Coalescence and explosion of compact neutron star binaries
- numerical relativity study -

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## Galactic compact NS-NS observed

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<th>$P$(day)</th>
<th>$e$</th>
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<th>$M_1$</th>
<th>$M_2$</th>
<th>$T_{GW}$</th>
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</tr>
</tbody>
</table>

4+1(GC) NS-NS, which will merge in Hubble time (13.7 Gyr), have been found.

*10^8 yrs Merger time

→ Galactic merger rate $\sim 1/10^4 – 1/10^6$ yrs
→ Merger in the Universe $\sim 10^5 – 10^7$ / yrs
→ Event-rate for aLIGO/VIRGO/KAGRA $\sim 1 – 100$ /yrs
(e.g. Kalogera+, 2007, Belczyski+, …)
Why NS-NS/BH-NS are important?

1. The most promising sources of gravitational waves
2. Invaluable laboratory for studying high-density nuclear matter
3. Possible origins of short-hard GRBs
4. Sources of strong EM emission

Numerical relativity plays a crucial role for all four issues.
I Gravitational waves & EOS

Status & Issues in numerical relativity
Evolve by GW emission

Tidal deformation at $r \sim 40\text{-}50\text{ km}$

Merger sets in at $f_{GW} \sim 1\text{ kHz}$

Case I
- High mass or Soft EOS
- Black hole is formed

Case II
- Stiff EOS
- “Massive NS”

Strong dependence on EOS & mass

"Inspiral" Adiabatic evolution $t_{GWorb} \gg$

Dynamical evolution “Merger” $t_{GWorb}$
Evolve by GW emission
Last 1 hour; $f_{GW} \sim 1$ Hz

Merger sets in at $r \sim 40$ km; $f_{GW} \sim 1$ kHz

Case I: NS is swallowed by BH
Case II: NS is disrupted

For small $R_{NS}$ or $M_{BH} \gg M_{NS}$ or small spin (talk later)

Strong dependence on EOS & spin
EOS *is* stiff: but still too many candidates

**Strong constraint!**
**But not strong enough**
Merger of $1.35-1.35M_{\text{sun}}$ NS with four EOSs

By hotokezaka + 2013

Massive neutron stars are formed

H4: $R=13.5\text{km}$

MS1: $R=14.5\text{km}$
Evolve by GW emission

Tidal deformation at $r \sim 40-50$ km

Merger sets in at $f_{GW} \sim 1$ kHz

Case I
Soft EOS
Black hole is formed

Case II
Stiff EOS
“Massive NS”

Black hole is formed

Adiabatic evolution
$t \tau_{GWorb} \gg$

Dynamical evolution
$t \tau_{GWorb} \sim$
Two interesting phases

1. Late Inspiral (Lai+, Hinderer+, Damour+, Baiotti+, Bernuzzi+):
   Effects of tidal deformation
   \( f \sim 500 - 1k \text{ Hz} \)

2. Merger \( \rightarrow \) MNS
   (Janka+, Hotokezaka+)
   Quasi-periodic GW from MNS: \( f \sim 2k - 4k \text{ Hz} \)

Both waveforms could be used for constraining EOS of neutron stars
Tidal effects in a binary inspiral
(originally pointed out by Lai+ 1992)

Close Binary System

→ Tidal deformation

→ Quadrupole is induced

5PN correction (very high):

\[ A \sim 2 \frac{GM}{r} 2 \frac{C}{r^6} \]

But \( C \sim MR^5 \), \( R \sim 5—8 \ M \)
For \( r \sim 2R \), it could play a role.
Late-phase chirp signal

- APR4
- H4
- MS1

TT4
TT4 + tidal (Hinderer-Flanagan)
Larger radius

Point

$t_{ret}$ (ms)
Latest EOB study (Damour, Nagar + 2012)

A static tidal approximation:
Quadrupole moment $= -\lambda$ (tidal field); linear approx.

