Mass ejection from neutron–star mergers in numerical relativity

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Outline

I. Brief introduction
II. Typical scenarios for NS mergers (both for NS-NS and BH-NS)
III. Dynamical mass ejection
IV. Early MHD/viscous ejection from NS-NS
V. Viscous (+neutrino-assisted) disk wind
VI. Summary
I Introduction (not necessary?)

Why mass ejection from NS binaries is important?

1. Electromagnetic counterparts of NS merger: Key for confirming gravitational-wave detection (talks by Tanaka & Cowperthwaite)

2. Possible site of r-process nucleosynthesis (talks by Foucart & Hotoke)

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Jet–ISM Shock (Afterglow)
Optical (hours–days)
Radio (weeks–years)

Ejecta–ISM Shock
Radio (years)

Kilonova
Optical (t ~ 1 day)

Merger Ejecta
Tidal Tail & Disk Wind
v ~ 0.1–0.3 c

Optical (t ~ 1 day)

GRB
(t ~ 0.1–1 s)

BH

Metzger & Berger 2012

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Gold seen in neutron star collision debris
Material ejected in gamma-ray bursts may be source of heavy elements

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In the following, I focus on

- Ejecta mass $M_{\text{eject}}$
- Electron fraction $Y_e$

Light curve

Abundance pattern

Tanaka & Hotoke 2013

Korobkin et al. 2012
II A Typical scenarios for NS-NS merger

• **Constraints from radio-telescope observations:**
  1. Approximately 2-solar-mass NSs exist
     (Demorest ea 2010, Antoniadis ea 2013)
     \(\Rightarrow\) equation of state (EOS) for NS has to be **stiff**
  2. Typical total mass of compact binary neutron stars
     \(\Rightarrow\) \(\sim 2.73\pm0.15\) solar mass (by Pulsar timing obs.)
Mass-radius relation for various EOS

- Strong constraint = EOS is stiff.
- Radius is still unconstrained
Compact NS-NS system in our galaxy

Total Mass of NS in compact NS-NS is likely to be in a narrow range, $m \approx 2.73 \pm 0.15 \, M_{\text{sun}}$

<table>
<thead>
<tr>
<th>PSR</th>
<th>$P$(day)</th>
<th>$e$</th>
<th>$M(M_{\text{sun}})$</th>
<th>$M_1$</th>
<th>$M_2$</th>
<th>$T_{GW}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1913+16</td>
<td>0.323</td>
<td>0.617</td>
<td>2.828</td>
<td>1.441</td>
<td>1.387</td>
<td>3.0</td>
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<tr>
<td>B1534+12</td>
<td>0.421</td>
<td>0.274</td>
<td>2.678</td>
<td>1.333</td>
<td>1.345</td>
<td>27</td>
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<tr>
<td>B2127+11C</td>
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<td>0.681</td>
<td>2.71</td>
<td>1.35</td>
<td>1.36</td>
<td>2.2</td>
</tr>
<tr>
<td>J0737-3039</td>
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<td>0.088</td>
<td>2.58</td>
<td>1.34</td>
<td>1.25</td>
<td>0.86</td>
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<tr>
<td>J1756-2251</td>
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<td>0.18</td>
<td>2.57</td>
<td>1.34</td>
<td>1.23</td>
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<tr>
<td>J1906+746</td>
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<td>0.085</td>
<td>2.61</td>
<td>1.29</td>
<td>1.32</td>
<td>3.1</td>
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<tr>
<td>J1913+1102</td>
<td>0.206</td>
<td>0.090</td>
<td>2.875</td>
<td>1.65</td>
<td>1.24</td>
<td>~5</td>
</tr>
<tr>
<td>A24</td>
<td>0.184</td>
<td>0.606</td>
<td>2.74</td>
<td>1.35</td>
<td>1.39</td>
<td>~0.75 $\times 10^8$ yrs</td>
</tr>
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II A  Typical scenarios for NS-NS merger

• **Constraints from radio-telescope observations:**
  1. Approximately 2-solar-mass NSs exist
     (Demorest ea 2010, Antoniadis ea 2013)
     → equation of state (EOS) for NS has to be **stiff**
  2. Typical total mass of compact binary neutron stars
     → ~ 2.73±0.15 solar mass (by Pulsar timing obs.)

