$r$-Process Powered Transients from Compact Object Mergers
“I’m partial to the name ‘blingnova’ to describe this kind of event, since what we are seeing is basically an ostentatious glimmering of riches,” Kasen said.
- from The Washington Post
Outline

- Introduction
- Mass ejection during mergers
- Evolution of the ejecta
  - Nuclear Processing
  - Radioactive decay
- Optical or infrared transients
- Implications for \( r \)-process production
- Observational constraints
Multi-Messenger Events

- Gravitational Waves (LIGO, VIRGO, etc.)
- Neutrinos
- Gamma Rays (progenitors of short GRBs?)
- Optical?
- Chemical Evolution

Lee & Ramirez-Ruiz (2007)
Multi-Messenger Events

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Lee & Ramirez-Ruiz (2007)
Binary In-spiral

- In-spiral driven by gravitational wave emission:
  \[ \tau_{\text{mr}} = 8 \times 10^9 P_d^{8/3} M_{2.8}^{-5/3} (1 + q)(1 + 1/q) \text{ yr} \]
- Tidal effects produce minimum stable angular momentum for polytropic binaries. Once more angular momentum is lost, binaries become dynamically unstable (Lai et al.’94).
Merger Dynamics

Rosswog & Ramirez-Ruiz (2002)
Merger Dynamics

Rosswog & Ramirez-Ruiz (2002)
Merger Mass Ejection

- Material is tidally ejected through the outer Lagrange points.
- In GR, material is also ejected from the collision region.
- Significant variation in the amount of unbound mass.
- Significant variation between Newtonian and GR models.

Bauswein et al. ’13
Ejected Mass Distribution

$$M_{ejected} \approx 0 - 0.1 M_\odot$$

- Homologous evolution sets in very quickly after coalescence
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
From One to Two Tails

<table>
<thead>
<tr>
<th>Type</th>
<th>Mass Ratio</th>
<th>Primary Mass ($M_\odot$)</th>
<th>Ejected Mass ($M_\odot$)</th>
<th>Ejecta Velocity ($c$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NS–NS</td>
<td>1.00</td>
<td>1.4</td>
<td>0.057</td>
<td>0.202</td>
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<td>NS–NS</td>
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<td>1.4</td>
<td>0.047</td>
<td>0.200</td>
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<td>NS–NS</td>
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<td>1.5</td>
<td>0.057</td>
<td>0.205</td>
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<tr>
<td>BH–NS</td>
<td>0.31</td>
<td>5.4</td>
<td>0.060</td>
<td>0.248</td>
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</table>
Ejecta Conditions

Korobkin, et al. ’12

Rosswog, et al. ’13
Nuclear Evolution of the Tails

Dynamical Timescale for the Ejected Material:

$$\tau_{ej} \approx 10 \, ms$$

Ejected Material is neutron rich:

$$Y_{e, ej} \approx 0.05 - 0.2$$

Low initial entropy:

$$s \lesssim 10$$
Nuclear Evolution of the Tails

Dynamical Timescale for the Ejected Material:

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Low initial entropy:

\[ s \lesssim 10 \]

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

Which implies a neutron to seed ratio:

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

Can they make r-process nuclei? easy!

see Lattimer & Schramm ’76 and Freiberghaus et al. ’99
Nuclear Network

- Density trajectories for particles from SPH simulations taken
- Energy from nuclear reactions self-consistently added back to entropy of material
- Start from NSE distribution
- Nuclear Network containing over 6000 isotopes
- Heavy nuclei breakup by either neutron induced fission or spontaneous fission, fission fragments distributed over a large portion of (Z,N) space
Final Abundances

- Pure r-process material
- Strong fission cycling
- Some dependence on initial conditions
- Broadly consistent with solar system r-process abundances
Isotopic Abundances

- Reasonable agreement with halo stars
- Mostly sensitive to fission fragment distributions
Nuclear Heating Rate

- Power law heating rate (confirms results of Metzger et al. ’10)
- Larger number of isotopes involved, sum of numerous individual decays
- Beta-decays and fission
- Fairly insensitive to initial conditions ($Y_e$ and entropy)
Optical 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

