Gravitational wave astronomy and BH-NS mergers: Uses for an astrophysical multitool

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Why use GW?

**Source:**
any accelerating charge
screening limits size...

**Strong coupling:**
Imaging often practical:
(common sources)
>> wavelength

- Easy to make & detect
- Easy to **obscure**

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**EM Waves**

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Outline

What happens in a BH-NS merger?
• Dynamics
  – Precession and inspiral
  – Merger
  – Post-merger (disk; fallback; wind)
• Emission
• Gravitational waves
  – Precession and inspiral
  – Merger

What can we measure?
Formation processes and Event rates
• Isolated evolution
• Short GRBs

What do we learn?
GR tests: Parity violation in gravity; …
Astrophysics: Progenitor models; short GRB engine mechanism; …
Nuclear: Nuclear matter; r-process nucleosynthesis (?)
THINGS TO ADD
- Pictures of G. Brown articles on HCE

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what happens in a bh-ns merger
•  - cartoon
•  - early time: gw and precession
•  - movie w disrupted dynamics. point: time of disrupt, residual as probe
•  lehner fallback time
•  manou movies: emphasize
•  - what next? : em, other signatues, poss with delayed em emission
•   - short grb
•   - r process in disk
GW astronomy and mergers: what we learn
BH-NS merger movies

See script ‘open-youtube-movies.sh’

Campanelli:

• * with precession:
  http://www.youtube.com/user/Lazarus135#p/a/u/1/89EWKM7e6YQ
    – See http://www.black-holes.org/explore2.html
• * without precession: more boring
  http://www.youtube.com/user/Lazarus135#p/u/3/n3ueqgsEz_Y
What happens in a BH-NS merger?

Cartoon:

Neutron star → Black hole + torus → Black hole

Accretion, neutrino cooling: Gamma-ray burst?
Cooling ejecta:

Lee and Ramirez Ruiz 2007
Nakar 2007
Oeschslin and Janka 2006
Faber et al 2006
Shibata et al 2006, 2007
...
What happens: Dynamics

Early:

Precession:

\[ H = H_{\text{orbit}} + O(L.S) \]
L.S ~ conserved
L ~ cone around J, widening

Orbit plane rotates

Movie: S. Hughes (gmunu.mit.edu) [two black holes]
What happens: Dynamics

**Tidal disruption:**
- BH tides disrupt
- Orbit along BH equator:
  - Disruption radius, ejected mass depend on BH spin
  - Tidal tail in plane
- Generic orbits
  - Disruption time depends on BH spin, alignment
  - Tidal tail fills volume [Rantsiou et al]
  - Ejected, fallback mass depends **STRONGLY** on spins $a>0.7$, alignment
Example: Mass vs spins (aligned)

Rantsiou et al 2008

\( a = 0.99 \)

Lots ejected

\( a = 0.75 \)

Little ejected
What happens: Dynamics

Accretion; fallback; winds

Prompt capture, disk: see movie

Fallback: \( \frac{dM}{dt} \sim t^{-5/3} \) (Newtonian: Rosswog; GR+MHD, \( a=0.7 \): Chawla et al 1006.2839)

Bursty (?) accretion \( \sim \) hours later

R-process in ejecta/winds: [Lattimer & Schramm 1974; Surman et al 2008; Metzger et al 2010]
What happens: GW

Early precession, modulation:

- occurs ~ at peak LIGO/Virgo sensitivity
What happens: GW

**Tidal termination** [example: NS-NS]
~ Terminates at tidal radius
   Radius depends on nuclear matter EOS

BH, fluid ringdown modified vs BH-BH, NS-NS:
• less excited by smooth merger
• Weakly (!) driven by accretion

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**Problem:**
Both occur at high frequency
Need future detectors (ET)
Each event, GW only:
- **Mass**
  - Must match!
  - $\frac{\text{df/dt}}{\text{mass}}$
  - [mass ratio : fine structure]
- **Distance**
  - $\text{SNR} \propto \frac{M^{5/6}}{d}$
- **Orbit orientation:**
  - Measure beaming?…but
  - Distance-inclination degeneracy
  - $\delta X/X \sim O(1)/\rho$
  - Significant vs beaming angle
- **(Black hole) spin**
  - Precession
  - Only if extreme

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**Spin-orbit coupling**

**Beamed, polarized emission**

Nissanke et al 0904.1017
Rule of thumb:

$$\frac{\delta X}{X} \approx O(1)/\rho$$

Real calculation:
Van der Sluys et al 0710.1897

$$a=0.5, \Theta=20^\circ$$

Table (SNR 17, 2-detector)

Roever et al gr-qc/0609131
Cutler and Flanagan
Van den Broeck and Sengupta
Bose and Ajith 0901.4936
Spin: Example of new parameter

- Coupling parameter (a)
- Transition vs SNR: localize parameters with loud sources, not otherwise

Example
vdS et al 0905.1323
What we can measure?

