Electromagnetic Emission from Neutron Star Mergers

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Electromagnetic Emission from Neutron Star Mergers

- Why EM emission from NS merger?
- Expected emission and prospects for observations
- Toward more realistic prediction
New astronomy with gravitational waves

Supernova

< 10-100 kpc
~1 event/100 yr

Merger of compact binary (neutron star/black hole)

< 200 Mpc
~10 events/1 yr

2017 -
- Advanced LIGO (US)
- Advanced Virgo (Europe)
- KAGRA (Japan)

==> Talks by K. Hotokezaka and S. Nissanke
~ 100 galaxies / deg$^2$ (< 200 Mpc)

SDSS
GW alert error
e.g. 6 deg x 6 deg
(not box shape in reality)

No electromagnetic counterpart
No gravitational wave astronomy

GW detection

EM transient search

1 deg

Source identification
Transient search (Level *)

0.5 deg © Australian Astronomical Observatory
Transient search (Level **)
Origin of r-process elements

Event rate

$R_{NSM} \sim 100 \text{ event/Myr/Galaxy}$

$= 10^{-4} \text{ event/yr/Galaxy}$

NS-NS merger rate

Within 200 Mpc

$\sim 30 \text{ events/yr}$

($\sim 0.3-300$)

Ejection per event

$M_{eij}(r\text{-process}) \sim 10^{-2} \text{ Msun}$

Emission

$M(\text{Galaxy, } r\text{-process}) \sim M_{eij}(r) \times (R_{NSM} \times t_G)$

$\sim 10^{-2} \times 10^{-4} \times 10^{10} \sim 10^4 \text{ Msun}$

Observational tests for NS merger scenario

Need to know EM emission from NS merger
Electromagnetic Emission from Neutron Star Mergers

- Why EM emission from NS merger?
- Expected emission and prospects for observations
- Toward more realistic prediction
EM signature from NS-NS merger

- On-axis short GRB
- Off-axis radio/optical afterglow
- Radioactive emission r-process nuclei
  - kilonova
  - macronova
  - r-process nova
  - “gold” nova!

Li & Paczynski 98, Kulkarni 05, Metzger et al. 2010

==> Talks by S. Wanajo and K. Hotokezaka
Why supernova is so bright?

- $10^9$ Lsun
- $10^8$ Lsun
- $10^7$ Lsun
- γ-ray
- optical

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**Fig. 1.5.**— Optical(-infrared) quasi-bolometric light curves of Type Ic SNe 1998bw (Patat et al. 2001), 1994I (Richmond et al. 1996), Type Ia SN 1992A, and Type II SN 1999em (Elmhamdi et al. 2003). The timescale around the peak is a few tens days in Type Ia and Ic SNe. In Type II SNe, plateau phases lasts until $\sim 100$ days after the explosion. After $\sim 100$ days after explosion, the behavior of all types of SNe is similar, which is determined by the decay timescale of $^{56}$Ni, and escaping efficiency of $\gamma$-ray.

SNe 1998bw, 1994I, 1992A in Fig. 1.5). This is because the SN ejecta is optically thick soon after the explosion and optical photons are trapped. As a result, the optical radiation from the surface is delayed.

At typical optical depth for electrons scattered is estimated as follows:

$$\tau_{\text{opt}} = n_e \sigma_R \sim (3 M_{\text{ej}} / 4 \pi R^3) n_e m_H \sigma_R \sim (3 \sigma / 8 \pi m_H) (M_{\text{ej}} / E_K)t^{-2} \sim 10^4 \left( \frac{t}{\text{day}} \right)^{-2}.$$

Here, we assume $M_{\text{ej}} = 4 / 3 \pi R^3 n_e m_H$ (ejecta are singly-ionized), and $E_K = 1 / 2 M_{\text{ej}} v^2 = 1 / 2 M_{\text{ej}} (R/t)^2$. As typical parameters, ejecta mass and kinetic energy are assumed to be $M_{\text{ej}} \sim 1 M_\odot$ and $E_K \sim 10^{51}$ erg. This simple estimate means that the effect of photon diffusion is important until $t \sim 100$ days (Fig. 1.5). The timescale of the LC ($\tau_{\text{LC}}$) is roughly scaled as following (Arnett 1982):

$$\tau_{\text{LC}} \propto \kappa^{1/2} M_{3/4}^{3/4} E_K^{-1/4},$$

(1.5)

