Electromagnetic emission from long-lived binary neutron star merger remnants

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• BNS mergers most promising source of GWs for advanced LIGO/Virgo, routine detections expected in the next years

→ Multimessenger astronomy

Abadie et al. 2010
**EM counterparts to BNS mergers**

- **Short gamma-ray bursts** (SGRBs)
  - “Standard” afterglows:
    - X-ray
    - UV/optical
    - radio
    - Berger 2014, Kumar & Zhang 2015
  - “Non-standard” **X-ray afterglows**:
    - (revealed by Swift)
    - Extended Emission
    - X-ray plateaus
    - X-ray flares

- Interaction of **dynamical ejecta** with ISM (radio)
  - Hotokezaka & Piran 2015

- **radioactively powered kilonova** (macronova)
**Non-standard X-ray afterglows of SGRBs**

- *Swift* revealed that a large fraction of SGRBs are accompanied by long-duration ($\sim 10^2$-$10^5$ s) and high-luminosity ($\sim 10^{46}$-$10^{51}$ erg/s) X-ray afterglows.
- Total energy can be higher than that of the SGRB.
- Unlikely produced by BH-torus system - indicative of ongoing energy injection ("long-lived engine").

**challenges BH-torus paradigm for SGRBs**

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What is a promising EM counterpart?

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**EM counterparts from BNS merger remnants**

**General Phenomenology** for BNS mergers leading to a long-lived (>100ms) remnant NS:

**Phase I** *(baryonic wind phase, ~1s)*:
- baryon pollution due to dynamical ejecta, neutrino and magnetically driven winds

**Phase II** *(Pulsar ‘ignition’ and pulsar wind shock)*:
- once baryon pollution suppressed positronnic pulsar wind drives strong shock through ejecta

**Phase III** *(Pulsar wind nebula phase)*:
- swept-up material provides cavity for a pulsar wind nebula (PWN) in analogy to CCSNe

- **NS can collapse to a BH at any time**
- can accommodate standard and time-reversal scenario
- **EM emission:** reprocessed spin-down energy → model predicts broad-band spectrum from radio to gamma rays
EM counterparts from BNS merger remnants

Phase I:

\[
\frac{dR_{ej}}{dt} = v_w(R_{ej}(t), t) \\
\frac{dE_{th}}{dt} = L_{EM}(t) + \frac{dE_{th,NS}}{dt} - L_{rad}(t)
\]

Phase II:

\[
\frac{dR_{ej}}{dt} = v_w(R_{ej}(t), t) \\
\frac{dR_{sh}}{dt} = v_{sh}(t) \\
\frac{dE_{th,sh}}{dt} = \frac{dE_{ah}}{dt} + \frac{dE_{th,vol}}{dt} + \frac{dE_{PWN}}{dt} - L_{rad, in}(t) \\
\frac{dE_{th,ush}}{dt} = -\frac{dE_{th,vol}}{dt} - L_{rad}(t) \\
\frac{dE_{th}}{dt} = \frac{dE_{th,sh}}{dt} + \frac{dE_{th,ush}}{dt} \\
\frac{dE_{nth}}{dt} = -\frac{E_{nth} dR_{n}}{R_{n}} - \frac{dE_{PWN}}{dt} + L_{rad, in}(t) + \eta_{TS}[L_{sd}(t) + L_{rad, pul}(t)] \\
\frac{dE_{B}}{dt} = \eta_{B_n}[L_{sd}(t) + L_{rad, pul}(t)] \\
\frac{dv_{ej}}{dt} = a_{ej}(t) \\
\frac{dR_{ej}}{dt} = v_{ej}(t) + \frac{1}{2} a_{ej}(t) dt \\
\frac{dR_{n}}{dt} = \frac{dR_{ej}}{dt} \\
\frac{dE_{th}}{dt} = \left[1 - f_{ej}(t)\right] \frac{dE_{PWN}}{dt} - L_{rad}(t) - L_{rad, in}(t) \\
\frac{dE_{B}}{dt} = \eta_{B_n}[L_{sd}(t) + L_{rad, pul}(t)]
\]

Phase III:

set of coupled ODEs
EM counterparts from BNS merger remnants

Pulsar wind nebula:

gas of electrons, positrons, photons
complicated radiative interactions,
non-thermal photon and particle spectra

- synchrotron cooling and self-absorption
- (inverse) Compton scattering
- pair production and annihilation
- Thomson scattering
- Photon escape

Particle balance equation:

\[ 0 = Q(\gamma) + P(\gamma) + \dot{N}_{C,\text{syn}}(\gamma) \]

Photon balance equation:

\[ 0 = \dot{n}_0 + \dot{n}_A + \dot{n}_{C,\text{NT}} + \dot{n}_C + \dot{n}_{\text{syn}} - \frac{c}{R_n} n(\Delta \tau_{C,\text{NT}} + \Delta \tau_{\gamma\gamma}) - \dot{n}_{\text{esc}} \]

Coupled set of integro-differential equations to be solved at every time step
EM counterparts from BNS merger remnants

Fig.: Reconstructed X-ray afterglow lightcurves (0.3-10 keV) for standard scenario (SGRB at merger)

- delayed onset of strong X-ray radiation ≈1-10s after merger (high optical depth at early times)
- bright, isotropic, long-lasting X-ray signal peaking at ≈10^2-10^4s after merger (L~10^{46}-10^{48} erg s^-1)
  - smoking gun for BNS merger event
  - timescale well suited for EM follow up of GW event
  - X-ray signal represents ideal EM counterpart
What is a promising EM counterpart?

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→ according to the model: non-standard X-ray afterglows represent ideal EM counterpart
In the time-reversal scenario...

1\textsuperscript{st} plateau:
\[ \sim 10^2 \text{s} \]
\[ L_X \sim 10^{46} - 10^{48} \text{ erg/s} \]

2\textsuperscript{nd} plateau:
\[ \sim 10^3 - 10^4 \text{ s} \]
\[ L_X \sim 10^{44} - 10^{46} \text{ erg/s} \]

Fig.: Reconstructed X-ray afterglow lightcurves (0.3-10 keV) for time-reversal scenario (SGRB at collapse of NS)

- two-plateau structures, late-time flares
In the time-reversal scenario... Ciolfi & Siegel 2015a

Fig.: Reconstructed X-ray afterglow lightcurves (0.3-10 keV) for time-reversal scenario (SGRB at collapse of NS)

- two-plateau structures, late-time flares
- Luminosity levels and time-scales for two-plateau structures are in agreement with SGRBs showing extended emission and X-ray plateaus

→ natural explanation for combined phenomenology of Swift X-ray lightcurves
Conclusions

• Proposed phenomenology and detailed numerical model for a large fraction of BNS mergers

  ➔ general model to compute broad band EM emission (radio to gamma rays) from post-merger system

  ➔ bridges the gap between numerical relativity simulations and the observational timescales of afterglows

  ➔ reveals a promising counterpart for GW astronomy

  ➔ combined with time-reversal scenario yields natural explanation for X-ray afterglows of SGRBs in a common phenomenology

  ➔ makes very specific predictions that can be tested observationally