Binary neutron star mergers & multimessenger signals

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August 15, 2017
Physics Motivation

- Examine effects of EOS in various scenarios, notably BNS mergers
- Study EM Events: sGRBs, **kilonovae/r-process**, FRBs
- LIGO:
  - Look for EM precursors
  - Localization via EM signals
  - Multimessenger astronomy (e.g. neutrinos if very close)
  - Fully nonlinear tidal effects
- Tests of GR:
  - alternative gravity
  - differentiate from exotic matter (boson stars)
  - dark matter
Our Evolution Code: Fluid

[Palenzuela, SLL, Neilsen, Lehner, Caballero, O’Connor, Anderson, 1505.01607]
[Neilsen, SLL, Anderson, Lehner, O’Connor, Palenzuela, 1403.3680]

- Barytropic, finite-temperature EOS
- EOS used are constrained by the most massive observed NSs
- Involves temperature and composition (electron fraction)
- MHD HRSC
- Adapts open-source neutrino leakage code from stellarcollapse.org
- Implements novel, local calculation of optical depth which tracks binary NS
Our Evolution Code: Other

[Palenzuela, SLL, Neilsen, Lehner, Caballero, O’Connor, Anderson, 1505.01607]
[Neilsen, SLL, Anderson, Lehner, O’Connor, Palenzuela, 1403.3680]

- HAD
- Distributed
- Fully nonlinear GR (BSSN scheme)
- AMR with subcycling in time
- GR wave extraction
- Tracers (simply advected or geodesic)
Choice of Realistic, microphysical EoS

Choose range of EoS that satisfy observational constraint:

- NLS—stiff—large radii
- DD2—moderate—intermediate radii
- SFHo—soft—small radii
Initial Data

- Use Lorene package to generate binaries in quasi-circular orbits
- Total mass $2.7M_\odot$
- 45 km initial separation...4-5 orbits prior to merger
- Finest resolution: 230 meters in neighborhood of each star

<table>
<thead>
<tr>
<th>EoS</th>
<th>q</th>
<th>$\nu$</th>
<th>$m_b^{(1)}, m_g^{(1)}$ [$M_\odot$]</th>
<th>$m_b^{(2)}, m_g^{(2)}$ [$M_\odot$]</th>
<th>$R^{(1)}$ [km]</th>
<th>$R^{(2)}$ [km]</th>
<th>$C^{(1)}$</th>
<th>$C^{(2)}$</th>
<th>$J_0^{ADM}$ [G M_\odot^2/c]</th>
<th>$\Omega_0$ [rad/s]</th>
<th>$f_0^{GW}$ [Hz]</th>
<th>$M_{eject}$ [$10^{-3}M_\odot$]</th>
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<td>1.47, 1.36</td>
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<td>11.90</td>
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<td>11.85</td>
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<td>7.31</td>
<td>1773</td>
<td>564</td>
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</table>
Novel Optical Depth Calculation [PRD 1403.3680]

- conventional to shoot rays and integrate opacity, but non-local, somewhat arbitrary which rays to consider
- instead at each point (i) start with minimum depth of neighbor, (ii) add depth to get to neighbor
- easy, works well, tracks binaries, gradient matches opacity
Magnetic Effects [PRD 1505.01607]

- DD2; magnetic dipole; “effective driver” for subgrid instabilities
  [Giacomazzo+ 1410.0013] $10^{13} \rightarrow 10^{16}$ G
- Dynamics largely the same with subgrid model “on”
- However, subgrid model causes: (i) twice material ejected (magnetic pressure) (ii) less flat $Y_e$ distribution (iii) additional extra material mostly equatorial
Separation

- $q = 1$ corresponds to equal mass case
- unequal cases merge earlier than equal
- smaller (radius) stars less sensitive to mass ratio
Waveforms

- $t = 0$ corresponds to first contact for $q = 1$ binary
- times of contact for unequal cases shown w/ vertical lines
Could aLIGO differentiate among EOS?

Best case scenario ("Zero Detuned, High Power") configuration of aLIGO could differentiate among stiffest and softest EOS at 100 Mpc.
Post-Merger GW Power Spectral Densities

- Spectra characterized by various peaks differing among EOS
- Dominant $f_{\text{peak}}$ associated with rotation and quadrupolar structure
- Using language of [Bauswein, Stergioulas, PRD’15]
- Peak frequencies agree within 5% with similar mass ratios of [Bernuzzi, Dietrich, Nagar PRL’15]
Table 2. Prominent oscillation frequencies (kHz) in the power spectral densities of the post-merger gravitational waveform compared with predicted values.

