Mass ejection from NS-NS merger and Kilonova/Macronova

Kenta Hotokezaka
(Hebrew University of Jerusalem)

Collaborators:
K. Kiuchi, T. Muranushi, Y. Sekiguchi, and M. Shibata (YITP)
K. Kyutoku (UWM), H. Okawa (Waseda U), and K. Taniguchi (U. of Tokyo)
M. Tanaka (NAOJ), S. Wanajo (RIKEN)
T. Piran (Hebrew U. of Jerusalem)
Outline

• Electromagnetic counterparts of Gravitational waves

• Mass ejection at binary neutron star merger

• A kilonova/macronova candidate associated with a short GRB 130603B
Gravitational-wave astronomy

Compact binary merger

Advanced LIGO

Advanced Virgo

KAGRA

Expected rate (NS-NS merger) Abadie et al (2010)

1st generation (Initial LIGO, Virgo) 2nd generation (Advanced LIGO, Virgo, KAGRA)

0.0002 ~ 0.2 /yr \(\Rightarrow\) 0.4 ~ 400 /yr
NS-NS merger: Dynamics and GW waveform

Density $M_1 = 1.4M_{\odot}$

Density $M_2 = 1.3M_{\odot}$

Numerical relativity computation.

Hotokezaka, et al. (2013)
Gravitational wave from compact binary merger

Matched filter analysis

Data: Noise + GW

Theoretical Template

Compute the overlap between data and template

Because the advanced detectors will watch $\sim 10^5$ galaxies, many signals will be expected around the detection threshold.
Electromagnetic counterparts of GWs

✓ Confirmation of the detection of GWs from NS-NS around detection threshold, (like Neutrino burst associated with supernova 1987A)

✓ Localization of GW sources (GW localization is not good), => Determine host galaxies.

✓ They carry different information from GWs. (e.g. Mass of ejected radioactive nuclei)

But to discover them won’t be easy. => Theoretical expectations are needed to make observational strategies.
1. Dynamical ejecta: Tidal tail & shocked matter
2. Wind driven by viscosity, neutrino, recombination
3. A GRB jet may be launched at a certain time.
Expected Lightcurve

Luminosity

$\log(L)$ [erg/s/Hz]

$\log(t)$ [s]

-2 0 2 4 6 8 10

time

GRB (X~γ)

Extended Emission (X)

Merger Breakout (X)

GRB Afterglow (X)

GRB Afterglow (visible)

Merger Breakout (radio)

Kilonova / Macronova (NIR)

Merger remnant (radio)

Refs:
Nakar (2007)
Norris & Bonnell (2006)
Sari, Piran, Narayan (1998)
Li & Paczynski (1998)
Nakar & Piran (2012)
Kyutoku, Ioka, Shibata (2012)
Kelley, Mandel, Ramirez-Ruiz (2012)
Expected Lightcurve ($4\pi$, independent of environment)

Luminosity vs. time graph showing various light emission features:
- GRB ($X\gamma$)
- Extended Emission ($X$)
- Merger Breakout ($X$)
- GRB Afterglow ($X$)
- GRB Afterglow (visible)
- GRB afterglow (radio)
- Merger remnant (radio)
- Kilonova / Macronova (NIR)

Logarithmic scale for luminosity ($\log(L)$) and time ($\log(t)$).
What is “kilonova/macronova”

A kilonova/macronova was proposed by Li & Paczynski in 1998 as an observable consequence of NS-NS mergers.

At NS-NS merger
✓ A fraction of material is ejected as radioactive nuclei.
✓ Ejecta can be bright object due to radioactive heating.
✓ Luminosity: Nova < NS-NS merger < Supernova.
Kilonova/Macronova and Ejecta property

Based on current understanding

- Luminosity: \( \propto M_{e j} t^{-1.3} \) ~ 100 – 1000 x Nova (at the peak of a lightcurve)
- Diffusion time: \( \propto v^{-2/3} M_{e j}^{1/3} \) ~ 5 days

- Higher ejecta mass => Brighter signal
- Faster ejecta velocity => Brighter signal

\[ \begin{align*}
\text{Escaping photons} & \quad \text{Heating by beta decay} \\
\text{Diffusion time} & \quad \text{time}
\end{align*} \]
Various outflows of NS-NS merger

Dynamical ejecta is likely dominant source of kilonova/macronova.
Numerical simulation for dynamical ejecta

We perform Numerical Relativity simulations using SACRA code Yamamoto + 2009

Solve
- Einstein equation
- Hydrodynamics with an Equation of State (4-different NS models)

Total mass = 2.6 ~ 2.9 Msun
Mass ratio = 0.8 ~ 1

For piecewise polytropic EOSs
See Read et al., (2009)
Mass ejection on equatorial plane

Model: 1.2M$_{\text{Sun}}$ – 1.5M$_{\text{Sun}}$, APR

300 km x 300 km

2400 km x 2400 km

$\log(\text{density g/cc})$
Mass ejection on equatorial plane

Model: 1.2Msun – 1.5Msun, APR

Mass ejection: $M_{ej} \sim 0.01\text{M}_{\odot}$, $v \sim 0.2c$
Ejection Mechanism ~tidal torque~

1. Lighter NS is elongated
2. Outer material get angular momentum

Feature:
Ejecta expand on the equatorial plane
Mass ejection on the Meridional plane (x-z plane)

Model: 1.2M_{\odot} – 1.5M_{\odot}, APR

300 km x 150 km

2400 km x 1200 km

log(density g/cc)
Mass ejection on the Meridional plane (x-z plane)

Model: 1.2Msun – 1.5Msun, APR

NS-NS Ejecta is spheroidal.
Ejection Mechanism ~shock heating~

Specific internal energy

- Equatorial plane
  - Spiral arm sweeps matter

- Meridian plane
  - Mass is ejected due to the HMNS formation

Model=135Msun-1.35Msun, APR
Dependence of Ejecta mass on NS EOS

If HMNS is formed,

Radius of NS

Mass of Ejecta

0.0001 < Mej < 0.01 M\(_{\text{sun}}\)

No massive neutron star formation

Similar result is obtained by MPS group.

