Anisotropic mass ejection from black hole-neutron star binaries: Diversity of electromagnetic counterparts

Koutarou Kyutoku
University of Wisconsin-Milwaukee

KK, Ioka, Shibata  PRD 88 (2013) 041502(R)

KK, Ioka, Okawa, Shibata, Taniguchi  in prep.
Why do we investigate BH-NS binaries?

• Gravitational waves masses, spins, equations of state of neutron stars...

• Electromagnetic radiation/counterparts
  - mass ejection
  macronova/kilonova from r-process element decays
  synchrotron radio emission from an ejecta-ISM shock
  - disk formation (including fallback material)
  short-hard gamma-ray bursts and afterglows
Main questions

How does mass ejection from BH-NS occur?

What are typical values of BH-NS ejecta quantities?
- computed by numerical-relativity simulations
  (LORENE initial condition+SACRA time evolution)

What are electromagnetic counterparts to BH-NS?
Are they different from those of NS-NS?
- estimated by back-of-the-envelope calculations
- radiation transfer simulations (Tanaka,KK+ arXiv:1310.2774)
Mass ejection
Tidal disruption of the neutron star

A typical case by numerical-relativity simulations

H4 EOS

\[ R_{\text{NS}} = 13.5 \text{km} \]
\[ M_{\text{BH}} / M_{\text{NS}} = 5 \]
\[ \chi_{\text{BH}} = 0.75 \]
(aligned spin)

\[ \log \rho \ (\text{g/cc}) \]
Mass ejection is anisotropic for BH-NS binaries.
Crescent-like ejecta geometry

\[ \varphi_{\text{ej}} \sim \pi : \text{set by} \ 2\pi \left( t_{\text{sc}} / t_{\text{orb}} \right) \]

both timescales are \( \propto \rho^{-1/2} \)

at tidal disruption radius

\[ r_{\text{tid}} \sim R_{\text{NS}} \left( M_{\text{BH}} / M_{\text{NS}} \right)^{1/3} \]

\[ \theta_{\text{ej}} \sim 1/5 : \text{set by} \ R_{\text{NS}} / r_{\text{tid}} \]

not specific to this EOS model
Important quantities

Ejection is efficient if the NS EOS is stiff (large $R_{NS}$) opposite to the binary NS mass ejection

\begin{align*}
\text{large ejecta mass} & \quad 0.01 - 0.1 M_\odot \\
\text{large kinetic energy} & \quad 5 \times (10^{50} - 10^{51}) \text{ erg} \\
\text{bulk velocity} & \quad v_{ej} \sim 0.2 c
\end{align*}
Observational implication
Baryon loading of the GRB jet

Less material above the remnant object
jet penetration is easier for BH-NS (but confinement?)

Hotokezaka+ (2013)

NS-NS (hypermassive NS)  BH-NS (BH-disk)
**Macronova/kilonova**

Photon diffusion from r-process decay heated ejecta

- **spherical ejecta**
- **BH-NS ejecta**
  - aspect ratio: $\nu_\parallel/\nu_\perp \sim 1/\theta_{ej} \sim 5$

**NS-NS:** $t_{peak,s} \sim \left( \frac{3\kappa M_{ej}}{4\pi c\nu_{ave}} \right)^{1/2} \sim 8\text{day}$

**BH-NS:** $t_{peak} \sim \left( \frac{\kappa M_{ej}\nu_\perp}{c\phi_{ej}\nu_\parallel^2} \right)^{1/2} \sim 4\text{day}$

Radiation transfer (3D Monte Carlo)

Tanaka, KK+ (2013)
Viewing-angle dependence

high luminosity $L_{\text{peak}} \sim f M_{\text{ej}} c^2 / t_{\text{peak}} \sim 10^{41}\text{erg s}^{-1}$

low luminosity $\sim \theta_{\text{ej}} L_{\text{peak}}$
polarization up to $\sim 4-5\%$ is possible

deformed photosphere

radiation transfer (3D Monte Carlo)
Tanaka, KK+ (2013)
Synchrotron radio emission

Ejecta decelerate when accumulate $M_{ej}$ from ISM blast waves shines like supernova remnants

