Kilonova Emission from a Binary Neutron Star Merger

in collaboration with

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Astrophysical Origins of the Periodic Table

Big Bang

stellar evolution, CCSNe
exploding white dwarfs
Core Collapse SNe?

log $N_{(S_{i_{total}})}$ ≡ 6

neutron-capture elements

N=50
N=82
N=126

Atomic mass

Lodders (2003)
Cameron (1959)
Neutrino-Driven Winds from Proto-Neutron Stars

Each supernova need eject only \( \sim 10^{-5} M_\odot \) in r-nuclei

...but not neutron-rich enough!

\[ \nu_e + n \rightarrow p + e^- \]

Solution: strong magnetic fields & rapid rotation? (e.g. BDM+07, Mosta+17)
Neutron Stars: Open Questions

The outcome of a NS merger depends on the uncertain EOS

Maximum mass?

Radius?

\[ M_{\text{max}} > 2M_{\odot} \]

Ozel & Freire 2016
Neutron Star Binary Mergers

“Heavy Ion” Colliders in the Sky

LIGO/Virgo

EM Observation

Bartos, Brady, Marka 2013
“Heavy Ion” Colliders in the Sky

LIGO/Virgo

EM Observation

Bartos, Brady, Marka 2013
Electromagnetic Counterparts of NS Mergers

Jet–ISM shock (afterglow)
Optical (hours–days)
Radio (weeks–years)

$\Gamma \beta > 1$
Gamma-rays, X-rays, radio

GRB
$t \sim 0.1–1 \text{ s}$

Ejecta–ISM shock
Radio (years)

Kilonova
Optical ($t \sim 1 \text{ day}$)

Merger ejecta
Tidal tail and disk wind
$v \sim 0.1–0.3 \text{ c}$

Sub-relativistic

BH

BDM & Berger 12
**Neutron-Rich Ejecta**

**“Dynamical” Ejecta**

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

\[ t_{\text{exp}} \sim \text{ms} \]

\[ v_{\text{ej}} \sim 0.2 - 0.3 \, c \]

**Accretion Disk Outflows**

\[ M_{\text{ej}} = f_w M_d \sim 3 \times 10^{-2} \left( f_w / 0.3 \right) \, M_\odot \]

\[ t_{\text{exp}} \sim 0.1 - 1 \, \text{s} \]

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

Composition depends on NS lifetime

\[ 2 < n/p < 10 \]

\[ \nu_e + n \rightarrow p + e^- \]
R-Process Network (neutron captures, photo-dissociations, α- and β-decays, fission)

T = 3.50 GK, \( n_n = 2.946 \times 10^3 \text{ cm}^{-3} \), \( R_{\text{mg}} = 639.5 \), \( s = 0.621 \text{ k}_{\nu}/\text{nuc} \), \( t = 0.0131 \text{ s} \)

Courtesy Gabriel Martinez-Pinedo as used in BDM et al. 2010
Final Isotopic Abundances

2nd peak: xenon, silver

3rd peak: platinum, gold

uranium, thorium

$Y_e = 0.1$

$n/p \approx 10$

BDM et al. 2010
Radioactive Heating of the Ejecta
(BDM et al. 2010; Roberts et al. 2011; Goriely et al. 2011; Korobkin et al. 2012; Lippuner & Roberts 2015)

charged decay products thermalize by coulomb scattering off background plasma

charged decay products

\[ 56_{\text{Ni}} + 56_{\text{Co}} \]

\[ \propto t^{-1.3} \]

\[ t_{\text{peak}} \]

\[ 10^4 \text{ km} \]

\[ 10 \text{ AU} \]
Radioactive Heating of the Ejecta
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\[ \propto t^{-1} \]

Li & Paczynski 98

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Radioactive Heating of the Ejecta

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\[ \propto t^{-1} \]

\[ \propto t^{-1.3} \]

\[ {^{56}\text{Ni}} + {^{56}\text{Co}} \]

Li & Paczynski 98

MERGERS OF NEUTRON STAR–BLACK HOLE BINARIES WITH SMALL MASS RATIOS: NUCLEOSYNTHESIS, GAMMA-RAY BURSTS, AND ELECTROMAGNETIC TRANSIENTS

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promising gamma-ray burst (GRB) central engine. We find between 0.01 and 0.2 \( M_\odot \) of the neutron star to be dynamically ejected. Like in a Type Ia supernova, the radioactive decay of this material powers a light curve with a peak luminosity of a few times \( 10^{44} \) ergs s\(^{-1} \). The maximum is reached about 3 days after the coalescence and is
Electromagnetic counterparts of compact object mergers powered by the radioactive decay of \( r \)-process nuclei

A "Kilo-nova"

\[ M_{ej} = 0.01M_\odot \]
\[ V_{ej} = 0.1 \text{ c} \]

BDM et al. 2010
GW170817: the first BNS Merger

LVC + EM Partners 17

NGC 4993, D = 41+/-3 Mpc

Cantiello et al. 18

Optical counterpart discovered at ~11 hours!