• **Numerical relativity simulations have shown that**
  ➢ Merger results typically in **high-mass neutron stars**
    (not BH) (Shibata et al. 2005, 2006.. recently many works….).
Possible outcomes of NS-NS mergers

Likely typical cases for $M = 2.6–2.8M_{\text{sun}}$

$M_{\text{thr}} > \sim 2.8M_{\text{sun}}$

Depends strongly on EOS
Mass ejection history for MNS formation

Time after merger

0                      10                   100                 1000 ms

Dynamical ejection (Sec. III)
(determined by dynamical timescale of NS)

MHD/viscous ejection (Sec. IV)
(by viscous timescale of remnant MNS)

Long-term viscous ejection (V)
(by viscous timescale of disk)

Neutrino irradiation (for neutrino emission timescale)
(minor effects but could play an assist)

Recombination
(Fernandez-Metzger ‘13)
II B Scenarios for BH-NS merger

• Almost no observational constraints but for black hole mass likely $\sim 5M_{\text{sun}}$
  $\Rightarrow$ Wide parameter space has to be explored

• Fate = two possibilities:
  1. Tidal disruption of NS
  2. Simple plunge of NS into BH
Condition for tidal disruption

For tidal disruption, \( (\text{Self gravity of NS}) < (\text{BH tidal force}) \)

\[
\frac{M_{NS}}{(\alpha R_{NS})^2} < \frac{M_{BH}(\alpha R_{NS})}{r^3} \quad (\alpha > 1) \Rightarrow 1 \leq \left( \frac{M_{BH}}{r_{ISCO}} \right)^3 \left( \frac{M_{NS}}{M_{BH}} \right)^2 \left( \frac{\alpha R_{NS}}{M_{NS}} \right)^3
\]

- For tidal disruption
  - Large NS Radius or
  - Small BH mass or
  - High corotation spin is necessary
For tidal disruption of plausible BH-NS with $M_{NS} = 1.35M_{\text{sun}}$, $R_{NS} \sim 12$ km, & $M_{BH} > 6 M_{\text{sun}}$

High BH spin is necessary $> \sim 0.5$

Foucart et al. (‘13,14,…); Kyutoku et al. (‘15)

$$1 \leq 0.1 \left( \frac{6M_{BH}}{r_{\text{ISCO}}} \right)^3 \left( \frac{7M_{NS}}{M_{BH}} \right)^2 \left( \frac{R_{NS}}{6M_{NS}} \right)^3 \left( \frac{\alpha}{1.7} \right)^3$$

$$\left( M_{BH} \leq r_{\text{ISCO}} \leq 9M_{BH} \right)$$

- Natural conclusion: BH-disk systems formed as a remnant should have a high BH spin
Mass ejection history for BH-NS
(in the presence of tidal disruption of NS)

Time after merger

0                      10                   100                 1000 ms

Dynamical ejection (Sec. III)
(determined by dynamical timescale of system)

Long-term MHD/viscous ejection (Sec. V)
(by viscous timescale of disk)
(Fernandez-Metzger 13, Just+ 15,...)

Neutrino irradiation
(would be minor)
III Dynamical mass ejection
NS-NS: Neutrino-radiation hydro simulation

Soft EOS (SFHo, R~11.9 km): 1.30-1.40 $M_{\odot}$

Rest-mass density

0.007 [ms]

Neutrino luminosity

Orbital plane

Tidal torque

Total mass ~ 0.01 $M_{\odot}$

Sekiguchi et al. 2016
NS-NS: Neutrino-radiation hydro simulation

Stiff EOS (DD2, $R \sim 13.2$ km): 1.30-1.40 $M_{\text{sun}}$

Rest-mass density

Orbital plane

0.014 [ms]

Neutrino luminosity

Tidal torque

Total mass $\sim 10^{-3} M_{\text{solar}}$

Neutrino wind

Sekiguchi et al. 2016
Ejecta mass depends on EOS: NS-NS case

Soft EOS $\rightarrow$ strong gravity $\rightarrow$ SHOCK $\rightarrow$ high-mass ejection

Total mass = 2.7 solar mass
Error bar for $1 < Q < 1.25$

Steiner
Mass ratio

Radius of 1.35 solar mass NS

Hotokezaka+ PRD ‘13 (See also Bauswein+ ’13; Bernuzzi + ‘15)
## Summary for dynamical ejecta in NR