Tidal deformability depends on EOS

Measurable limit with $\rho = 16$, $S/N=16$

Advanced detectors could measure tidal deformability

Numerical relativity calibrates this result (Bernuzzi+, Hotokezaka+)
**EOS dependence:** $M_1 = 1.3, \ M_2 = 1.4M_{\odot}$

- **APR4-130140 (Soft)**
  - $f$: 3.2—3.4 kHz
  - $h_t$ vs $t_{ret}$

- **ALF2-130140 (BH)**
  - $f$: 2.8—2.9 kHz
  - $h_t$ vs $t_{ret}$

- **MS1-130140 (Stiff)**
  - $f$: ~2 kHz
  - $h_t$ vs $t_{ret}$

- **H4-130140 (HMNS)**
  - $f$: 2.5—2.6 kHz
  - $h_t$ vs $t_{ret}$
$f \pm \Delta f$

$\Delta f \sim 0.2 \text{ kHz}$

**EOS is reflected in the typical frequency**
Relation between peak and radius

Radius of 1.6 solar-mass NS

Radius is constrained with ~1km error
GWs from NSNS: summary

• If $D < 100$ Mpc, \textit{late inspiral waveforms} could be used to constrain EOS (aLIGO/VIRGO/KAGRA)

• If $D < \sim 30$ Mpc, \textit{merger waveforms} could be used to constrain EOS (aLIGO/VIRGO/KAGRA)

• ET will be the robust detector for exploring EOS of NS
BH-NS binary (zero BH spin)

Piece-wise polytropic EOS

$M_{BH} = 2.7 M_{\text{sun}}$

$M_{NS} = 1.35 M_{\text{sun}}$

$R = 11.6 \text{ km}, \quad Q = 2$

$M_{BH} = 4.05 M_{\text{sun}}$

$M_{NS} = 1.35 M_{\text{sun}}$

$R = 11.0 \text{ km}, \quad Q = 3$

Log $\rho$ (g/cm$^3$)

Kyutoku + PRD 2011: See also Etienne +, Duez, Foucart +
Spinning BH-NS; more promising

\[ M_{\text{BH}} = 5.4 M_{\text{sun}} \]
\[ a = 0.75, \quad Q = 4 \]
\[ M_{\text{NS}} = 1.35 M_{\text{sun}} \]
\[ R = 11.6 \text{ km} \]

\[ M_{\text{BH}} = 2.7 M_{\text{sun}} \]
\[ a = -0.5, \quad Q = 2: \text{Counter rot} \]
\[ M_{\text{NS}} = 1.35 M_{\text{sun}} \]
\[ R = 11.6 \text{ km} \]

Kyutoku + PRD 2011: Piece-wise polytropic EOS
Condition for tidal disruption

BH tidal force > NS self-gravity

\[ Q := \frac{\varphi M_{\text{BH}} c R^6}{\varphi c R_{\text{NS}}^{2} G M_{\text{NS}}} \]

1 ~ 6

- ✓ Low-mass BH or
- ✓ Large NS radius or
- ✓ Large BH spin is necessary
$M_{\text{BH}} = 2.7 M_{\text{sun}}, \ a=0, \ M_{\text{NS}} = 1.35 M_{\text{sun}}$

- **sudden shutdown**
  - $R=15.2 \text{ km}$

- **BH ringdown**
  - $R=11.6 \text{ km}$

Green = Tayloy T4 (point particle + PN)
BH-NS with piecewise polytrope ($a=0$)

For all, $1.35-2.7M_{\text{sun}}$ $f$ [Hz]

Clear dependence of “cutoff” freq. on NS radius
But, amp is low...

Larger radius of NS
GW spectrum for $Q=3, M_{NS}=1.35M_{\text{sun}}$

Spin increases

Same EOS: $R=11.6 \text{ km}$

Kyutoku + 2011
With BH spin & high-mass BH

For all, \( a=0.75 \) 1.35 – 5.4\( M_{\text{sun}} \)

Kyutoku + 2011

Could be detected by advLIGO
Latest systematic study (Lackey, Kyutoku+ ‘13)  
> 100 simulations  

For all, \( a=0.50 \ 1.35 – 4.05M_{\text{sun}} \)
Fisher analysis with hybrid waveforms
(Lackey, Kyutoku + '13)

Pressure at $r=5 \times 10^{14}$ g/cc

Adiabatic index of EOS at NS core

NS radius (tidal deformability) will be constrained by ET
GWs from BH-NS binaries