For a spherical ejecta ($n_H = 1 \text{cm}^{-3}$ assumed)

$$R_{\text{dec},s} \sim \left( \frac{3M_{ej}}{4\pi mpn_H} \right)^{1/3} \sim 0.7 \text{pc}$$

$$t_{\text{dec},s} \sim R_{\text{dec},s}/v_{\text{ave}} \sim 7 \text{yr}$$

For a BH-NS ejecta

$$R_{\text{dec}} \sim 1.7 \text{pc} \theta_{ej,1/5}^{-1/3} \phi_{ej,\pi}^{-1/3}$$

$$t_{\text{dec}} \sim 18 \text{yr} \theta_{ej,1/5}^{-1/3} \phi_{ej,\pi}^{-1/3}$$
Proper motion of radio images

Typical proper motion in terms of the angle is

$$v_{ej} t_{\text{dec}} / D \sim 1 \text{pc}/100\text{Mpc} \sim 1 \text{mas}$$

Both images expand in time but only BH-NS images move in time.
Summary

• Black hole-neutron star binary mergers can eject substantial material with $\sim 0.01 - 0.1M_\odot$ during tidal disruption via hydrodynamic tidal torque.
• Ejecta is very anisotropic, is mostly concentrated around the orbital plane, and in particular has a “bulk” linear momentum and velocity $\sim 0.2c$.
• Anisotropy brings diversity of electromagnetic counterparts, such as different time evolution, large viewing-angle dependence, polarization, proper motion of radio images, and more …
Merger dynamics

- Approach due to GW backreaction
- NS deformation due to tidal force
- $r_{\text{tidal}} > r_{\text{ISCO}}$
  - Tidal disruption
  - Disk formation, mass ejection
- $r_{\text{tidal}} < r_{\text{ISCO}}$
  - Fall into the BH, ringdown
Mass shedding condition

BH tidal force = NS self gravity at the NS surface

\[
\frac{M_{BH} R_{NS}}{r_{\text{tidal}}^3} \sim \frac{M_{NS}}{R_{NS}^2} \Rightarrow r_{\text{tidal}} \sim M_{BH} \left( \frac{M_{NS}}{M_{BH}} \right)^{2/3} \left( \frac{R_{NS}}{M_{NS}} \right)
\]

BH innermost stable circular orbit

\[r_{\text{ISCO}} = \zeta(\chi) M_{BH} \quad (\zeta \text{ is a decreasing function of } \chi)\]

Disruption if this value is large

\[
\frac{r_{\text{tidal}}}{r_{\text{ISCO}}} \sim \frac{1}{\zeta(\chi)} \left( \frac{M_{NS}}{M_{BH}} \right)^{2/3} \left( \frac{R_{NS}}{M_{NS}} \right)
\]
Important parameters

Important nondimensional parameters

• Mass ratio of the BH to NS: \( Q \equiv \frac{M_{BH}}{M_{NS}} \)
• NS compactness: \( C \equiv \frac{M_{NS}}{R_{NS}} \)
• Nondimensional BH spin: \( \chi \equiv \frac{a_{BH}}{M_{BH}} \)

For a fixed value of the NS mass, tidal disruption if

• The BH mass is small, i.e., \( Q \) is small
• The NS radius is large, i.e., \( C \) is small
• The BH spin is large, i.e., \( \chi \) is large
Timescale estimation

Sound crossing timescale $\sim$ dynamical timescale

$$t_{cs} \sim t_{dyn} \sim \rho^{-1/2}$$

Orbital timescale = period at tidal disruption

$$t_{orb} = 2\pi \left[ \left( M_{BH} + M_{NS} \right)/r_{tid}^3 \right]^{-1/2}$$

Tidal disruption radius

$$r_{tid} \sim R_{NS} \left( M_{BH}/M_{NS} \right)^{1/3}$$

Thus

$$t_{orb} \sim 2\pi \left[ Q/(Q + 1) \right]^{1/2} \rho^{-1/2}$$
GW memory

In addition to nonlinear and GRB jet memory “ejecta memory” by \( M_{\text{ej}} \sim 0.01 - 0.1 M_\odot, v_{\text{ej}} \sim 0.2c \)

\[
\delta h \sim \frac{2M_{\text{ej}} v_{\text{ej}}^2}{D} \sim 10^{-24} \left( \frac{M_{\text{ej}}}{0.03 M_\odot} \right) \left( \frac{v_{\text{ej}}}{0.2c} \right)^2 \left( \frac{D}{100\text{Mpc}} \right)^{-1}
\]

Detectable by ET for massive ejecta with \( \geq 0.1 M_\odot \)

Former two are weak toward the rotational axis
Ejecta memory is strongest toward this axis