Ejecta mass depends significantly on NS EOS & mass

<table>
<thead>
<tr>
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<th>Nearly equal mass (M_{\text{tot}} \sim 2.7 M_{\text{sun}})</th>
<th>Unequal mass: (m_1/m_2 &lt; 0.9) (M_{\text{tot}} \sim 2.7 M_{\text{sun}})</th>
<th>Small total mass system (&lt; 2.6 M_{\text{sun}})</th>
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<td><strong>Soft EOS</strong> ((R=11-12 \text{ km}))</td>
<td>(\text{HMNS} \rightarrow \text{BH}) (M_{\text{eje}} \sim 10^{-2} M_{\text{sun}})</td>
<td>(\text{HMNS} \rightarrow \text{BH}) (M_{\text{eje}} \sim 10^{-2} M_{\text{sun}})</td>
<td>(\text{MNS (long lived)}) (M_{\text{eje}} \sim 10^{-3} M_{\text{sun}})</td>
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<td>(\text{MNS (long lived)}) (M_{\text{eje}} \sim 10^{-2.5} M_{\text{sun}})</td>
<td>(\text{MNS (long lived)}) (M_{\text{eje}} \sim 10^{-3} M_{\text{sun}})</td>
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- Typical velocity: \(0.15—0.25 \text{ c}\)

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Foucart et al ’16
Shibata unpublished
Sekighichi+ ‘17
High temperature $\Rightarrow \gamma \gamma \rightarrow e^- + e^+$, $n + e^+ \rightarrow p + \bar{\nu}_e$

Neutrino irradiation $\Rightarrow n + \nu \rightarrow p + e^-$

Electron fraction (x-y)

Neutrino luminosity

Electron fraction (x-z)

Green = neutron rich

Sekiguchi et al. (2016)
Electron fraction profile: **Broad**

Sekiguchi et al. 2015 PRD

- Average depends on EOS but **typically peak at 0.2—0.3**
- **Broad distribution** irrespective of EOS
- Similar results by Radice+16, Lehner+15,16
Neutrino-radiation hydrodynamics simulation
SFHo ($R \approx 11.9$ km): $1.25-1.55 \, M_{\text{sun}}$

$0.002 \, [\text{ms}]$

$Y_e$

More neutron-rich except for disk surrounding BH

Green = neutron rich

Sekiguchi et al. (2017 hopefully)
Electron fraction distribution:
Broad irrespective of EOS and mass

→ Good for producing a variety of r-elements

Asymmetric binary

Soft EOS

Stiff EOS

Electron fraction distribution

See also Radice ‘16
Neutrino irradiation from MNS increases

- the ejecta mass by ~0.001 solar mass
- Average value of $Y_e$ by ~0.03
- Note that neutrino luminosity decreases in ~100 ms

See also, Perego et al. 2014; Goriely et al. 2015; Martin et al. 2015; Foucart et al. 2016
BH-NS merger (SFHo EOS: density)

\[ M_{\text{BH}} = 5.4 M_{\odot}, \quad M_{\text{NS}} = 1.35 M_{\odot}, \quad a_{\text{BH}} = 0.75 \]

Mass ejection occurs by tidal force of BH

Kyutoku et al. hopefully 2017
BH-NS with NS mass $1.35M_{\text{sun}}$

Data: Kyutoku et al. 2015

High BH spin is important for mass ejection

Soft EOS results in $M_{\text{ejecta}} < \sim 0.01 M_{\text{sun}}$

Stiff EOS results in high mass $> 0.01 M_{\text{sun}}$

$M_{\text{NS}}=1.35$ solar mass

$M_{\text{BH}}=9.45, a=0.75$

$M_{\text{BH}}=9.45, a=0.50$

$M_{\text{BH}}=6.75, a=0.50$

Radius of $1.35$ solar mass NS

High BH spin is important for mass ejection
BH-NS merger (SFHo EOS: electron frac)\n\[ M_{\text{BH}} = 5.4 M_{\odot}, \ M_{\text{NS}} = 1.35 M_{\odot}, \ a_{\text{BH}} = 0.75 \]

Very neutron rich $Y_e \sim 0.1$

Kyutoku et al. hopefully 2017
• Quite low electron fraction irrespective of EOS (Foucart et al., ‘13, 14, 15…, Kyutoku+ hopefully ‘17)
• Likely to primarily produce heavy r-elements
Dynamical ejecta properties in NR