**Why supernova is so bright?**

- Radioactive decay of $^{56}$Ni
Heating source of supernova

\[ ^{56}\text{Ni} \rightarrow ^{56}\text{Co} + \gamma + \nu_e \]

\[ \tau \sim 9 \text{ days} \]

\[ ^{56}\text{Co} \rightarrow \begin{cases} 
^{56}\text{Fe} + \gamma + \nu_e \\
^{56}\text{Fe} + e^+ + \gamma + \nu_e 
\end{cases} \]

\[ \tau \sim 100 \text{ days} \]

Peak time

\[ t_p \sim 20 \text{ day} \left( \frac{M}{1M_\odot} \right)^{1/2} \left( \frac{v}{10,000 \text{ km s}^{-1}} \right)^{-1/2} \left( \frac{\kappa}{0.1 \text{ cm}^2 \text{ g}^{-1}} \right)^{1/2} \]

+ Shock heating (but negligible for compact progenitor)
Keys for optical emission

For supernovae

1. Something should be ejected
   Yes

2. Heating sources
   \(^{56}\text{Ni} (~0.1 \text{ Msun})\)

3. Mass, velocity, and element abundance
   \(\text{Mej} \sim 1 - 10 \text{ Msun}\)
   \(v \sim 10,000 \text{ km/s}\)
   Abundance: H/He/C/O/Si/Fe
Mass ejection clearly occurs in NS mergers.

$V \sim 0.1 - 0.2 \, c$

$M \sim 10^{-3} - 10^{-2} \, M_{\odot}$

Talks by K. Hotokezaka and O. Korobkin

Hotokezaka+13
Not $^{56}$Ni but many radioactive r-process nuclei

Talks by S. Wanajo and O. Korobkin
Keys for optical emission

For NS merger

1. Something should be ejected
   Yes!

2. Heating sources
   Radioactive r-process nuclei

3. Mass, velocity, and element abundance
   Mej $\sim$ 0.001 - 0.01 M$_\text{sun}$
   $v \sim$ 0.1 - 0.2 c
   Abundance: r-process elements
"kilonova"

Li & Paczynski 98
Metzger+10

**Timescale**

\[ t_p \sim 1 \text{ day} \left( \frac{M}{0.01M_\odot} \right)^{1/2} \left( \frac{v}{0.2c} \right)^{-1/2} \left( \frac{\kappa}{0.1 \text{ cm}^2 \text{ g}^{-1}} \right)^{1/2} \]

**Luminosity**

\[ L \sim 10^{42} \text{ erg s}^{-1} \left( \frac{M}{0.01M_\odot} \right)^{1/2} \left( \frac{v}{0.2c} \right)^{1/2} \left( \frac{\kappa}{0.1 \text{ cm}^2 \text{ g}^{-1}} \right)^{-1/2} \]

**Opacity of Fe**

\~ 20 mag at 200 Mpc
(Im-class telescopes)
1. Opacity of r-process-dominated ejecta?
2. Characteristic feature of NS merger?
Monte Carlo photon transfer

Ionization (LTE)

$X(x,y,z,\text{element,ion})$

$T(x,y,z)$

opacity

$\tau(x,y,z,\text{wavelength})$

$T(x,y,z)$

Saha equation $\times 92 \times 30^3$

2000 bins

$b$-$b$ transition $\times 10^6 \times 30^3$

$10^9$ photon

Monte Carlo photon transfer

$t(i) \rightarrow t(i+1)$

$T(x,y,z)$
Higher opacity by factor of 100!
The derived opacities can be input into a multi-term, wavelength, time-dependent radiative transfer code to estimate the relative number of distinct terms and levels and lines, they can be used to derive fairly robust models reasonably capture the statistical distribution of tor strengths of all permitted radiative dipole transitions §3). Without fine tuning the structure model, the composition of the material ejected by the two ions of similar complexity have similar properties, which potentially be ejected in the disk wind. In both cases, material may be ejected in NSMs: 1) During the merger, expansion medium. 2) Following the merger, mate-

$$C = \Pi_i \frac{g_i!}{n_i!(g_i - n_i)!}$$

Kasen+13
Fainter than previously expected by a factor of 10.

