

How do GW constrain?
Pre-merger tidal distortion

Tidal disruption

Post-merger remnant
  Hypermassive NS modes, lifetime
  Disk modes [weak]

Stack events?  [Many faint >> one strong?  : Markakis et al 2010 1008.1822]
Nuclear Matter

Pre-merger tidal distortion

\[ \lambda = \frac{Q}{\mathcal{E}} = \frac{\text{size of quadrupole deformation}}{\text{strength of external tidal field}} \]
Nuclear Matter

NS-NS

Conservative
100 Mpc away; part of inspiral

Aggressive
Plausible signal; all of inspiral

Detection limits

Hinderer et al 2010, PRD

Damour, Nagar, Villian 2012, PRD
Nuclear Matter

Tidal disruption
Small BH horizon
(low M, high a)

Larger NS

Foucart 1207.6304
Nuclear Matter

BH-NS

Just $\lambda$

$R : 10\text{-}40\%$

at 100 Mpc

\[ f^{1/2} \tilde{h}(f) \text{ (Hz}^{-1/2}\text{)} \]

\[ f_{gw} \text{ (Hz)} \]

\[ q=2, M_{NS}=1.35 M_{\odot} \]

Lackey et al, PRD 2012
Nuclear Matter

Post-merger remnant

Hypermassive NS modes, lifetime

Method: Frequencies of remnant

Systematics:
  MRI, neutrino cooling/P support;
  EOS?

Disk modes

Examples:
  Janka, Stergoulias,
  Japan: Shibata et al group
  SXS: Duez et al
  Illinois: Shapiro et al group
  Lehner; +….
What to expect

• Timeline
  – Gradual increase in sensitivity  [Abadie et al in prep; Mandic talk]

• Science
  – EM counterparts: engine, host (+nucleosynthesis?)
  – Compact object mass, spin distributions
    • But can we interpret them? Scenarios with robust predictions (fallback-dominated)?
  – Nuclear matter?
    • Possible (stacking weak; high rate; alt noise curve; …)
    • Systematics? Work in progress (MCMC)