Electromagnetic counterparts to binary neutron star mergers

Koutarou Kyutoku (KEK)

Collaborators:
Kunihito Ioka (KEK), Masaru Shibata (YITP)
Summary

Electromagnetic counterparts to gravitational waves from binary neutron star mergers will be important, and we still have no “perfect” counterpart model.

We propose a possibility of ultra-relativistic outflows and associated X-ray-to-radio bands, second-to-day timescale emission from the shock breakout at the binary merger, ejecta-ISM shock, and synchrotron.

This model is bright enough and has tight association with GWs, but it will be challenging to observe.
Binary neutron star mergers

The most promising sources of gravitational waves
- neutron star masses, spins (if any), and radii
- supranuclear-density matter equations of state
- a way to (purely) gravitational-wave cosmology

Many electromagnetic signals are also expected
- short-hard gamma-ray bursts and afterglows
- radioactive decays of rapid-process elements
- interaction with surrounding interstellar media
Electromagnetic counterparts

The neutron star merger must be highly energetic

EM emission with GWs are naturally expected

- detectable strength
- frequent association
- unique feature
- accurate localization

and so on are desired

Metzger&Berger (2012)
Short-hard gamma-ray burst

The most energetic explosion “Binary merger hypothesis” should be tested by simultaneous detection (or its absence) of GWs and short-hard gamma-ray bursts

Afterglows will localize events with sufficient accuracy

From encyclopedia of science
Problem: jet opening angle

Not necessarily accompany GWs due to the beaming

Two events suggest jet angle $< 10$ deg.

A few % of mergers accompany GRBs even if all mergers leads to the bursts
Mass ejection from the merger

- tidal torques by the rapidly (differentially) rotating, non-axisymmetric hypermassive neutron star
- heating by shocks generated at/after the merger

Nearly spherical:

“$4\pi$-counterpart”

mass: $10^{-2} - 10^{-3} M_\odot$

velocity: $0.15 - 0.25c$

kinetic E: $\sim 10^{50}$ erg

Hotokezaka, KK+ (submitted)

Movies made by Kenta Hotokezaka
Emission mechanisms

1. ejecta-ISM shock radio flare (Nakar\&Piran 2011)
   synchrotron radiation like GRB afterglow and SNR
   O(year) to the peak: loose association with GWs

2. kilonova/macronova (Li\&Paczynski 1992, Metger+ 2010)
   radioactive decay of r-process elements
   O(day) optical transients: many contaminations

No emission mechanism is perfect as counterparts
We need yet another electromagnetic counterpart!
Shock breakouts just at the merger

A contact surface is heated up to \(~50\text{MeV}\), so that hot material escape into the cold, low-density crust.

The shock breakout should result unavoidably.
Shock and post-shock acceleration

A smaller mass is accelerated to a higher velocity
(Whitham 1958, Sakurai 1960, Johnson&Mckee 1971)

Shock acceleration
the acceleration of shock waves as they descend
the density gradient = the neutron star crust

Post-shock acceleration
the acceleration of ejected material by
converting thermal E. to kinetic. E and
by the pressure gradient inside them

\[ v \propto \rho^{-0.2} \]
Ultra-relativistic outflows

Based on a spherical SNe model (Tan, Matzner, Mckee 2001)

Ejecta mass is $\sim 10^{-4} - 10^{-5} M_\odot$

Though $\sim 10^{-9} M_\odot$, more than $10^{46}$ erg is expected for $\Gamma > 10$
Blast waves and synchrotron emission

Ultra-relativistic -> fast and high-energy emission

How to observe in practice?
- GW alert
- galaxy monitor
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appendix
Horizon distance/detection rate

The signal-to-noise ratio threshold is taken to be $\sim 8$

For a best-oriented binaries (face-on to the detector),

$445/927/2187 \text{Mpc}$ for NSNS/BHNS/BHBH binaries

Detection rates are estimated with models

Abadie+ (2010)

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$^a$To convert the rates per MWEB in Table II into detection rates, optimal horizon distances of $33 \text{ Mpc} / 445 \text{ Mpc}$ are assumed for NS-NS inspirals in the Initial / Advanced LIGO-Virgo networks. For NS-BH inspirals, horizon distances of $70 \text{ Mpc} / 927 \text{ Mpc}$ are assumed. For BH-BH inspirals, horizon distances of $161 \text{ Mpc} / 2187 \text{ Mpc}$ are assumed. These distances correspond to a choice of $1.4 \, M_\odot$ for NS mass and $10 \, M_\odot$ for BH mass. Rates for IMRIs into IMBHs and IMBH-IMBH coalescences are quoted directly from the relevant papers without conversion. See Section III for more details.

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Why we need counterparts?

One/two GW detectors cannot localize GW sources

$O(10 \text{ degrees}^2)$ for future GW detector networks

EM detection helps
- param. estimation
- host galaxy search
+ EM mechanisms
+ (psychologically)
  add GW evidences
How to localize by GWs?