(see also Kasen+13, Barnes & Kasen 13)
Observations should discover a new transient object from 10 min exposure time. Limiting magnitudes for different sizes of telescopes with different wavelengths vary significantly. For optical wavelengths, there are several projects such as Palomar transient factory (PTF, Law et al. 2009; Rau et al. 2009), La Silla-QUEST Variability Survey (Drake et al. 2009). In Figure 8, we show the limiting magnitudes deduced from Law et al. (2009). Because of the red color, the detection in blue wavelengths is more challenging. The expected emission of models with a soft EOS APR4 (red) is brighter than that with a stiff EOS H4 (stiff) (see also Hotokezaka+13; Bauswein+13). For larger optical telescopes, the field of view tends to be smaller. Among 4m-class telescopes, Canada-France-Hawaii Telescope (CFHT)/Megacam and the Blanco 4m telescope/DECAM for the Dark Energy Survey (DECam) have a wide field of view (~0.6 deg, solid line). However, for 1m-class telescopes, the field of view is smaller. Among 4m-class telescopes, only Subaru/HSC or 8m-class telescope (e.g., Subaru) will be able to detect a bright event in NIR wavelengths.

In Figure 9, we show a color-color diagram with various wavelengths. For small masses (10^{-3} Msun), the emission is mostly in the blue wavelengths. For larger masses (10^{-2} Msun), the emission is mostly in the red wavelengths. The brighter emission is caused by a larger ejecta mass, and thus, brighter emission results in a large ejecta mass, and thus, brighter emission. After the detection of GW signal, EM follow up observations are crucial. The expected emission of models with a soft EOS APR4 (red) is brighter than that with a soft EOS. For larger optical telescopes, the field of view tends to be smaller. Among such large telescopes, only Subaru/HSC will be able to detect even the faintest case. For larger optical telescopes, the field of view tends to be smaller. Among such large telescopes, only Subaru/HSC will be able to detect even the faintest case.

**Softener EOS/Higher NS mass ratio**

**Brighter emission**

(see also Hotokezaka+13; Bauswein+13)
What about BH-NS Mergers?

**NS-NS**

\[ \text{Mej} \sim 10^{-4} - 10^{-2} \text{ Msun} \]

\[ \text{N} \sim 40 (0.4-400) / \text{yr} \]

\[ \text{(Abadie+10)} \]

**BH-NS**

\[ \text{Mej} \sim < 10^{-1} \text{ Msun} \]

\[ \text{N} \sim 10 (0.2-300) / \text{yr} \]

\[ \text{(Abadie+10)} \]
The BH-NS and NS-NS mergers have fainter absolute magnitude and redder colors than supernovae. The arrows show the direction of the brightness change. The color-magnitude (HR diagram) and color-color diagrams for the BH-NS merger model APR4Q3a75 (black) and the NS-NS merger model APR4-1215 (gray). These models are compared with Type Ia (blue), IIP (purple), and Ibc (red) supernovae. All the magnitudes are in AB magnitudes.

The BH-NS and NS-NS mergers may be possible. Figure 10 shows the color-magnitude diagrams for BH-NS and NS-NS merger events. Observations at the red edge of optical wavelengths can be expected typical larger distances to BH-NS mergers. Even with even higher brightness of BH-NS mergers, the observed brightness of BH-NS mergers can be comparable to or even higher than that of NS-NS mergers. In such cases, the observed emission from BH-NS mergers can be bluer than that from NS-NS mergers. Thanks to these properties, we might be able to distinguish BH-NS events from NS-NS mergers by the radioactively powered emission. When the mass ejection from a BH-NS merger is considered, the EM counterparts of GW sources may be able to distinguish BH-NS and NS-NS mergers.

- Very red SED (peak at NIR)
- Extremely broad-line (feature-less) spectra
- Identification of r-process elements is difficult
The redshifts of the afterglow, 0.3–10-keV X-ray data, are consistent with the favoured range of kilonova behaviour from recent detailed calculations. The primary evidence for a compact transient source in the NIR in epoch 1 is that this phenomenon is strikingly reminiscent, in a qualitative sense, of the merger process—in other words, an event similar to a faint, short-lived kilonova (a "macronova" or an "r-process supernova") due to the decay of radioactive species produced and initially ejected during the neutron-rich material. Although these models are still far from being fully realistic, a robust conclusion is that the optical flux will be greatly diminished by line blanketing in the rapidly expanding remnant. The NIR F160W filter (1.6 μm) is optimal for detecting the predicted r-process kilonova optical emission. The bright optical afterglow was apparent to the depth of the data in the optical.

We note that the complete absence of late-time optical emission is unsurprising, as the extrapolation of the afterglow (red dashed line), assuming that it also decays as a smoothly broken power law, is consistent with the favoured range of kilonova behaviour from recent calculations. The fact that this source was also identified as a faint point source in epoch 2 and is absent to the depth of the data in the optical is consistent with the optical afterglow decaying steeply after about 0.3 d and is modelled here as a smoothly broken power law.