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

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

\[ L_m \approx 0.88 \beta^{1/2} L_0 = 2.1 \times 10^{44} \text{ ergs s}^{-1} \times \left( \frac{f}{0.001} \right) \left( \frac{M}{0.01 \, M_{\odot}} \right)^{1/2} \left( \frac{3V}{c} \right)^{1/2} \left( \frac{K}{K_c} \right)^{-1/2} \]

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

\[ \times \left( \frac{f}{0.001} \right)^{1/4} \left( \frac{M}{0.01 \, M_{\odot}} \right)^{-1/8} \left( \frac{3V}{c} \right)^{-1/8} \left( \frac{K}{K_c} \right)^{-1/8} \]

Wednesday, July 31, 13
Radiative Transfer Calculations

- Follow radiation transport in homologous ejecta using MC radiation transport code SEDONA
- Directly calculate gamma-ray thermalization rate
- Gray opacities appropriate to iron assumed for current work
Light Curves

- Viewing angle effects larger than effects of mass ratio at peak
- Angle effects washed out at late times
Limits from SGRB Observations

SGRB Magnitudes from Berger ’10

Wednesday, July 31, 13
Geometry from Photometry?

- Depending on relative velocities of tails, could see significant color evolution
- Flattening of color evolution does not occur in any of our detailed models

\[ t_m \propto \left( \frac{M_{\text{tail}}}{0.01M_\odot} \right)^{1/2} \left( \frac{3v}{c} \right)^{-1} \]

\[ T_{\text{eff}} \propto \left( \frac{M_{\text{tail}}}{0.01M_\odot} \right)^{1/4} \left( \frac{3v}{c} \right)^{-3/4} \left( \frac{t}{1\text{day}} \right)^{-3/4} \]
The Opacity of $r$-Process Material

- Opacities of decay products not well known
- Our past calculations use a gray optical opacity
- Current calculations are for densities four or five orders of magnitude too high
- Maybe spectral signatures can more clearly distinguish tail geometries?

C. Fryer (Private Communication)
What is the opacity?

• Number of possible transitions goes approximately as square of number of permutations of valence electrons

\[ C = \prod_i \frac{g_i!}{n_i!(g_i - n_i)!} \]

• Lanthanides have an open \( f \)-shell, gives large complexity measure

• \( r \)-process produced lanthanides expected to dominate opacity

Kasen et al. ’13
Redder, Longer Transients

- Increase the opacity by an order of magnitude, maybe 100
- Increase timescale and decrease opacity

Kasen et al. ’13
Merger Rates

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

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>Source</th>
<th>$R_{\text{low}}$</th>
<th>$R_{\text{med}}$</th>
<th>$R_{\text{high}}$</th>
<th>$R_{\text{max}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>NS-BH (MWAY$^{-1}$ Myr$^{-1}$)</td>
<td>0.05 [18]</td>
<td>3 [18]</td>
<td>100 [18]</td>
<td></td>
</tr>
<tr>
<td>BH-BH (MWAY$^{-1}$ Myr$^{-1}$)</td>
<td>0.01 [14]</td>
<td>0.4 [14]</td>
<td>30 [14]</td>
<td></td>
</tr>
<tr>
<td>IMRI into IMBH (GC$^{-1}$ Gyr$^{-1}$)</td>
<td>3 [19]</td>
<td>20 [19]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>IMBH-IMBH (GC$^{-1}$ Gyr$^{-1}$)</td>
<td>0.007 [20]²</td>
<td>0.07 [20]</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
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...

\[ t_{\text{coalesce}} \approx 10^{6-8} \text{ yr} \]

from Argast et al. 2004
SGRB 130603B

- SGRB detected at $z=0.356$ by the Swift BAT
- Early optical detection of afterglow
- Followed up ~9 days afterward with HST
- Point source seen at the position of the GRB

Berger et al. ’13
SGRB 130603B

- Late time emission consistent with standard afterglow, different power laws between different studies
- Also consistent with kilonova with $M \sim 0.01$ Msun and $v \sim 0.1c$
SGRB 130603B

More to come:

- Better background subtraction
- Is the point source really transient?
Conclusions

- Significant amount of neutron rich mass is ejected during NS-NS mergers
- Amount of mass ejected depends on cold NS mass radius relation
- Decay of radioactive isotopes produced in tails can produce observable optical transient, makes possible *in situ* observation of the production of the $r$-process
- Opacities of ejected material biggest question
- Potentially observed one in association with SGRB 130603B