Mass ejection from binary neutron star mergers in numerical relativity

Masaru Shibata

Center for Gravitational Physics, Yukawa Institute for Theoretical Physics, Kyoto University
Outline

I. Brief introduction
II. Typical scenario for NS-NS mergers
III. Dynamical mass ejection
IV. MHD/viscous ejection
V. Summary
I Introduction

Why mass ejection from NS binaries is important?

1. Electromagnetic counterparts of NS merger: Key for confirming gravitational-wave detection (talks by Korobkin……)

2. Ejecta could produce r-process heavy elements (talks by Foucart…….)

Gold seen in neutron star collision debris

Metzger & Berger 2012
In the following, I focus in particular on

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

---

**Light curve**

Tanaka & Hotoke 2013

**Abundance pattern**

Korobkin et al. 2012
II  Typical scenario for NS-NS merger

- **Radio-telescope observation shows:**
  1. Approximately $2-M_\odot$ 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
     $\Rightarrow \sim 2.73\pm0.15\ M_\odot$ (by Pulsar timing obs. for 8 NS-NS)

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

**Prompt BH formation**
- $m > M_{\text{thr}}$
- $m_1 \approx m_2$
- $m_1 \neq m_2$
- BH
- BH+disk

**Massive NS formation**
- $m < M_{\text{thr}}$
- $m < M_{\text{max,spin}}$
- HMNS
- MNS

**Likely typical cases**
- $M_{\text{thr}} > \sim 2.8 M_{\odot}$
- Depends strongly on EOS
- Irrespective of EOS

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

Cool down

$M = 2.6—2.8 M_{\odot}$
Mass ejection history for MNS formation

Time after merger

0          10        100       1000 ms

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

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

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

Neutrino irradiation (for neutrino emission timescale)
(minor effects but could play a role)

He Recombination
(Fernandez-Metzger ‘13)
III Dynamical mass ejection

- Mass ejection during the merger
- Ejecta mass depends on binary parameters & equations of state for NS (Hotokezaka et al. ‘13, ….)
NS-NS: Neutrino-radiation hydro simulation

**Soft EOS (SFHo, $R \approx 11.9$ km):** $1.30-1.40 \, M_\odot$

Rest-mass density

Orbital plane

Tidal torque

Neutrino luminosity

$\nu_e$,

$\bar{\nu}_e$

$\nu_e$

$\nu_{\text{other}}$

**Total mass $\sim 0.01 \, M_\odot$**

Sekiguchi et al. 2016

**Weak neutrino wind**
NS-NS: Neutrino-radiation hydro simulation

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

Rest-mass density

Orbital plane

0.014 [ms]

Neutrino luminosity

Tidal torque

较强中微子风

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

x-z plane

Weak Shock heating

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 $1 < Q < 1.25$

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>
<th></th>
<th>Nearly equal mass ( (M_{\text{tot}} \sim 2.7 , M_\odot) )</th>
<th>Unequal mass: ( m_1/m_2 &lt; 0.9 ) ( (M_{\text{tot}} \sim 2.7 , M_\odot) )</th>
<th>Small total mass system ( (&lt; 2.6 , M_\odot) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soft EOS ( (R=11-12 , \text{km}) )</td>
<td>HMNS ( \rightarrow ) BH ( M_{\text{eje}} \sim 10^{-2} , M_\odot )</td>
<td>HMNS ( \rightarrow ) BH ( M_{\text{eje}} \sim 10^{-2} , M_\odot )</td>
<td>MNS (long lived) ( M_{\text{eje}} \sim 10^{-3} , M_\odot )</td>
</tr>
<tr>
<td>Stiff EOS ( (R=13-15 , \text{km}) )</td>
<td>MNS (long lived) ( M_{\text{eje}} \sim 10^{-3} , M_\odot )</td>
<td>MNS (long lived) ( M_{\text{eje}} \sim 10^{-2.5} , M_\odot )</td>
<td>MNS (long lived) ( M_{\text{eje}} \sim 10^{-3} , M_\odot )</td>
</tr>
</tbody>
</table>

- Typical velocity: \( 0.15—0.25 \, c \) irrespective of models

- Foucart et al. ’16
- Shibata unpublished
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

