3D Simulations of Core-Collapse Supernovae

Nucleosynthesis During Compact Object Mergers

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What is the source of the $r$-process?

- Long time emphasis on CCSNe as the source of the $r$-process, pretty easy to make GCE work, but problems getting required conditions
- NS-NS, BH-NS mergers now becoming more favored, but maybe some issues with GCE

![Graph](from Roederer et al. ’14)
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From Sneden et al. ‘08
Merger Mass Ejection

- Dynamical Ejecta
  - Material is tidally ejected through the outer Lagrange points
  - GR -> matter ejected from collision region

- Disk winds (e.g. Surman et al. ’08, Wanajo et al. ’11, Just et al. ‘14)

- Disk outflows from viscous heating and alpha recombination
  (Lee et al. ’09, Fernandez & Metzger ’13)

Bauswein et al. ’13
Dynamical Timescale for the Ejected Material:

\[ \tau_{ej} \approx 10 \, ms \]

Ejected Material is neutron rich:

\[ Y_e \sim 0.05 - 0.4 \]

Tidal material has low initial entropy:

\[ S \sim 1 - 30 \]

Initial distribution will be in NSE, clustered around doubly magic nuclei.

Which implies a neutron to seed ratio:

\[ \frac{N}{S} \approx \frac{\bar{Z}}{Y_e} - \bar{A} > 100 \]

Can they make r-process nuclei? easy!

see Lattimer & Schramm '76 and Freiberghaus et al. '99
- Pure r-process material
- Fission cycling
- Relatively small dependence on initial conditions
The effect of weak interactions

Lippuner, LR, Duez et al. in prep

Wanajo, et al. ‘14
The effect of weak interactions

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Wanajo, et al. ‘14
Merger Rates

Merger rates from both population synthesis and extrapolation from known NS-NS binary population are very uncertain.

Predicted Merger Rates (from Abadie et al. ’11)

<table>
<thead>
<tr>
<th>Source</th>
<th>$R_{\text{low}}$</th>
<th>$R_{\text{re}}$</th>
<th>$R_{\text{high}}$</th>
<th>$R_{\text{max}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>NS-BH (MWEB$^{-1}$ Myr$^{-1}$)</td>
<td>0.05 [18]$^e$</td>
<td>3 [18]$^f$</td>
<td>100 [18]$^g$</td>
<td></td>
</tr>
<tr>
<td>BH-BH (MWEB$^{-1}$ Myr$^{-1}$)</td>
<td>0.01 [14]$^h$</td>
<td>0.4 [14]$^i$</td>
<td>30 [14]$^j$</td>
<td></td>
</tr>
<tr>
<td>IMRI into IMBH (GC$^{-1}$ Gyr$^{-1}$)</td>
<td>3 [19]$^k$</td>
<td></td>
<td>20 [19]$^l$</td>
<td></td>
</tr>
<tr>
<td>IMBH-IMBH (GC$^{-1}$ Gyr$^{-1}$)</td>
<td>0.007 [20]$^m$</td>
<td></td>
<td>0.07 [20]$^n$</td>
<td></td>
</tr>
</tbody>
</table>

6 known NS-NS binaries will merge within a Hubble time.

Known pulsars in neutron star binaries (from Oslowski et al. ’11)