◆ Mass:
  - **NS-NS**: $\sim 10^{-3} - 0.02 \, M_{\text{sun}}$ depending on each mass & EOS: Soft EOS & $\sim 2.7 \, M_{\text{sun}}$ is favorable (Hotoke+ 13, Sekiguchi+ 15, 16, Radice+ 16, Lehner+ 15, 16)
  - **BH-NS**: 0—0.1 $M_{\text{sun}}$: Stiff EOS is favorable; high BH spin is also the key (Foucart+ ’13-15, Kyutoku+15):
    - $M_{\text{eject}} \sim 0.2—0.5 \, M_{\text{disk}}$

◆ Electron fraction
  - **NS-NS**: Broad distribution of $Y_e$ with average $<Y_e> \sim 0.2—0.3$: For asymmetric case, $<Y_e>$ could be $< 0.2$
  - **BH-NS**: Peak at $Y_e < 0.1$ (Foucart+ ’13-15, Kyutoku+ ‘17)

◆ Typical velocity: 0.15—0.25 c; max could be $\sim 0.8$ c
IV Early Viscous/MHD ejecta for NS-NS

• MHD/viscous effects are likely to play a role (Fernandez-Metzger+ ‘13—15, Just et al. ‘15 ….)

• But, previous simulations are studied only for torus surrounding BH (or very artificial NS)

• Realistic remnants = MNS + torus, for which no well-resolved MHD or viscous simulations

• MNS of differential rotation has potential for mass ejection
Physical state for the merger remnants

- Remnant MNS are *magnetized & differentially rotating* → subject to MHD instabilities
- MHD simulations (e.g., Price & Rosswog, ‘07, Kiuchi et al. ‘14, ‘15) suggest that magnetic fields would be significantly amplified by Kelvin-Helmholtz instability → turbulence may be induced
High-resolution GRMHD for NS-NS

\[ \Delta x = 17.5 \text{ m} \]

Kuichi et al. 2015

\[ \tau_{KH} \propto \Delta x \]

Kelvin-Helmholtz instability:

\( \Rightarrow \) Magnetic field should be amplified by winding

\( \Rightarrow \) Quick angular momentum transport? (not yet seen)
Magnetic energy: Resolution dependence

B field would be amplified in $\Delta t << 1$ ms → turbulence?

Still NOT convergent...

Purely hydrodynamics or radiation hydrodynamics is not likely to be appropriate for this problem

$$\tau_{KH} \propto \Delta \chi$$

$B_{\text{max}} = 10^{13}$ G

$p_{\text{max}} = 10^{13}$ ergs

Kiuch et al. 2015
Shear motion at the merger

→ huge number of vortexes are formed and magnetic field is quickly amplified

→ further shear motion → turbulence

→ turbulent (effectively global) viscosity
For post-merger dynamics,

- Obviously **more resolved MHD simulation** is needed
  → But it is not feasible due to the restriction of the computational resources (in future we have to do)
- **One alternative for exploring the possibilities is viscous hydrodynamics** (Radice ‘17, Shibata et al. ‘17)

✓ Note that we do not know whether viscous hydrodynamics can precisely describe turbulence fluid
Viscous neutrino radiation hydrodynamics for post-merger MNS (S. Fujibayashi et al. in preparation)

Employ covariant & causal GR viscous hydro (Israel & Steward)

Initial condition: Merger remnant of $1.35 - 1.35 M_{\text{sun}}$ NS-NS

Alpha viscosity: $\nu = \alpha_v c_s^2 \Omega^{-1}$ with $\alpha_v = 0.01$

EOS: DD2 ($R_{\text{NS}} = 13.2$ km)

$\Rightarrow$ Dynamical ejecta mass $\sim 0.001 M_{\text{sun}}$

Wide $1500 \times 1500$ km 

$300 \times 300$ km

Density in $x$-$z$ plane
Evolution of angular velocity

Fujibayashi et al. in preparation

Play a role in the late-time viscous ejection

Relax to uniform rotation in viscous timescale $\sim 10$ ms

Kinetic energy of $\sim 10^{52}$ erg is released $\rightarrow$ early viscous ejection
Ejecta mass and $Y_e$ distribution

$t < 10 - 20$ ms: Differential rotation of MNS $\rightarrow$ rigid rotation $\rightarrow$ viscous heating $\rightarrow$ ejecta of mass $> 10^{-2.5} M_{\text{sun}}$

Fujibayashi et al. in prep.