Example: Orbital phase (beta, sigma)

\[
\psi_f(t_f) = 2\pi f t_{\text{ref}} - \phi_{\text{ref}} + \psi_N \sum_{k=0}^{5} \psi_k (\pi m f)^{(k-5)/3}
\]

\[
\psi_N = \frac{3}{128\eta}, \quad \psi_0 = 1, \quad \psi_1 = 0,
\]

\[
\psi_2 = \frac{5}{9} \left( \frac{743}{84} + 11\eta \right), \quad \psi_3 = -16\pi,
\]

\[
\psi_4 = \frac{5}{72} \left( \frac{3058673}{7056} + \frac{5429}{7} \eta + 617\eta^2 \right),
\]

\[
\psi_5 = \frac{5}{3} \left( \frac{7729}{252} + \eta \right) \pi + \frac{8}{3} \left( \frac{38645}{672} + \frac{15}{8} \eta \right) \ln \left( \frac{v}{v_{\text{ref}}} \right) \pi.
\]

\[
v = (\pi M f)^{1/3}
\]

\[
\Psi(f) = 2\pi f t_c - \phi_c - \pi/4
\]

\[
+ \frac{3}{128} (\pi M_c f)^{-5/3} \left[ 1 + \frac{20}{9} \left( \frac{743}{336} + \frac{11}{4} \eta \right) v^2 \right] v^3
\]

\[
- 4(4\pi - \beta) v^3
\]

\[
+ 10 \left( \frac{3058673}{1016064} + \frac{5429}{1008} \eta + \frac{617}{144} \eta^2 - \sigma \right) v^4
\]

\[
+ \left( \frac{38645\pi}{252} - \frac{65}{3} \eta \right) \ln v
\]

\[
+ \left( \frac{11583231236531}{4694215680} - \frac{640\pi^2}{3} - \frac{6848\gamma}{21} \right) v^6
\]

\[
+ \eta \left( \frac{15335597827}{3048192} + \frac{2255\pi^2}{12} + \frac{47324}{63} - \frac{7948}{9} \right) v^6
\]

\[
+ \left( \frac{76055}{1728} \eta^2 - \frac{127825}{1296} \eta^3 - \frac{6848}{21} \ln 4 \right) v^6
\]

\[
+ \pi \left( \frac{77096675}{254016} + \frac{378515}{1512} \eta - \frac{74045}{156} \eta^2 \right) v^7
\]

\[
\beta = \frac{\hat{L}}{M^2} \cdot \left[ \left( \frac{113}{12} + \frac{25m_2}{4m_1} \right) S_1 + \left( \frac{113}{12} + \frac{25m_1}{4m_2} \right) S_2 \right]
\]

\[
= \frac{1}{12} [(113(m_1/M)^2 + 75\eta) \hat{L} \cdot \hat{a}_1 + (1 \leftrightarrow 2)]
\]

\[
\sigma = \frac{\eta}{48} [-247\hat{a}_1 \cdot \hat{a}_2 + 721(\hat{L} \cdot \hat{a}_1)(\hat{L} \cdot \hat{a}_2)]
\]
What can we measure?

**NS specific** (hard)
- Tidal disruption point (degenerate: a, EOS)

Each event with EM counterpart:
- EM emission vs
  - spin-orbit misalignment (beaming)
  - Masses, spins (~ disk mass; “central engine”)
- Host galaxy
  - Metallicity & star formation: past and present
- Optical counterpart, non-afterglow
  - r-process in mergers or not?
  - Ejecta, disk mass vs BH mass, spin

Population:
- $M, m_2/m_1, |S|$ distribution (BH masses & spins)
- EM counterpart: $m_1$ vs $Z$ (BH mass vs metallicity)
- spin-orbit misalignment (SN kicks)
- Rate (common envelope, etc)

 GW not required (just trigger)
What can we eventually measure?