<table>
<thead>
<tr>
<th>EoS</th>
<th>q</th>
<th>$f_1$</th>
<th>$f_2$</th>
<th>$f_3$</th>
<th>$f_4$</th>
<th>$f_{\text{peak}}$</th>
<th>$f_{\text{spiral}}$</th>
<th>$f_2 - 0$</th>
<th>$f_c$</th>
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<td>—</td>
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<td>1.6</td>
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<td>—</td>
<td>—</td>
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<td>1.9</td>
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<tr>
<td>DD2</td>
<td>0.85</td>
<td>2.58</td>
<td>1.92</td>
<td>1.62</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>1.42</td>
</tr>
<tr>
<td>DD2</td>
<td>0.76</td>
<td>2.32</td>
<td>1.86</td>
<td>1.62</td>
<td>—</td>
<td>—</td>
<td>—</td>
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<td>SFHo</td>
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<td>3.45</td>
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<td>2.20</td>
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<td>3.2</td>
<td>2.4</td>
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<tr>
<td>SFHo</td>
<td>0.85</td>
<td>3.29</td>
<td>2.29</td>
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<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>1.65</td>
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</table>

Note. The frequencies $f_1$, $f_2$, $f_3$, and $f_4$. Correspond to various peaks of the post-merger GW spectrum (see figure 3). $f_{\text{peak}}$ and $f_{\text{spiral}}$ are the predicted peak frequencies from [48]. The correspondence between $f_1$ and $f_{\text{peak}}$, $f_2$ and $f_{\text{spiral}}$, and either $f_3$ or $f_4$ with $f_2 - 0$ suggests consistency with the model presented in [48] (which was tailored for the equal mass case, but reports errors < 5% for mass ratios $q = 0.92$). $f_c$ is the computed contact frequency (8).
Remnant’s peak GW Frequency

In terms of contact frequency:  

\[ f_c = \frac{1}{\pi M_g} \left( \frac{m_g^{(1)}}{M_g C_1} + \frac{m_g^{(2)}}{M_g C_2} \right)^{-3/2} \]

yields fit:  

\[ f_{\text{peak}}[\text{kHz}] = -1.61 + 2.96 f_c \left[ \frac{2.7 M_\odot}{M} \right] [\text{kHz}] \]
NL3 (left), DD2 (middle), SFHo (right) for $q = 0.85$ 3ms after merger

- SFHo remnant more centrally condensed and hotter
- SFHo also drives decompression of hot material to lower densities where positron capture raises electron fraction
DD2, \( q = 1 \) (left), \( q = 0.85 \) (middle), \( q = 0.75 \) (right)

- Decreased electron fraction in unequal cases—tidal ejecta
- Spiral arm apparent in unequal cases
Ejecta Properties: Electron Fraction

- Amount of ejecta increases with mass ratio
- Electron Fraction decreases with mass ratio
- As mass ratio decreases, ejected material is cooler, dominated by neutron-rich, tidal tail material
- Lower temperature inhibits positron production and neutron capture... $Y_e$ similar to original NS material
Estimates of possible EM signals

**Kilonova:** \([\text{Barnes,Kasen,2013}]\)

\[
t^k_{\text{peak}} \approx 0.25 \text{ days} \left[ \frac{M_{\text{eject}}}{10^{-2} M_\odot} \right]^{1/2} \left[ \frac{v}{0.3c} \right]^{-1/2}
\]

\[
L \approx 2 \times 10^{41} \text{ erg/s} \left[ \frac{M_{\text{eject}}}{10^{-2} M_\odot} \right]^{1/2} \left[ \frac{v}{0.3c} \right]^{1/2}
\]

**Radio emission from collision with ISM:** \([\text{Nakar,Piran,2011}]\)

\[
t_{\text{peak}} \approx 6 \text{ yr} \left[ \frac{E_{\text{kin}}}{10^{51} \text{ erg}} \right]^{1/3} \left[ \frac{n_0}{0.1 \text{ cm}^{-3}} \right]^{-1/3} \left[ \frac{v}{0.3c} \right]^{-5/3}
\]

\[
F(\nu_{\text{obs}}) \approx 0.6 \text{ mJy} \left[ \frac{E_{\text{kin}}}{10^{51} \text{ erg}} \right]^{7/8} \left[ \frac{n_0}{0.3 \text{ cm}^{-3}} \right]^{11/4} \left[ \frac{\nu_{\text{obs}}}{1 \text{ GHz}} \right]^{-3/4} \left[ \frac{d}{100 \text{ Mpc}} \right]^{-2}
\]

