Signatures of Black Hole Formation (and Other Puzzles) in Neutron Star Binary Mergers

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Stellar mass black holes form in core-collapse supernovae and neutron star binary mergers. Combined GW+EM observations can probe NS-NS mergers (CCSNe more challenging).
Motivations: Joint GW-EM detections, black hole formation in NS-NS mergers, the origin of short GRBs, $r$-process nucleosynthesis.

These topics can be probed with optical observations.

Implications for EM follow-up of GW sources and the path forward.
NS-NS Mergers

What are the EM signatures and remnants of NS-NS mergers?

Finding EM counterparts is a challenge, but also an essential component for interpretation of GW data.
Gamma-Ray Bursts

What are the progenitors of short gamma-ray bursts?

Circumstantial evidence for NS-NS mergers, but no direct evidence
**r-Process Nucleosynthesis**

Is \( r \)-process nucleosynthesis dominated by NS-NS mergers?

\[
\dot{M}_{A>130} \sim 10^{-7} \, M_\odot \, \text{yr}^{-1}
\]

\[
\dot{M}_{A>130, \text{BNS}} \sim (\dot{N}/10^{-5} \, \text{yr}^{-1})(M_{\text{ej}}/10^{-2} \, M_\odot)
\]
GW, Short GRBs, BH, r-Process
Compact Object Merger Ejecta

**Dynamical tidal tails**

\[ M_{\text{ej}} \sim 10^{-3} - 10^{-1} \, M_\odot \]

\[ v_{\text{ej}} \sim 0.2c \]

\[ Y_e \sim 0.1 \]

**Disk outflows** (v / recomb. powered)

\[ M_{\text{ej}} \sim 10^{-3} - 10^{-2} \, M_\odot \]

\[ v_{\text{ej}} \sim 0.1c \]

\[ Y_e \sim ? \]
$r$-Process Nucleosynthesis

$T = 3.50$ GK, $n_n = 2.946e+35$ cm$^{-3}$, $R_{n/s} = 639.5$, $s = 0.621$ k$_b$/nuc, $t = 0.0131$ s

- Solar $r$-process abundances
- Current abundances

Gabriel Martinez-Pinedo
Radioactive Heating

Metzger et al. 2010
Light Curves

\[ R = vt \]
\[ \rho = \frac{3M}{4\pi R^3} \]
\[ \tau = \kappa \rho R \]
\[ t_d = \frac{\tau R}{c} \]

\[ t_p \approx 15 \text{ d} \left( \frac{v}{10^4 \text{ km/s}} \right)^{-1/2} \left( \frac{M}{M_\odot} \right)^{1/2} \left( \frac{\kappa}{\kappa_{\text{Fe}}} \right)^{1/2} \]

\[ L_p \approx 10^{43} \text{ erg/s} \left( \frac{v}{10^4 \text{ km/s}} \right)^{1/2} \left( \frac{M}{M_\odot} \right)^{1/2} \left( \frac{\kappa}{\kappa_{\text{Fe}}} \right)^{-1/2} \left( \frac{f}{10^{-5}} \right) \]

NS-NS: \( v \sim 0.1c, \ M \sim 0.01 \ M_\odot, \ f \sim 10^{-6}, \ \kappa = \kappa_{\text{Fe}} \)

\[ \Rightarrow t_p \sim 1 \text{ day}, \ L_p \sim 10^{41} \text{ erg s}^{-1} \]
Opacity

Kasen et al. 2013, Barnes & Kasen 2013
Spectral Energy Distribution

Kasen et al. 2013, Barnes & Kasen 2013
GRB 130603B

E Bet al. 2013

Late-time optical
Late-time near-IR

Magellan/MACS
2013 Jun 04.00 UT

Magellan/LDSS3
2013 Jul 10.04 UT

Subtraction

ACS/F606W
2013 Jun 13.03 UT

WFC3/F160W
2013 Jun 13.15 UT

ACS/F606W
2013 Jul 03.32 UT

WFC3/F160W
2013 Jul 03.26 UT

Absolute magnitude

Rest-frame time (d)
Neutrino Irradiation by Surviving NS

Neutrino emission from a surviving NS can raise the electron fraction in a polar outflow to $>0.3$, changing composition and opacity of the ejecta.

Metzger & Fernandez 2014
Neutrino Irradiation by Surviving NS

$$M_{\text{wind}} \sim 10^{-3} M_\odot \quad v_{\text{wind}} \sim 0.1 \text{ c}$$

Kasen et al. 2015
Light Curves: Blue vs. Red

Kasen et al. 2015
Searches of LIGO Sources

Wide-field optical imaging program with DECam (PI: Berger) to search for and characterize NS-NS mergers
Summary

A wide range of questions regarding NS-NS mergers can be addressed observationally with EM follow-up of GW sources.

One observational manifestation is a “kilonova” – rapid and faint transient due to the radioactive decay of r-process nuclei.

The formation timescale of a BH (if any) is encoded in the properties of the kilonova emission.
Light Curves

Tanaka & Hotokezaka 2013