Third-generation: tomography

Example: NS-NS:
- \( \frac{d\text{Volume}(z) \cdot \text{rate}(z)}{1+z} \)
  = “rate per redshift bin”

- \( O(10^5-10^6) \) detections
  - Rate vs distance
  - Mass distribution vs distance

- Reach \( \sim \) peak SFR

(astro-ph/0601463): Fig. 4
**Example**: BH mass (via BH-NS)

**Idea**: Chirp mass traces BH mass

Typical BH mass evolves with z

**Qualitative**: $O(10^4/\text{bin}) \rightarrow O(1\%)$ accuracy!

**Important!**: Metallicity evolves, irregular

Initial->final relation uncertain (winds)

Belczynski et al 0904.2784
Isolated binary evolution

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

Movie: John Rowe

Formation of Hulse-Taylor (B1913+16)
Voss and Tauris 2003
Predicted merger, GW detection rates

**Mergers:** $<10/\text{gal/Myr}$

**Detections:** $O(30/\text{yr})$, aLIGO network

[ROS et al 0908.3635]
Formation model: Key points

- **Mass transfer:**
  Small orbit $\rightarrow$ MT essential
  GW radiation “fast” (< 10 Gyr)
  only for tight orbits

  Mass transfer phenomenological:
  parameterized (via energy or J) to unbind envelope

  Visible connections!:
  - (recycled?) Pulsar binaries
    - **Good:**
      - Long-lived remnants!
      - Precise measurements
    - **Challenges:**
      - Pulsar population statistics challenging:
        many potential (time-evolving?) biases: L distrib; galaxy distrib;
        beaming, B/L evolution, accn, …
      - P-dP/dt diagram flow/popsyn still phenomenological
      - Theory: PSR-BH binaries should $\sim$never$ be recycled

Example: Hulse-Taylor
\[
\tau_{gw} \simeq 0.3\text{Gyr}
\]
\[
a \simeq 2.7R_{\odot} \ll O(10^3 R_{\odot}) \simeq R_{\text{giant}}
\]
Formation model unknowns

- **Supernova kicks**
  - **Isotropic kicks?**
    - Hobbs vs Arzoumanian
      - **Group:** explore all
  
- **Polar?**
  - **Motivation:** Spin-kick alignment?
    - (e.g., neutrino/B/.. kick)
      - For: obs claims (Lai et al 2001; Wang; Ng Romani Kaplan et al 2008);
      - Against: Willems et al 2008 (low kicks required to fit PSR-NS e; high kicks seem required for others)

- **Impact for us:**
  - huge rate reduction b/c never “kicking closer”
    - Kuranov et al 0901.1055; Postnov & Kuranov 0710.4465
    - **Group:** not explored extensively now; could be

**Crab motion**
Formation model unknowns

• Supernova kicks
• Evolution model
  – Hertzprung gap merger
    • ultracompacts survive/not
    • **big** effect on BH rate
    • Changes background
      LISA binary #
  – NS maximum mass
  – Bondi rate in CE; AIC

Belczynski 0811.1602

Formation model unknowns

- Evolution model
- Supernova kicks
- **Winds**
  - Strong effect on star->BH mass
  - Recent update

Belczynski et al 2002

"original" winds + scale factor

Belczynski et al 2009

"revised" winds

**Graphical Note:**
- M_{bh} [M_{\odot}] vs Wind scaling factor
- M_{zams} = 150 M_{\odot}
- Z=0.15 Z_{\odot}
- Z=0.30 Z_{\odot}
- Z= Z_{\odot}

Belczynski et al 2009

"revised" winds
Formation model unknowns

- Evolution model
- Supernova kicks
- Winds
- **Metallicity distribution:** (input uncertainty)
  - Formation, detection rate *sensitive*
  - Wide distribution of conditions
  - Metallicity evolves strongly with $z$
    (Pei, Fall, Hauser)

=> typical detected binary from *highly atypical region*?

[ROS and Kopalappu, 0812.0591]

Panter et al 2008
Merger physics

**Tidal disruption point**
Disruption terminates signal
[Faber et al PRL 89 1102f]
Not in band ($f \sim f_{\text{breakup}} \sim 1000$ Hz)
Golden binaries? + aLIGO

Lee and Ramirez-Ruiz 2007

**Sloshing of hypermassive transient/remnant disk**
Not in band
Weak
- need implausibly close (20 Mpc)
+ aLIGO

Oechslin and Janka PRL 99 1102 (2007)

**Tidal-orbit coupling**
Change **early** part of signal
Limit “Love number”
Flanagan and Hinderer, PRD 75 1502 (2008)
: aLIGO can weakly constrain
What can we learn?