1.35-1.35 solar case

- **Broad distribution irrespective of EOS**
- **Average depends on EOS but typically peak at 0.2—0.3**
  - Similar results by Radice+16, Lehner+15,16
Neutrino-radiation hydrodynamics simulation
SFHo ($R\sim11.9$ km): $1.25-1.55 \, M_\odot$

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 (SFHo)
- Stiff EOS (DD2)

Sekiguchi+ ‘16
See also Radice ‘16
- Quite low electron fraction irrespective of EOS (Foucart et al., ‘13, 14, 15…, Kyutoku+ hopefully ‘17)
- Likely to primarily produce heavy r-elements
Neutrino irradiation: subdominant effect

Neutrino irradiation from MNS increases

- the ejecta mass by $\sim 0.001 \, M_\odot$
- Average value of $Y_e$ by $\sim 0.03$ or more (for longer term)
- Note that neutrino luminosity decreases in $\sim 100$ ms

See also Perego et al. 2014; Goriely et al. 2015; Martin et al. 2015; Foucart et al. 2016
& talks by Foucart and Perego
Dynamical ejecta properties in NR

◆ Mass:
  • \( \sim 0.001 - 0.02 \, M_\odot \) depending on each mass & EOS: Soft EOS & \( \sim 2.7 \, M_\odot \) is favorable for large ejecta (Hotoke+ 13, Sekiguchi+ 15,16, Radice+ 16, Lehner+ 15,16)

◆ Electron fraction
  • Broad distribution of \( Y_e \) with average \( <Y_e> \sim 0.2-0.3 \): For asymmetric case, \( <Y_e> \) could be < 0.2

◆ Typical velocity: \( 0.15 - 0.25 \, c \); max could be \( \sim 0.8 \, c \)
IV Early Viscous/MHD ejecta

- MHD/viscous effects are likely to play a key role (Fernandez-Metzger+ ‘13—15, Just et al. ‘15 ….)
- However, previous simulations studied only for torus surrounding BH (or artificial NS)
- Realistic remnants = MNS + torus: for MNS no well-resolved MHD or viscous simulations were done

- MNS of differential rotation has potential for significant mass ejection induced by MHD instability

- MHD simulations (e.g., Price & Rosswog ‘07, Kiuchi+ ‘15) suggest that magnetic fields would be significantly amplified by Kelvin-Helmholtz instability

→ turbulence may be induced
High-resolution GRMHD for NS-NS

Kiuchi et al. ‘15

Kelvin-Helmholtz instability in the shear layer

- Vortexes
- Magnetic fields are amplified by winding
- Quick angular momentum transport? (not yet seen)

Grid spacing
$\Delta x = 17.5\text{m}$
Magnetic energy: Resolution dependence

B field would be amplified in $\Delta t \ll 1 \text{ ms} \rightarrow$ turbulence?

Still NOT convergent...

Higher resolution

Purely hydrodynamics/radiation hydrodynamics /low-resolution MHD are likely to be inappropriate for this problem

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

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

$\frac{\Delta t}{t_{mrg}} \ll 1 \text{ ms}$ à turbulence?

Kiuch et al. 2015
Shear motion at the merger

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

→ Turbulence → Turbulent viscosity

→ Effectively viscous fluid (likely)
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 our 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 hydrodynamics (Israel & Steward, ’79, Shibata+ ‘17)

**Initial condition:** Merger remnant of 1.35-1.35\(M_\odot\) NS-NS at 50 ms after the merger

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

**Equation of state:** DD2 \((R_{NS} = 13.2 \text{ km}, \text{stiff})\)

- Dynamical ejecta mass \(\sim 0.001 \text{ } M_\odot\)

**Axis symmetric simulation**

Wide 1500\(\times\)1500 km 300\(\times\)300 km

Density in \(x\)-\(z\) plane
Evolution of angular velocity

Relax to uniform rotation in viscous timescale $\sim 10^{-20}$ ms

Kinetic energy of $\sim 10^{52}$ erg is released $\rightarrow$ early viscous ejection

Play a role in the late-time viscous ejection
Early viscous ejecta

For $t < 10-20$ ms:

- Differential rotation of remnant NS
- Rigid rotation
- Viscous heating
- Outward motion
- Ejecta from disk of mass $\sim 10^{-2.5} M_\odot$