<table>
<thead>
<tr>
<th>Name</th>
<th>$P$ (ms)</th>
<th>$\dot{P}$ ($10^{-18}$ s/s)</th>
<th>$P_{\text{orb}}$ (h)</th>
<th>$M_{\text{obs}}$ ($M_{\odot}$)</th>
<th>$M_{\text{emp}}$ ($M_{\odot}$)</th>
<th>$e$</th>
<th>$t_{\text{merg}}$ (Gyr)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>J0737–3039A</td>
<td>27.7</td>
<td>1.74</td>
<td>2.454</td>
<td>1.337$^{+0.005}_{-0.005}$</td>
<td>1.259$^{+0.005}_{-0.005}$</td>
<td>0.088</td>
<td>0.085</td>
<td>1</td>
</tr>
<tr>
<td>J0737–3039B</td>
<td>27.7</td>
<td>8.8$^{+10}_{-10}$</td>
<td>2.454</td>
<td>1.250$^{+0.005}_{-0.005}$</td>
<td>1.337$^{+0.005}_{-0.005}$</td>
<td>0.088</td>
<td>0.085</td>
<td>1</td>
</tr>
<tr>
<td>B2127+11C</td>
<td>31.53</td>
<td>4.99</td>
<td>8.05</td>
<td>1.358$^{+0.01}_{-0.01}$</td>
<td>1.380$^{+0.01}_{-0.01}$</td>
<td>0.681</td>
<td>0.2</td>
<td>1</td>
</tr>
<tr>
<td>J1906+0746</td>
<td>144.07</td>
<td>2.028$^{+10}_{-10}$</td>
<td>3.098</td>
<td>1.248$^{+0.01}_{-0.01}$</td>
<td>1.365$^{+0.01}_{-0.01}$</td>
<td>0.085</td>
<td>0.3</td>
<td>1</td>
</tr>
<tr>
<td>H1913+16</td>
<td>59.03</td>
<td>8.63</td>
<td>7.752</td>
<td>1.441$^{+0.005}_{-0.005}$</td>
<td>1.386$^{+0.005}_{-0.005}$</td>
<td>0.617</td>
<td>0.4</td>
<td>1</td>
</tr>
<tr>
<td>J1756–2251</td>
<td>28.46</td>
<td>1.02</td>
<td>7.67</td>
<td>1.312$^{+0.01}_{-0.01}$</td>
<td>1.258$^{+0.01}_{-0.01}$</td>
<td>0.181</td>
<td>1.5</td>
<td>1</td>
</tr>
<tr>
<td>B1534+12</td>
<td>37.90</td>
<td>2.43</td>
<td>10.098</td>
<td>1.333$^{+0.01}_{-0.01}$</td>
<td>1.345$^{+0.01}_{-0.01}$</td>
<td>0.274</td>
<td>2.7</td>
<td>1</td>
</tr>
<tr>
<td>J1811–1736</td>
<td>114.18</td>
<td>0.91</td>
<td>41.20</td>
<td>1.62$^{+0.01}_{-0.01}$</td>
<td>1.11$^{+0.01}_{-0.01}$</td>
<td>0.828</td>
<td>&gt;10</td>
<td>1</td>
</tr>
<tr>
<td>J1518+4904</td>
<td>40.935</td>
<td>0.027</td>
<td>207.216</td>
<td>0.72$^{+0.01}_{-0.01}$</td>
<td>2.00$^{+0.01}_{-0.01}$</td>
<td>0.249</td>
<td>&gt;10</td>
<td>1</td>
</tr>
<tr>
<td>J1829+2456</td>
<td>41.004</td>
<td>0.05</td>
<td>28.0</td>
<td>1.14$^{+0.01}_{-0.01}$</td>
<td>1.36$^{+0.01}_{-0.01}$</td>
<td>0.139</td>
<td>&gt;10</td>
<td>1</td>
</tr>
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</table>
EoS Dependence of Mass Ejection

- Smaller radius -> larger velocity at collision -> increased mass ejection

- Hotokezaka EoSs: APR4, ALF2, H4, and MS1

- Bauswein EoSs: Finite temperature supernova EoSs
Chemical Evolution Signal

\[ M_{r,MW} \sim 10^4 M_\odot \]
\[ r_{NS-NS} \sim 10^{-4} \text{yr}^{-1} \]
\[ M_{\text{eject}} \sim 10^{-2} M_\odot \]

\[ \rightarrow M_{r,NS-NS} \sim 10^4 M_\odot \]

but...

\[ t_{\text{coalesce}} \approx 10^{6-8} \text{ yr} \]
\[ M_{\text{eject}} \sim 10^{-2} M_\odot \]

from Argast et al. 2004
Dynamically formed binaries in dense stellar clusters

- Form binaries in dense stellar clusters at high-$z$, either through dynamical capture or GW emission
- Small initial separations, short in-spiral time
- DM halos containing clusters eventually incorporated into the MW halo
Dynamically formed binaries in dense stellar clusters

- Similar r-process mass injection to what is expected from CCSNe
- Possible solution one of the GCE problems for mergers
- First step, more detailed GCE models required

 Ramirez-Ruiz, Trenti, LR, et al. '14
Nuclear Heating Rate

- Larger number of isotopes involved, sum of numerous individual decays
- Power law heating rate (Metzger et al. ’10)
- Beta-decays and fission
- Fairly insensitive to initial conditions (for low $Y_e$ and S)
Optical/Infrared Signal

- Model tidal ejecta as decay heated homologously expanding sphere (Li & Paczynski ’98)
- General properties of transients only depend on four parameters: heating rate, opacity, velocity, and mass of ejected material
- Reasonable values for these parameters predict

\[
L_m \approx 0.88 \beta^{1/2} L_0 = 2.1 \times 10^{44} \text{ ergs s}^{-1}
\]

\[
t_m \approx 1.5 \beta^{1/2} t_c
\]

\[
= 0.98 \text{ days} \left( \frac{M}{0.01 M_\odot} \right)^{1/2} \left( \frac{3V}{c} \right)^{-1/2} \left( \frac{\kappa}{\kappa_e} \right)^{1/2}
\]

\[
T_{\text{eff, } m} \approx 0.79 \beta^{-1/8} T_1 = 2.5 \times 10^4 \text{ K}
\]

from Li & Paczynski ’98
Optical/Infrared Transients from $r$-process decays

LR, et al. ‘11
SGRB 130603B

- SGRB detected at $z=0.356$ by the Swift BAT
- Early optical detection of afterglow
- Point source seen at the position of the GRB
- Consistent with kilonova with $M\sim0.01$ Msun and $v\sim0.1c$

Tanvir et al. ’13, Berger et al. ‘13
Summary

- BNS and BHNS currently seem more favorable scenarios for $r$-process production
- Some problems with details of GCE, but some ways around this
- Kilonovae provide opportunity to observe $r$-process production \textit{in situ}, already have possible first detection
Ejecta Conditions w/o and w/ Neutrinos

Goriely, et al. ‘11

Wanajo, et al. ‘14