**Does gravity violate parity?** [Yunes, ROS et al arXiv:1005.3310]

- Many theoretical GR extensions add “Chern-Simons” parity-violating term

\[
S = \frac{1}{16\pi} \int d^4x \sqrt{-g} \left( R + \frac{1}{4} \theta \, \mathbf{R} \cdot \mathbf{R} + (\nabla \theta)^2 + V(\theta) \right)
\]

- Weak effect: **preferred handedness**: amplifies over cosmological distances

- Test:
  - Short GRB: source of circularly polarized GW of “known” amplitude (if host known)
  - Test if any source (or population of all L, R handed) agrees with predictions:

\[
\frac{\rho^2}{\rho_{GR}^2} = 1 + 2 \langle v \rangle \quad \text{and} \quad \frac{\delta(\dot{\theta}/a)}{\delta D} = H_0 \dot{q}q \approx O(1)
\]

\[
= 1 + 2 \langle f \rangle D\pi \frac{\delta(\dot{\theta}/a)}{\delta D}
\]

- Only propagation test. Better than (non-propagating) solar system tests
What will we learn?

Example: Reproduce # of MW NS-NS binaries

- Not all parameter combinations allowed

Examples:
- Kick strength: $v_1, v_2 \sim 300$ km/s
- CE efficiency: $\alpha \lambda > 0.1$
- Mass loss: $f_a < 0.9$

Lots of physics in correlations

..similarly for GW detections with *first few*
What will we learn?

**First O(30) detections:**
- What are the masses, spins of BHs at birth?
- Are some short GRBs BH-NS mergers? If so,
  - how does the central engine work?
  - What trends with host Z?
- Roughly what processes make them?
- Is there weak gravitational parity violation? MOND? Graviton mass? Modified gravity in strong field?

**Third generation:**
- Mass, spin distributions versus redshift
  - EM counterpart: confirm trends with host Z
- What progenitor-model parameters reproduce the observed population?
What will we learn?

R-process via mergers?

• Bright, isotropic EM counterparts expected [Metzger 2010]
• Easy to see with transient sky surveys (PTF; LSST)
• Detection rate \( \sim \) constant; set by average r-process \( \frac{dM}{dt} \) from mergers
  
  If all r-process from mergers

\[
10^{-6} M_\odot/yr = dM/dt = \langle R_{mgr} M_{ej} \rangle
\]

Large mass

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[Diagram showing detection rate vs. \( N_{merge} \) and SN rate with LSST and Palomar Transient Factory as examples. Upper limit, ROS 2010.]

Upper limit, ROS 2010
Spin?

Alignment = signature!

Isolated binaries
Aligned spins

References include
• Belczynski, Kalogera, Bulik 2002; Belczynski
• O’ Shaughnessy et al. in prep
  + astro-ph/0610076; 0609465; 0504479

Star forming gas

Interacting clusters’ stellar mass binaries
Random spin alignment

References include
• Sadowski et al 2008
• O’ Shaughnessy et al PRD 76 061504
  O’ Leary et al astro-ph/0508224
Conclusion

• Gravitational waves turn BH-NS population from mystery to tool:
  – Known population
  -> Better known formation process
  -> Constrained GRB engine, nuclear matter, r-process
  -> “Standard candle” enabling pure-GR tests

Even valuable by their absence...
Quiz: GRB 070201

Overlaps M31
(d<1Mpc<<d_{LIGO})

What could you learn if
- Detection?

- No detection?
  - Could be farther away merger
  - Could be non-merger in M31

Point: GW from BH-NS isolate multiple GRB progenitors!

Fig. 1. — The IPN3 (IPN3 2007) (γ-ray) error box overlaps with the spiral arms of the Andromeda galaxy (M31). The inset image shows the full error box superimposed on an SDSS (Adelman-McCarthy et al. 2006; SDSS 2007) image of M31. The main figure shows the overlap of the error box and the spiral arms of M31 in UV light (Thilker et al. 2005).
Masses of compact remnants

Theory

- Most NS born
  \[ \sim 1.4 \, M_\odot \]
  [Fryer & Kalogera 2001; Timmes, Woosley, & Weaver 1996]

- Final compact mass
  \[ \sim \text{constant} \] [Timmes et al 1996]

- Small fraction at higher masses

- Accretion (binary evolution) rarely increases mass much [Belczynski et al 2006]

…all standard
Young/proto NS models

Excellent multimessenger candidate:
EM, GW, neutrino signatures

GW emission modes:
Magnetar Perturbations (crust/EM: Duncan-Thompson)
_______...K. Kokkotas talk
+ LIGO SGR storm paper 0905.0005