Hotokezaka + (2013)

Bauswain + (2013)
Most of ejecta has the velocity $0.1c \sim 0.2c$
We should follow up GW events with telescopes larger than 4m-size.
A Golden event: the short GRB 130603B
～ kilonova/macronova candidate～

If this event is really “Kilonova/Macronova”

✓ This could be direct evidence of compact binary merger hypothesis of short GRBs.

✓ Macronovae will be promising EM counterpart of GWs.

✓ A compact binary merger really produces ~0.02M_{\odot} of r-process elements

Tanvir et al., Nature, 2013
de Ugarte Postigo et al, 2013
Short GRB130603B

http://www.swift.ac.uk/burst_analyser/00557310/

BAT–XRT data of GRB 130603B

BAT: Black --- XRT: WT: Blue; PC: Red

GRB prompt emission
Swift BAT

GRB Afterglow
Swift XRT

\[ E_{\gamma,iso} = (2.1 \pm 0.1) \times 10^{51} \text{erg} \]

\[ T_{90} = 0.18 \pm 0.02 \text{s} \]

redshift

\[ z = 0.356 \]
Short GRB 130603B

Figure 9: Light curves of GRB 130603B, indicated detections with dots and upper limits (3-$V$) with arrows. V-band photometry has been scaled and plotted together with the g-band. The vertical lines indicate the times when spectra were obtained. Dotted lines indicate the light curve fits to a power law temporal decay from 0.3 to 3 days after the burst. We include data from the literature [21, 22]. The dashed blue line is the expected r-band light curve of a supernova like SN1998bw, the most common template for long GRBs after including an extinction of $A_V=0.9$ magnitude. The most constraining limits indicate that any supernova contribution would be at least 100 times dimmer than SN 1998bw in the r-band, once corrected of extinction (blue dashed-dotted line).

2.2 Spectral energy distribution of the afterglow and extinction

In this section we aim to fit the X-ray to optical/NIR SED using the method followed in [23, 24] to derive the extinction in the line of sight of the GRB and determine some spectral parameters. The procedure is briefly explained below.

The flux calibrated spectrum has been analysed after removing wavelength intervals affected by telluric lines and strong absorption lines. We then rebinned the spectrum in bins of approximately 8˚A by a sigma-clipping algorithm. To check the flux calibration of the X-shooter spectrum, we compare the continuum with the flux densities obtained from the extrapolation of the photometry at the time of the spectrum (mid time around 8.56 hr). We include the X-ray spectrum from the X-ray telescope (XRT) on board Swift. We used XSELECT (v2.4) to...

Flux density (Jy)

- K-band
- H-band
- J-band
- z-band
- i-band
- r-band
- g-band
- u-band
- 2keV x 10

Observer-time since burst (days)

Rest-frame time since burst (days)

Near-infrared excess Hubble Space telescope
A macronova associated with the short GRB 130603B?

- Hubble Space Telescope imaging

Tanvir et al., Nature, 2013

9 days after the burst

30 days

The host galaxy

macronova candidate
NIR wavelengths are taken or deduced from those of PTF (Law et al. 2009), CFHT/magnitudes for wide-field telescopes (5WFIRST (Green et al. 2012) and WISH (Yamada et al. 2012), respectively. The distance to the NS merger event is set to be 200 Mpc.

Fig. 8.—Expected observed $JHK$ magnitude for model NSM-all and 4 light curves in AB magnitude.
More than $\sim 0.01\text{Msun}$ r-process ejecta are ejected

If dynamical ejecta are dominant contribution to this bump.


The observed lightcurves can be explained with Kilonova/Macronova
Produced by dynamical ejecta $\sim 0.02\text{Msun}$
GW – EM observation and r-process

1. GW observation ➔ when/where we should follow up.

2. EM observation ➔ Total mass of ejecta can be estimated. (r-process element)

3. Collecting many events ➔ \( m_r(r) \) [mass/yr/galaxy]

In order to achieve this, precise understanding of nuclear heating and opacity for various type of ejecta is important.

Rebecca, Oleg, Shinya, and Masaomi’s talks
Summary

Detection of Electromagnetic counterparts will be important. They depend on baryon outflows.

0.0001M_{sun} – 0.01M_{sun} of baryons will dynamically ejected with Velocity 0.1c – 0.3c.

A Kilonova/Macronova candidate associated with a short GRB 13060B has discovered. Estimated dynamical ejecta \sim 0.02M_{sun}.

Future
We should understand possible parameter space of ejecta mass, velocity, opacity, and heating rate for various type of ejecta to estimate ejecta mass.