EM counterparts from long-lived BNS merger remnants

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EM counterparts to NS 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**
  Li & Paczynski 1998, Rosswog 2005, Metzger+ 2010,
  Barnes & Kasen 2013, Piran+ 2013, Tanaka & Hotokezaka 2013

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**Figure 1.**

- Jet–ISM Shock (Afterglow)
  - Optical (hours–days)
  - Radio (weeks–years)
- GRB
  - \( t \approx 1 \text{ s} \)
- Ejecta–ISM Shock
  - Radio (years)
- Merger Ejecta
  - Tidal Tail & Disk Wind
  - \( v \approx 0.1–0.3 \, \text{c} \)
- Kilonova
  - Optical (t – 1 day)
- \( \theta_{\text{obs}} \)
- \( \theta_{j} \)
- BH
- Metzger & Berger 2012
What is a promising EM counterpart?

<table>
<thead>
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Product of BNS mergers

- observationally: $M_{\text{TOV}} \gtrsim 2 M_\odot$  \(\text{Demorest+ 2010, Antoniadis+ 2013}\)
- progenitor masses peak around $1.3 - 1.4 M_\odot$
  \(\rightarrow\) remnant NS mass typically $\approx 2.3 M_\odot - 2.4 M_\odot$  \(\text{Belczynski+ 2008}\)
- supramassive to hypermassive limit at $\approx 1.2 M_{\text{TOV}} \gtrsim 2.4 M_\odot$  \(\text{Lasota+ 1996}\)

$\longrightarrow$ the most likely outcome should be a long-lived (supramassive) NS
General Phenomenology for BNS mergers leading to a long-lived (>100ms) remnant NS:

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

Phase II (Pulsar ‘ignition’ and pulsar wind shock ~sec-min):
- cold, uniformly rotating NS
- baryon pollution suppressed → spin-down emission, pulsar wind inflates nebula, drives shock through ejecta

Phase III (Pulsar wind nebula phase ~min-days):
- swept-up material provides cavity for a pulsar wind nebula (PWN) in analogy to CCSNe
- NS may collapse to a BH at any time
- EM emission: reprocessed spin-down energy → model predicts broad-band spectrum from radio to gamma rays

Rowlinson et al. 2013

Daniel Siegel & Ciolfi 2016a
Outflows from BNS merger remnants

- **neutrino-driven wind** (from hot remnant NS)
  - $(\sim \text{ms}-\text{ls})$
  - $\dot{M}_{\text{in}} \sim (10^{-4} - 10^{-3}) M_\odot \text{s}^{-1}$

- **magnetically driven wind** (from remnant NS)
  - $(\sim \text{ms}-\text{ls})$
  - $\dot{M}_{\text{in}} \sim (10^{-3} - 10^{-2}) M_\odot \text{s}^{-1}$

- **delayed outflows** (from accretion disks)
  - $(\sim \text{ls})$
  - $M_{\text{tot}} \lesssim 10^{-3} - 10^{-2} M_\odot$

**References:**
- Dessart et al. (2009)
- Siegel et al. (2014)
- Siegel et al. (2017)
- Fernández & Metzger (2013)
- Just et al. (2015)
Post-merger evolution

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Post-merger evolution: evolution equations

Phase I:
\[
\begin{align*}
\frac{dR_{ej}}{dt} &= v_w(R_{ej}(t), t) \\
\frac{dE_{th}}{dt} &= L_{EM}(t) + \frac{dE_{th,NS}}{dt} - L_{rad}(t)
\end{align*}
\]