- For the case that tidal disruption occurs, GWs have a characteristic feature
- Tidal disruption occurs only for low-mass BH for *zero BH spin*. But, tidal disruption occurs for a realistic mass of BH is BH spin $> \sim 0.5$
- GWs from tidal disruption events could be used for constraining EOS
- In particular, ET will be powerful
II Merger as high-energy phenomena:
Theoretical study for short-hard GRB models
NS-NS simulation with microphysics

Sekiguchi, Kiuchi, Kyutoku, Shibata
PRL107, 2011
NS-NS simulation with microphysics

Contour in x-z plane; only after the merger

- High-neutrino luminosity near pole (white region)
- Now, no neutrino heating, pair annihilation
Related quantities

- **HMNS**: $T \sim 20-30$ MeV
- **BHtorus**: $T \sim 10$ MeV
- **HMNS**: $L \sim 3-5 \times 10^{53}$ erg/s
- **BHtorus**: $L \sim 1 \times 10^{53}$ erg/s

- **Red**: $M = 1.35-1.35 \ M_{\text{sun}}$
- **Green**: $M = 1.5-1.5$
- **Blue**: $M = 1.6-1.6$

Long-lived HMNS

HMNS : $T \sim 20-30$ MeV
BHtorus: $T \sim 10$ MeV
HMNS : $L \sim 3-5 \times 10^{53}$ erg/s
BHtorus: $L \sim 1 \times 10^{53}$ erg/s
BH($a=0, M=4.05M_{\text{sun}}$) — NS($1.35M_{\text{sun}}$): New Shen’s EOS

Kiuchi et al. (2013?)

See also Deaton + (2013) for other work
Something is likely to occur ...
Neutrino luminosity

\[ \alpha = 0.5 \quad \alpha = 0 \]

- Neutrino luminosity is also high \( \sim 10^{53} \text{ erg/s} \):
- In the presence of viscosity/B-field, the luminosity could be enhanced.
Annihilation rate \((\text{Beloborodov } '08)\)

\[
\frac{dE_{KK}}{d\tau} \sim \cos(\phi) \phi^2 \epsilon^2 \frac{O_0}{2M_{\text{Opening}}} (E_{KK}^0)^2 \frac{\varphi}{\tau^2} \frac{1}{\phi \epsilon e} \frac{1}{2} 
\]

\[
\sim 10^{51} \text{ergs/s} \quad \frac{\varphi}{\tau} \frac{1}{\varphi \epsilon} \frac{7}{cm0.1\gamma} \frac{1}{r} \frac{1}{N_{\text{opening}}} \frac{1}{\phi \epsilon 10\text{MeV}} \frac{1}{\phi \epsilon} 
\]

\[
\varphi \propto \frac{E_{KK}^0}{\phi \epsilon} \frac{1}{\epsilon} \frac{10\text{ergs/s}}{10\text{ergs/s}} \frac{1}{0.1} \frac{1}{\phi \epsilon} 
\]

Could supply SGRB power

- Neutrino heating and pair creation are important
- We should take into account them in the future
GRMHD simulation

$1.4-1.4M_{\text{sun}}$: EOS: H4=Nucleon + hyperon (stiff)

Hot magnetized torus is formed

Strong B-field & efficient heating of torus by MHD process; but no jet in this setting

Kiuchi+ 2013
Evolution of magnetic energy

- Saturation level ≈ 6-7 $10^{48}$ erg (2-3 % of kinetic energy)

Would like to see convergence → “Kei” computer in prog.
Status

• Simulations with neutrino-heating and finite-temperature EOS is ongoing (Kyoto, Caltech/Cornell/CITA/Was)
• High-resolution simulation with B-field is ongoing (AEI, Kyoto, Illinois…)
• Simulation with microphysics & high-res B-field is next step
III Electromagnetic counter parts
Larger possibility for detection

Emission by mass ejection

May be a MNS

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

GRB
(t ~ 0.1–1 s)

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

BH

Radio flare

Ejecta–ISM Shock
Radio (years)

Kilonova
Optical (t ~ 1 day)
Mass ejection and EM counter parts

• **Neutron-rich & high-velocity ejecta could generate observable EM signals via**