Triangulation by time delays between GW detectors
For three detectors, we obtain two crosses of circles
The fourth detector=KAGRA improves the situation

\[ t_{\text{delay}} = \frac{d \cos \theta}{c} \]
Radio flare

Ejecta forms blast waves colliding the ISM, and magnetic fields amplified & electrons accelerated

Radio synchrotron

$O(\text{year})$ to the peak...

Can we really declare association with GWs?

Piran+ (2012)
macronova/kilonova

Neutron-rich ejecta may accompany the r-process nucleosynthesis and radioactive nuclei formation similar to SNe, only 1000 times brighter than novae

Shine in optical/UV O(<day) to the peak

Uncertainty in r-process reaction, opacity...

Metzger+ (2010)

Shock acceleration in the envelope

Newtonian

\[ \beta_s = A \left( \frac{\tilde{E}_{in}}{\tilde{m}} \right)^{1/2} \left( \frac{\tilde{m} M_{ej}}{\rho r^3} \right)^{\alpha_{nr}} \]

\[ \alpha_{nr} \simeq 0.19 \]

Semi-analytic

\[ \Gamma_s \beta_s = p(1 + p^2)^{0.12}, \]

\[ p = A \left( \frac{\tilde{E}_{in}}{\tilde{m}} \right)^{1/2} \left( \frac{\tilde{m} M_{ej}}{\rho r^3} \right)^{\alpha_{nr}} \]

\[ \rho = \rho_h \times \begin{cases} \left( \frac{R}{r_c} - 1 \right)^n \left( \frac{r}{r_c} \right)^{-k_\rho} & , \quad r < r_c \\ \left( \frac{R}{r} - 1 \right)^n & , \quad r_c < r < R \end{cases} \]
Post-shock acceleration

Rankine-Hugoniot relation at the strong shock

\[ \frac{\beta_s}{\beta_2} = \frac{7}{6} \text{ for non-rela, } \frac{\Gamma_s}{\Gamma_2} = \sqrt{2} \text{ for ultra-rela} \]

After converting internal energy to thermal energy

\[ \frac{\beta_f}{\beta_s} = \frac{6\sqrt{2}}{7} = 1.21 \text{ for non-rela} \]
\[ \Gamma_f \approx \left( \frac{\Gamma_s}{\sqrt{2}} \right)^{1+\sqrt{3}} \] (Johnson&Mckee 1971)
Post-shock acceleration

Semi-analytic

\[
\frac{\Gamma_f \beta_f}{\Gamma_s \beta_s} \simeq C_{nr} + (\Gamma_s \beta_s)^{\frac{1}{3}}
\]

\[C_{nr} = 2.03\]

Reproduce simulations

The distribution of velocity-kinetic E. is given taking the mass into account
Neutron star crust

Chamel & Haensel (2000)

Oertel + (2012)
Estimation of the ejecta mass

Crust density profile: $\rho \propto (R - r)^n$, here $n \approx 3$
assume a core-crust interface is at some density $\rho_0$
Shock velocity: $v \propto \rho^{-0.2}$ for polytropic index $n = 3$
assume $v_{\text{ini}}$ is the core sound velocity $\sim 0.25c$
$v_{\text{esc}} = \sqrt{2GM/R} \sim 0.7c$ for a typical HMNS
Acceleration from initial to escape velocity gives
the ratio between the density $\rho_{\text{esc}}/\rho_0$
Integrate this with geometrical reduction gives the ejecta mass to be $10^{-2} \sim 10^{-3} M_{\text{crust}}(\sim 0.01M_\odot)$
Blast wave evolution

Blandford-McKee’s solution (Blandford&McKee 1973): the evolution of relativistic self-similar blast waves

An initial shell has energy $E$ and Lorentz factor $\Gamma$

BM begins when the shell obtains $\sim E$ from the ISM

$$R(t) \propto t^{1/4}, \Gamma(t) \propto t^{-3/8}$$

For a refreshed shock $E(> \Gamma) \propto \Gamma^{1-s}$

$$R(t) \propto t^{(s+1)/(s+7)}$$

$$\Gamma(t) \propto t^{-3/(s+7)}$$ (Rees&Meszaros 1998)
Assumption for refreshed shocks

Fully adiabatic evolution (no radiation energy loss)
A radius-Lorentz factor closure relation: $R = 4\Gamma^2 ct$
this exact factor depends on situations
When the slower shell rear-ends, it is decelerated
by the material accumulated by all the faster shells
$E_0 \left( \frac{\Gamma}{\Gamma_0} \right)^{1-s} \sim \Gamma^2 R^3 n_H m_p c$
These relations determine the time evolution
Synchrotron radiation

Emission by relativistic electrons in a magnetic field
- electron acceleration behind a shock
- magnetic field amplification behind the shock

Fit the GRB afterglow and SNR well

Assume that the same model holds also in our case
- a smaller mass leads earlier deceleration
- more energetic electrons contribute to radiation
Synchrotron radiation

The electron number density in the Lorentz factor is assumed to have a power-law distribution

high frequency: cooling, low frequency: absorption