Phase II:
\[
\begin{align*}
\frac{dR_{ej}}{dt} &= v_w(R_{ej}(t), t) \\
\frac{dR_{sh}}{dt} &= v_{sh}(t) \\
\frac{dR_{n}}{dt} &= \frac{dR_{sh}}{dt} - \frac{d\Delta_{sh}}{dt} \\
\frac{dE_{th,sh}}{dt} &= \frac{dE_{th}}{dt} + \frac{dE_{th,vol}}{dt} + \frac{dE_{PWN}}{dt} - L_{rad,in}(t) \\
\frac{dE_{th,ush}}{dt} &= -\frac{dE_{th,vol}}{dt} - L_{rad}(t) \\
\frac{dE_{th}}{dt} &= \frac{dE_{th,sh}}{dt} + \frac{dE_{th,ush}}{dt} \\
\frac{dE_{nth}}{dt} &= -\frac{E_{nth}}{R_n} \frac{dR_{n}}{dt} - \frac{dE_{PWN}}{dt} + L_{rad,in}(t) + \eta_{TS}[L_{sd}(t) + L_{rad,pul}(t)] \\
\frac{dE_B}{dt} &= \eta_{B_n}[L_{sd}(t) + L_{rad,pul}(t)]
\end{align*}
\]

Phase III:
\[
\begin{align*}
\frac{dv_{ej}}{dt} &= a_{ej}(t) \\
\frac{dR_{ej}}{dt} &= v_{ej}(t) + \frac{1}{2}a_{ej}(t)dt \\
\frac{dR_{n}}{dt} &= \frac{dR_{ej}}{dt} \\
\frac{dE_{th}}{dt} &= [1 - f_{ej}(t)] \frac{dE_{PWN}}{dt} - L_{rad}(t) - L_{rad,in}(t) \\
\frac{dE_B}{dt} &= \eta_{B_n}[L_{sd}(t) + L_{rad,pul}(t)]
\end{align*}
\]

set of coupled ODEs

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EM counterparts from long-lived BNS merger remnants

Rowlinson+2013

\[BNS\text{ merger} \rightarrow \text{differentially rotating NS remnant (Phase I)}\]

\[\text{shock and PWN (Phase II-III)}\]

\[\text{X-rays} \rightarrow \text{shocked ejecta} \rightarrow \text{unshocked ejecta} \rightarrow \text{nebula} \rightarrow \text{X-rays}\]
Post-merger EM emission

- **hot ejecta** (continuous heating by nebula): emission is in the X-rays
- **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 ~$10^2$-$10^4$s after merger ($L\sim 10^{46}$-$10^{48}$ erg s$^{-1}$)

Fig.: Reconstructed X-ray lightcurves (0.3-10 keV)

Siegel & Ciolfi 2016b

\[
\eta_{B_p} = 0.5 \\
M_{in} = 10^{-3} \text{M}_\odot \\
t_{dr} = 0.1 \text{s} \\
t_{dr} = 10 \text{s} \\
\kappa = 10 \text{cm}^2 \text{g}^{-1} \\
f_{coll} = 0.1, \\
\dot{B} = 3 \times 10^{16} \text{G} \\
f_{coll, P_I} = 0.1
\]
Post-merger EM emission

Fig.: X-ray light curves and effective temperature evolution (example)

- at timescale of peak brightness, predominantly thermal emission in the X-rays (continuous heating by the nebula)
- heating by r-process nucleosynthesis typically subdominant up to $t \sim 1d$
- degree of ionization of ejecta matter important: if low, peak might be shifted toward lower frequencies
Post-merger EM emission: EM counterpart to GWs

- bright, isotropic, long-lasting X-ray signal peaking at $\sim 10^2$-$10^4$ s after merger ($L \sim 10^{46}$-$10^{48}$ 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: BNS post-merger X-ray transients represent ideal EM counterpart
Conclusions

• majority of BNS mergers should lead to long-lived NSs

• proposed post-merger phenomenology and detailed numerical model for those events

  ➤ general model to compute broad band EM emission (radio to gamma rays)

  ➤ bridges the gap between numerical relativity simulations and the observational timescales of EM transients

  ➤ reveals strong thermal transient (peaking in the X-rays, but also UV and optical counterparts at later times), promising counterpart for GW astronomy

  ➤ together with NS component masses from GW signal can tightly constrain EOS (using supramassive NS assumption)

  Ciolfi & Siegel (2015), ProcSci (SWIFT 10)108

  ➤ natural explanation for combined phenomenology of Swift X-ray lightcurves (not this talk), and late-time kilonova emission

  ➤ makes very specific predictions that can be tested observationally

  ▲▲ see also “time-reversal” scenario

  Ciolfi & Siegel (2015), ApJL 798, L36


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