NS merger-> hypermassive: (Shapiro; Rezzolla; …)
- Disruption radius & EOS [Faber; Read; ..]
- Bar modes of remnant
- Caveats: B field; neutrino cooling

AIC: WD->NS:
• Very like SN:
  – 1-parameter family vs rotation
• Observations constrain mechanism (not EOS)

Problem: Short GW range
Range low -- often only MW...hard
Not all short GRBs

Further references
– Isolated NS modes: Kokkotas;
  LIGO SGR papers : 0808.2025; 0905.0005
  LIGO GRB 070201: 0711.1163
– Isolated proto-NS (merger/AIC): Thompson talks;
  Metzger et al 0712.1233; Dessart et al 0705.3678
– NS mergers: Read et al & refs therein
Short GRBs: Review

GRBs generally

• “Fireball model”: central engine hidden (unless post-blast wave signature: SN = long?)
• Non-fireball post- or pre-burst signal needed

Two classes

Long: Post-burst (some) are SN; correlate to early SFR; …
Short: ….

Swift website
Short GRBs (BATSE view)

- Cosmological
- One of two classes
- Hard: often peaks out of band
- Flux power law
  \[ \frac{dP}{dL} \sim L^{-2} \]
  \(\rightarrow\) most (probably) unseen

Many sources at limit of detector (BATSE)
Short GRBs: Review

Merger motivation?
• No SN structure in afterglow

<table>
<thead>
<tr>
<th>Selected short GRBs</th>
<th>Host</th>
<th>$L/L_*$</th>
<th>SFR $M_\odot$/yr</th>
</tr>
</thead>
<tbody>
<tr>
<td>GRB 050509b</td>
<td>E</td>
<td>3</td>
<td>$&lt; 0.1$</td>
</tr>
<tr>
<td>GRB 050709b</td>
<td>Sb/Sc</td>
<td>0.1</td>
<td>0.2</td>
</tr>
<tr>
<td>GRB 050724</td>
<td>E</td>
<td>1.5</td>
<td>$&lt; 0.03$</td>
</tr>
<tr>
<td>GRB 051221</td>
<td>S</td>
<td>0.3</td>
<td>1.4</td>
</tr>
<tr>
<td>GRB 060502</td>
<td>E</td>
<td>1.6</td>
<td>0.6</td>
</tr>
</tbody>
</table>

(Nakar, 2006: Table 3)

• Occasional host offsets

GRB 051221 (Soderberg et al 2006)
• In both old, young galaxies

GRB 050709 (Fox et al Nature 437 845)
• Energetics prohibit magnetar
Short GRB event rates?

Luminosity & beaming
Method:
• Ratio (triggered/blind)~
  “Fraction that aren’t seen”
  ~ low limit of luminosity function
  & beaming

Plot:
• Expected all-sky sGRB detection rates
  If none fainter & no beaming
• Ratio between dotted line,
  model =>
  Reduction factor:
  beaming + luminosity

...application of GW+GRB rate constraints
degenerate w/ beaming, luminosity

O’ Shaughnessy et al 0706.4139
Event rates: Empirically

- **Hulse-Taylor binary**: (Nobel Prize, 1993)
  - PSR B1913+16
  - Weisberg & Taylor (2003)

**Neutron Binary System**
- separated by $10^6$ miles
- $m_1 = 1.44m_\odot$; $m_2 = 1.39m_\odot$; $\varepsilon = 0.617$

**Prediction from general relativity**
- spiral in by 3 mm/orbit
- rate of change orbital period
Event rates: Empirically

PSR statistics

- Known selection bias
- Model for
  - Luminosity
  - MW distribution
  - Beaming
  - Lifetime...

...see Ilya Mandel’s talk yesterday

NS-NS merger rate in Milky Way
ROS and Kim, in prep; see also
Kim et al astro-ph/0608280
Kim et al ASPC 328 261 (2005)
Event rates: Short GRBs

sGRB coincident signals?

Overall: O(70-200/yr) all sky (above BATSE/Swift photon count cut cut)

Estimate: Roughly uniform in $z$: luminosity function

Horizon range limits (aligned)

$$R_{GRB+GW} \sim D_{LIGO} H_o \frac{R_{GRB}}{\Delta z}$$

$$\sim 0.1 R_{GRB} \sim O(7 - 20/yr)$$

$$\sim 0.2 R_{GRB} \sim O(14 - 40/yr)$$

cf Dietz 0904.0347
Beware short-distance/low-L extrapolation
HOLDING MATERIAL: PARITY VIOLATION