$Y_e > ~0.25$

This depends on initial condition
Viscous hydrodynamics for post-merger MNS  
(S. Fujibayashi et al. in preparation)

Electron fraction

Wide $1500 \times 1500$ km  
$300 \times 300$ km
Dynamical + MHD/viscous ejecta in NR

Total ejecta mass could be \( \sim 0.01 \, M_{\text{sun}} \) or more

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- \(<Y_e> \sim 0.2—0.3\) (likely)
- \(Y_e\) has a wide distribution \(\rightarrow\) Good for nucleo-synthesis

To be studied
V Long-term viscous disk wind

- Studies have been done mostly for BH-disk systems (Fernandez-Metzger, ‘13-15, Just+ ’15, Siegel-Metzger ’17; Natural model for BH-NS merger)
  - 10—20% of mass of disk surrounding a spinning BH is likely to be ejected by viscous ejection
  - Due to $Y_e$ freeze-out in the absence of strong neutrino sources, low $Y_e$ matter could be ejected
Basic Picture
(Fernandez-Metzger ’13,14, Just ’15, ……)

- Neutrino irradiated ejection → $Y_e$ is increased
  (weak effect for BH-NS)

- Viscous ejection of mass 10—20% of torus mass
  $Y_e$ freeze out → Low $Y_e$ is preserved (good r-process)
Concern

✓ Initial disk model is rather artificial, in particular,
  • $j=\text{const}$ angular momentum distribution is often used, but it’s unphysical, and in this case, torus becomes geometrically thick leading to easy ejection:

\[
\begin{align*}
\text{j=const torus} & \quad \text{High entropy} \\
\downarrow & \\
\text{Overestimated mass ejection?} & \quad \text{Overestimated neutrino heating?}
\end{align*}
\]

~ Kepler disk

More realistic
Throughout mass ejection of BH-NS merger

- For tidal disruption of NS, high BH spin is necessary → remnant should be high-spin BH + disk
  - Dynamical ejecta: $M_{\text{eject}} \sim 0.2–0.5M_{\text{disk}}$ (e.g., Kyutoku+ ’15)
  - Viscous ejecta from disk could be $\sim 0.1–0.2 M_{\text{disk}}$
    → Comparable to dynamical ejecta
  - Dynamical ejecta has small $Y_e < 0.1$ (e.g., Forcart+, ‘14)
  - Viscous ejecta is also likely to give $Y_e \sim 0.1–0.2$
    because of the absence of strong neutrino sources and resulting freeze-out effect
    (Fernandez-Metzger ’13, 14, Just + ’15, Siegel-Metzger ’17)

→ Likely to be a strong site for the r-process nucleosyn.

Conclusion seems to be robust
Long-term viscous disk wind: NS-NS case

- Remnant MNS-disk systems have been studied only with artificial treatments of MNS
  - The presence of a strong neutrino emitter like MNS would change $Y_e$ significantly (Metzger-Fernandez ‘13, Perego+ ’14, Fujibayashi+ ‘17)

 ✓ Caution:
  - Luminosity of MNS decreases with time
  - Low-$Y_e$ disk initial condition may not be realistic for MNS-disk system
  - Need more realistic studies from NR merger simulation
IV Summary

◆ **NS-NS:**
  
  • Dynamical + subsequent short-term MHD/viscous ejection are likely to provide ejecta mass of $> 0.01 \, M_{\odot}$ irrespective of EOS and each mass of binary
  
  • $Y_e$ is mildly low & broadly distributed: good
  
  • Long-term evolution of post-merger MNS-torus:  ???

◆ **BH-NS:** likely robust conclusion

  • Dynamical ejection could provide $0.01 - 0.1 \, M_{\odot}$, in the case of TD and resulting $Y_e$ is low $< 0.1$
  
  • Post-merger BH-torus could also eject mass 20—50% of disk mass by viscous effect $\Rightarrow M_{\text{eje}} > \sim 0.01 \, M_{\odot}$: $Y_e$ could also be mildly low $\sim 0.1 - 0.2$