Fujibayashi et al. in prep.
Only dynamical ejecta

Ejecta mass depends significantly on NS EOS & mass

<table>
<thead>
<tr>
<th></th>
<th>Nearly equal mass ( M_{\text{tot}} \sim 2.7 , M_\odot )</th>
<th>Unequal mass: ( m_1/m_2 &lt; 0.9 ) ( M_{\text{tot}} \sim 2.7 , M_\odot )</th>
<th>Small total mass system (&lt; 2.6 , M_\odot )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soft EOS ((R=11-12 , \text{km}))</td>
<td>HMNS (\rightarrow) BH (M_{\text{eje}}\sim10^{-2} , M_\odot)</td>
<td>HMNS (\rightarrow) BH (M_{\text{eje}}\sim10^{-2} , M_\odot)</td>
<td>MNS (long lived) (M_{\text{eje}}\sim10^{-3} , M_\odot)</td>
</tr>
<tr>
<td>Stiff EOS ((R=13-15 , \text{km}))</td>
<td>MNS (long lived) (M_{\text{eje}}\sim10^{-3} , M_\odot)</td>
<td>MNS (long lived) (M_{\text{eje}}\sim10^{-2.5} , M_\odot)</td>
<td>MNS (long lived) (M_{\text{eje}}\sim10^{-3} , M_\odot)</td>
</tr>
</tbody>
</table>

➢ Typical velocity: 0.15—0.25 \(c\) irrespective of models

Foucart et al ’16
Shibata unpublished
Dynamical + MHD/viscous ejecta in NR

<table>
<thead>
<tr>
<th>Soft EOS ((R=11-12\ km))</th>
<th>Nearly equal mass ((M_{\text{tot}} \sim 2.7 , M_\odot))</th>
<th>Unequal mass: (m_1/m_2 &lt; 0.9) ((M_{\text{tot}} \sim 2.7 , M_\odot))</th>
<th>Small total mass system (&lt; 2.6 , M_\odot)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MNS (\rightarrow) BH (M_{\text{eje}} \sim 10^{-2} , M_\odot)</td>
<td>MNS (\rightarrow) BH (M_{\text{eje}} \sim 10^{-2} , M_\odot)</td>
<td>MNS (long lived) (M_{\text{eje}} \sim ???)</td>
<td></td>
</tr>
<tr>
<td>Stiff EOS ((R=13-15\ km))</td>
<td>MNS (long lived) (M_{\text{eje}} \sim 10^{-2} , M_\odot)</td>
<td>MNS (long lived) (M_{\text{eje}} \sim 10^{-2} , M_\odot)</td>
<td>MNS (long lived) (M_{\text{eje}} \sim ???)</td>
</tr>
</tbody>
</table>

Total ejecta mass could be \(\sim 0.01 \, M_\odot\) or more

To be studied
Viscous hydrodynamics for post-merger MNS
(S. Fujibayashi et al. in preparation)

Electron fraction $Y_e$

Wide $1500 \times 1500$ km

$300 \times 300$ km
$Y_e$ distribution & entropy

- Outer layer of torus/disk is ejected with $Y_e$ preserved
  $\Rightarrow Y_e$ distribution depends on initial condition

Fujibayashi et al. in prep.
Long-term mass ejection from merger remnant

Viscosity-driven ejecta could be $M_{ej} \sim 10^{-3} M_\odot$ if the ejection is sustained for $\sim$ a few seconds.

See also talks by Foucart & Perego for neutrinos.
Summary

Mass ejection history for MNS formation

- **Dynamical ejection**
  - \( M_{\text{ej}} \sim 10^{-3} - 10^{-2} \, M_\odot \), \( Y_e \) = Broad distr. with \( <Y_e> \sim 0.2 - 0.3 \)

- **MHD/viscous ejection from remnant NS**
  - \( M_{\text{ej}} \sim 10^{-2.5} \, M_\odot \), \( Y_e \sim 0.2 - 0.5 \)

- **MHD/Viscous ejection from disk**
  - \( M_{\text{ej}} \sim 10^{-3} \, M_\odot \), \( Y_e \sim 0.3 - 0.5 \)