We imaged the location of the burst with the NASA/ESA Hubble Space Telescope (HST) at two epochs, the first (epoch 1) and the second (epoch 2) if it is not to appear visually as a faint point source in epoch 2, such late-time emission is likely to be less than 25% of the level in the Swift period. Although the evidence constraining SGRB jet opening angles is limited at present by Swift, although the evidence constraining SGRB jet opening angles is limited at present by Swift, this suggests either that the rate of compact binary mergers is low, implying a correspondingly low expected rate of gravitational-wave detections. A compilation of optical and NIR epoch-1 points is given by bold symbols. The optical afterglow decays steeply after about 0.3 d and is modelled here as a smoothly broken power law.

**Figure 2**

Optical, NIR and X-ray light curves of GRB 130603B. The blue data points (full symbols) show optical observations from the Space Telescope (HST) at two epochs, the first (epoch 1) and the second (epoch 2). The cyan curve shows that even the brightest SGRBs are 10–13 times fainter than the X-ray flux (erg s⁻¹ cm⁻²). The red data points (open symbols) show the NIR flux, on the other hand, is consistent with the favoured range of kilonova behaviour from recent calculations. The black horizontal line denotes the detection limit, which is consistent with the favoured range of kilonova behaviour from recent calculations. The black horizontal line denotes the detection limit, which is consistent with the favoured range of kilonova behaviour from recent calculations.
Link between observations and theory

Mass ejection
Mej \sim 0.02 \text{ Msun}

Hotokezaka, Kyutoku, MT, Kiuchi, Sekiguchi, Shibata, Wanajo
Prospects for observations

200 Mpc

Magnitude

Time (days)

soft EOS

(consistent with GRB 130603B)

stiff EOS

1m

4m

8m
GW alert error box
e.g. 6 deg x 6 deg

Typical 8-10m telescope

0.3 deg

8m LSST (2020-)
3.5 deg

8m Subaru
Hyper Suprime-Cam

1 deg

1.5 deg
Subaru/ Hyper Suprime-Cam
2013 -

1.75 deg^2
116 CCDs
3m
3t!
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1. Merger simulations

2nd component? (neutrino-driven wind?)

Talks by R. Surman and S. Wanajo

\( \log (\rho \ [g/cm^3]) \)

\( \log \{Q \nu \ [\text{erg/cm}^3/s]\} \)

\( (a) \) M3A8m3a5, \( t = 50 \) ms

\( (b) \) M3A8m3a5, \( t = 50 \) ms

Figure 5. Snapshots for the BH-torus model M3A8m3a5 at \( t = 50 \) ms (top row) and \( t = 2 \) s (bottom row). At early times neutrino-driven ejecta dominate the outflow, whereas at late times the viscous component is more important. Plot (a) shows the total net neutrino-heating rate (left panel), overlaid with arrows indicating the vectors of the energy-integrated energy flux for electron neutrinos multiplied by \( 4\pi r^2 \), and the density (right panel), overlaid with arrows for the velocity vector. The neutrino-heating rate includes neutrino absorption on nucleons as well as neutrino-pair annihilation; in the black region neutrino cooling dominates heating. The maximum arrow lengths correspond to values of \( 5 \times 10^{53} \) erg s\(^{-1}\) and \( 7 \times 10^{9} \) cm s\(^{-1}\) in the left and right panels, respectively. Plot (b) shows the entropy (left panel) and the electron fraction (right panel). Plots (c) and (d) display the same quantities as plots (a) and (b), respectively, but with the neutrino information replaced by temperature. The longest arrow in plot (c) defines a velocity of \( 2 \times 10^{9} \) cm s\(^{-1}\).

Note that other radial scales as well as the density ranges for the plots at \( t = 50 \) ms and \( 2 \) s are different.

\( \Rightarrow \) EM emission can be brighter/bluer (e.g., Metzger+14)

\( \Rightarrow \) higher Ye\( \Rightarrow \) lower A

\( \Rightarrow \) lower Ye\( \Rightarrow \) higher A

Just+14  Wanajo+14
2. Atomic data

No good dataset of bound-bound transitions for highly-ionized r-process elements
(current simulations include only up to doubly ionized elements)

==> Talks by J. Lawler and C. Hansen

* Nuclear data are rather OK (for EM emission)
Poor prediction at early time

Your input is welcome!!
Not so useful for stellar observations??
Summary

• EM emission from NS merger
  • Important as a counterpart of GW sources
  • r-process nucleosynthesis
  • Numerical relativity + full radiative transfer
  • Link between observations and progenitor/properties of dense matter (GRB 130603B)

• Toward more realistic prediction
  • Better understanding of merger phenomena
  • Atomic data (for >triply ionized elements)