  ➢ **Kilo-nova/Macro-nova:** Production and Decay of r-process-heavy nuclei
    (Li & Paczynski 1998, Kulkarni 05, Metzger+ ‘10, .... Barnes+ ’13, Tanaka-Hotokezaka ‘13)
    
    Required mass $>\sim 0.01 \, M_{\text{sun}}$

  ➢ **Long-term radio flare** (Nakar-Piran 2011)
    Required kinetic energy $>\sim 10^{49} \, \text{erg}$ with a large $v/c > \sim 0.1$; need high-density of ISM
r-process → β-decay or fission → heating material → UV ~ IR
Li-Paczynski’s estimate (i)

- Ejected material is heated by r-process elements, but initially the ejecta is optically thick

\[
\frac{\rho r \kappa}{\rho \varepsilon c} \cdot \frac{t}{t_{\text{diff}}} = - \frac{1}{\mathcal{H}} = \Xi \text{Typical density} \quad \frac{3M}{4M^3} \text{Mean free path} \quad \mathcal{H} \text{Typical optical depth} \quad r \text{Ejecta size} \quad : \text{Ejecta velocity} \quad \nu t_{\text{expdiff}} \ll \text{Diffusion} \quad \omega t_{\text{expdiff}} > t \text{Free stream of photon}
\]
Li-Paczynski’s estimate

At \( t_{\text{exp}} \) Luminosity becomes maximum

\[
L_{\text{max}} \sim 3 \times 10^{31} \text{ ergs/s} \quad \mathcal{E} \quad 41
\]

30 ergs/s M15.0 mag

\[
M = 20.0 \text{ mag} \quad @ \quad 100\text{Mpc}
\]

\[
m = 21.5 \text{ mag} \quad @ \quad 200\text{Mpc}
\]

These depend on mass, velocity, & opacity
Model luminosity curve of NS-NS@200Mpc
(M. Takana & Hotokezaka, ‘13)
GRB130603b: Kilonova?

Curve by M. Tanaka and Hotokezaka, arXiv: 1306.3742

X-ray

NIR

UV

Tanvir et al.: arXiv: 1306.4971
See also Berger et al.: 1306.3960

z=0.356
Long-term radio flare (Nakar & Piran 2011)

- Ejecta sweeps interstellar matter → Shock → synchrotron emission

\[
M_{\text{ej}} = \frac{4M}{3} \mathcal{E}_s \left( \frac{v}{c} \right)^3 \quad t \approx \frac{0.003 \mathcal{E}_s^{1/3} \phi v^{21/3}}{\phi c^{21/3}} \\
F_K \approx 0.8Jy \quad \phi \frac{E_{\text{ej,kin}}^{50.75}}{\phi \tau^{0.9}} \quad 2.8 \quad \phi \frac{\mathcal{M}_{\text{ej}}^{22}}{\phi c^{22}} \quad \frac{K}{4Hz}
\]

<table>
<thead>
<tr>
<th>Radio Facility</th>
<th>Obs Freq.</th>
<th>Field of view</th>
<th>1 hr</th>
<th>ns² 1 hr horizon†</th>
<th>ns² 10 hr horizon†</th>
<th>nsbh 1 hr horizon†</th>
<th>nsbh 10 hr horizon†</th>
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<td>1.4</td>
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<td>360 Mpc</td>
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<td>30</td>
<td>170 Mpc</td>
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<td>1000</td>
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<td>40 Mpc</td>
<td>300 Mpc</td>
<td>250 Mpc</td>
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</tbody>
</table>

Uncertainties: Mass and velocity as well as configuration
Many uncertainties

- Opacity $\rightarrow$ Significant difference between iron-type and heavier r-process elements (Kasen et al. ’13, Tanaka & Hotokezaka ‘13);
  $\rightarrow$ Opacity is quite high in the UV band
- Ejecta mass $\rightarrow$ Need numerical relativity
- Ejecta speed $\rightarrow$ Need numerical relativity
- Ejecta configuration $\rightarrow$ Need numerical relativity
- R-process $\rightarrow$ More realistic simulations including electron fraction, neutrino heating/cooling

Many issues in numerical relativity and associated numerical works
First step: Merger of 1.3-1.4 $M_{\text{sun}}$ NS:

EOS=APR4; stiff but relatively soft:

NS radius $\sim$ 11 km

Log $\rho$ (g/cm$^3$)

Mass ejection by
Shock + torque exerted by HMNS

Hotokezaka + ‘13
Much wider view: $L \sim 1200$ km

Merger sets in at $t \sim 11$ ms

Initial blue: atmosphere

Average velocity
$\sim 0.2 - 0.3$ c
Max $\sim 0.7 - 0.8$ c
Amount of ejection depends strongly on EOS

(Relatively) Soft EOS is favoured

Kinetic energy $E_{*_{\text{esc}}} \left(10^{50} \text{ erg}\right)$

Compact NS

Large-radius NS

Factor $\sim 10$

$0.0005 - 0.01 \ M_{\text{sun}}$

$10^{49} - 10^{51} \text{ erg}$

$\text{M}_{*_{\text{esc}}} \left(\text{M}_{\text{sun}}\right)$

Compact NS

Large-radius NS

Factor $\sim 10$

$t - t_{\text{merge}} \ (\text{ms})$
Long-run with plausible mass: NEW
BH($a=0.75, M=9.45M_{\odot}$) — NS($1.35M_{\odot}$)

Note: Similar work has been done by Fourcart+ 2013
Mass ejection (> 0.01$M_{\text{sun}}$)

Mass ejection is anisotropic for BH-NS binaries

Only ejecta with escape velocity is shown
Effect of morphology is important

\[ t \sim \frac{\varphi^3 M_H}{\tau \frac{M_v}{\phi \epsilon}} \sin N \]

\[ \sim 3 \text{ days} \quad \frac{\varphi \varpropto \frac{M_v}{\tau}}{\varpropto \frac{\tau}{\phi \epsilon}} \]

\[ H \quad \frac{\varphi \varpropto \frac{H}{\tau}}{\varpropto \frac{\tau}{\phi \epsilon}} \]

\[ \sin^{1/2} N \]

\[ L_{\text{max}} \sim 3 \times 10^{31} \text{ ergs/s} \quad \varpropto \frac{M_c f^{2 \text{ r-proc}}}{t M_c} \]

\[ \varphi \varpropto \frac{M_v}{\tau} \quad \frac{1/2}{\varpropto \frac{\tau}{\phi \epsilon} 0.0050} \]

\[ \varphi \varpropto \frac{H}{\tau} \frac{21/2}{\varpropto \frac{\tau}{\phi \epsilon} 10^2} \]

\[ \sin^{21/2} N \]
Issue for the mass ejection

• Scenario basically OK
• First step: Properties of mass ejection should be clarified: total mass, energy, morphology, dependence on EOS & binary masses
• Are magnetic power and neutrino wind important for mass ejection?
• Advanced steps: NR simulation data + r-process calculation; details of light-curve & spectrum?
  (Many calculations were based on one-zone cal)
• Detailed study of fall back signal is interesting

Many things to do; new topic in NR
Summary

• Many systematic simulations for NS-NS and BH-NS coalescence are ongoing: Many gravitational waveforms are in hand.
• Quantitative modeling of GW is necessary
• Advanced numerical simulations (+neutrinos, magnetic fields, ...) are also ongoing: However, more detailed modeling with high grid resolution will be necessary
• Study for electromagnetic counter parts is new field that should be developed soon
BH formation case: APR4, mass = 1.3-1.6M_{\odot}

**Wider view:** L \sim 1200 \text{ km}

Merger sets in at t \sim 11 \text{ ms}

Initial blue: atmosphere

Not very spherical

Orbital plane

X-Z plane
Kasen+ ’13 (last week)

r-process elements

line expansion opacity (cm$^2$ g$^{-1}$)

wavelength (angstroms)
Smaller peak luminosity
→ Bad
Longer time scale
→ Good

Barnes-Kasen ‘13
Optical Search Following a GW Trigger

Range of kilonova models with different ejecta mass $M_{ej} \sim 10^{-3} - 0.1 M_\odot$ and velocity $v \sim 0.1-0.3$ c

Timescale: 10 times
Luminosity: 0.1 times

$H = 0.1 \text{ cm}^2\text{g}$

$\Rightarrow$

$H = 10 \text{ cm}^2\text{g}$

Modify the file by Metzger @Santa-barbara