<table>
<thead>
<tr>
<th>EoS</th>
<th>q</th>
<th>(L[10^{40} \text{ erg/s}])</th>
<th>(t^k_{\text{peak}}[\text{days}])</th>
<th>(M_{\text{eject}}[10^{-3} M_\odot])</th>
<th>(v/c)</th>
<th>(E_{\text{kin}}[10^{50} \text{ ergs}])</th>
<th>(t_{\text{peak}}[\text{yr}])</th>
<th>(F(1 \text{ GHz})[\text{mJy}])</th>
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<td>0.008</td>
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<td>0.45</td>
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<td>0.43</td>
<td>0.3</td>
<td>0.31</td>
<td>1.9</td>
<td>1.9 \times 10^{-2}</td>
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<tr>
<td>DD2</td>
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<td>4.1</td>
<td>0.05</td>
<td>0.42</td>
<td>0.3</td>
<td>0.29</td>
<td>1.8</td>
<td>1.7 \times 10^{-2}</td>
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<td>4.6</td>
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<td>8.6</td>
<td>0.13</td>
<td>2.2</td>
<td>0.25</td>
<td>1.8</td>
<td>4.6</td>
<td>6.5 \times 10^{-2}</td>
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Neutrino Emission

- Softest EoS most luminous and highest average neutrino energies for any mass ratio because highest temperature
Neutrino Analysis via (post-processed) ray tracing

$q = 0.85$ **Top:** electron neutrino surface  **Bottom:** electron antineutrino surface
Neutrino Analysis via (post-processed) ray tracing

**DD2 Top:** electron neutrino surface  \hspace{1cm} **Bottom:** electron antineutrino surface
Neutrino Emission: Detectability

Assume 10kpc distant in SuperKamiokande-like water Cherenkov detector

<table>
<thead>
<tr>
<th>EoS</th>
<th>$q$</th>
<th>$t$</th>
<th>$\langle E_{\bar{\nu}_e} \rangle$ [MeV]</th>
<th>$\langle E_{\nu_e} \rangle$ [MeV]</th>
<th>$L_{\bar{\nu}_e}$ [$10^{53}$ erg/s]</th>
<th>$R_{\nu}$ [#/ms]</th>
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<td>12.6 (15.1)</td>
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<td>15.3 (17.9)</td>
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BNS Conclusions

- **GW:**
  - Peak frequency of remnant can be estimated via a fit based on the contact frequency
  - Stiffer EoS more sensitive to mass ratio because larger radius

- **Ejecta:**
  - Decreasing mass ratio makes kilonova more likely
  - Obtaining individual masses from GW would benefit EM observations
  - Neutron rich ejecta...peaked around 0.2
  - promising for r-process IR afterglow

- **Neutrino Emission:**
  - Soft EOS more luminous
  - Smaller mass ratios result in more dispersed neutrino surfaces, smaller max temps
The $m = 1$ Instability

- The $l = 2$ $m = 2$ mode dominates the GW signal of BNS mergers,
- The weaker $l = 2$ $m = 1$ mode develops via a recently noticed instability
  - Seen more recently in [Corvino+, CQG’10]
    [Dietrick+, PRD’15] [East+, PRD’16] [Radice+, PRD’16]
- “Benefits”:
  - Occurs at half the frequency of dominant mode where noise is less
  - Lasts longer because less damped: (i) less GW radiative (ii) instabilities driving it
  - Occurs postmerger, and be specifically targeted in time and frequency
$m = 2$ develops into $m = 1$ for $q = 0.85$ DD2

- colors indicate increasing radii (red-black-blue)
- average mass density on equatorial plane

See also

[East, Paschalidis, Pretorius, Shapiro, 1511.01093]
and [Radice, Bernuzzi, Ott, 1603.05726]
Growth of $m = 1$ Mode in GW Signal for DD2
Density Decomposition into Azimuthal Modes for DD2

$q = 1$

$q = 0.76$
Effect of EoS on $m = 1$ mode instability

![Graph showing the effect of EoS on $m = 1$ mode instability](image-url)
Detectability

Using:

\[ \rho^2 \simeq \frac{2}{S_n(f)} \int_0^T h^2 \, dt \]

We arrive at

\[ \rho_{m=1} \simeq 11 \times \left[ \frac{6 \times 10^{-24} \text{Hz}^{-1/2}}{\sqrt{S_n(f_{m1})}} \right] \left[ \frac{\Psi_{4_{m=1}}^0}{5 \times 10^{-5}} \right] \left[ \frac{1.3 \text{kHz}}{f_{m1}} \right]^2 \left[ \frac{T}{10 \text{ms}} \right]^{1/2} \left[ \frac{10 \text{Mpc}}{L} \right] \]

Not particularly encouraging, but...
Detectability

- The $m = 1$ mode **lasts longer** than the $m = 2$ mode
- Occurs at **low frequency** and hence in more sensitive region of LIGO’s noise curve
- Its frequency is precisely half that of the $m = 2$ and can therefore be **explicitly targeted**
- Could benefit from BNS mode stacking [Yang+, ’17] [Bose+, ’17]

for sub-threshold SNR of unity, reach to 100 Mpc to see $m = 1$ mode

Provides another avenue for extracting information about the equation of state

- Weaker for stiff EoS than for soft EoS
- For smaller mass ratios, $m = 1$ becomes stronger and saturates earlier