GW-EM Joint Discovery Paper (Abbott+ 2017)

Viewing Angle ~ 10-40°
0.01 Msun “Kilonova” model from Metzger et al. 2010 (their Fig. 4)

GW170817 counterpart from Cowperthwaite et al. 2017

Theoretical fit:
\[ L(t) \propto t^{-1.3} \]
0.01 Msun "Kilonova" model from Metzger et al. 2010 (their Fig. 4)

GW170817 counterpart from Cowperthwaite et al. 2017

~t^{-1.3}
Spectral Evolution

absorption “troughs” in NIR?
distinct peaks in optical and NIR at 2.5 days
distinct emission components?
absorption “troughs” in NIR
Kilonova Colors

- **Fe or light r-nuclei**
  - $T \sim 5500\,\text{K}$
  - $t_{\text{peak}} \sim 1\,\text{day}$
  - Metzger et al. 10
  - Roberts et al. 11

- **Heavy r-nuclei with lanthanides**
  - $T \sim 2500\,\text{K}$
  - $t_{\text{peak}} \sim 1\,\text{week}$
  - Barnes & Kasen 13
  - Tanaka & Hotokezaka 13

Graph showing relative flux vs. wavelength (angstroms) with peaks at different temperatures and time scales.
Kilonova Colors

**Fe or light r-nuclei**

\[ T \sim 5500 \, \text{K} \]

\[ t_{\text{peak}} \sim 1 \, \text{day} \]

Metzger et al. 10
Roberts et al. 11

**Heavy r-nuclei with lanthanides**

\[ T \sim 2500 \, \text{K} \]

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Barnes & Kasen 13
Tanaka & Hotokezaka 13

\[ \frac{n}{p} < 3 \]

\[ \frac{n}{p} > 3 \]

R-Process Isotopic Abundance Distribution

2nd peak: e.g. Xenon, Silver
3rd peak: e.g. Platinum, Gold

Metzger et al. 2010

Kilonova Colors with wavelength (angstroms) and relative flux.
“Blue” + “Red” Kilonova Models

BDM & Fernandez 2014

Blue KN (polar dynamical ejecta)

Red KN (disk wind)

\[ \frac{n}{p} < 3 \]

\[ \frac{n}{p} > 3 \]
2 Component Model: Everybody’s Data on GW170817

Blue KN: $1.6 \times 10^{-2} \, M_\odot$, $v \sim 0.26 \, c$

Red KN: $4 \times 10^{-2} \, M_\odot$, $v \sim 0.1 \, c$

Villar+18; Cowperthwaite+17
Homogeneous Purple Kilonova?
(e.g. Tanaka+17, Waxman+17)

Fine-tuned $Y_e$ distribution (delta function at $Y_e = 0.25$) required to get $X_{La} = 10^{-3}$ (purple kilonova)...

Mixing?

Only if mixing happens *after* r-process complete ($t > 1$ s)
Found! (an) astrophysical r-process site

Burbidge, Burbidge, Hoyle & Fowler (1957)

Lattimer & Schramm (1974)

Galactic r-process rate:
\[ \dot{M}_{A>100} \sim 7 \times 10^{-7} M_\odot \text{ yr}^{-1} \]
\[ R_{\text{BNS}} \approx 1540^{3200}_{1220} \text{Gpc}^{-3} \text{yr}^{-1} \]
\[ (\text{LVC 2017}) \]
\[ M_r \sim 2 \times 10^{-3} - 4 \times 10^{-2} M_\odot \]

GW170917

total r-process: $5 \times 10^{-2} M_\odot$
gold $\sim 10 M_\oplus$
platinum $\sim 50 M_\oplus$
uranium $\sim 5 M_\oplus$
Red KN Ejecta from Disk Winds

\[ M_{\text{red}} = 4 \times 10^{-2} \, M_\odot \]
\[ v_{\text{red}} = 0.1 \, c \]

too much and too slow to be tidal tail

\[ M_{\text{ej}} \sim 0.3-0.4 \, M_\odot \]

\[ V_{\text{avg}} = 0.11 \, c \]
Blue Dynamical Ejecta?

high velocity $v_{\text{blue}} \sim 0.2-0.3 \, c$

=> ejecta from collision interface

large ejecta mass
$M_{\text{blue}} = 1.5 \times 10^{-2} \, M_\odot$

=> NS radius < 11 km
(Nicholl et al. 2017)

But not all dynamical ejecta will have high $Y_e$
Blue Ejecta from Magnetar Wind?

Strong Magnetic Field enhances wind mass-loss rate and velocity

\[ v_B \approx \sqrt{3} c \sigma^{1/3} = \sqrt{3} \left( \frac{B^2 R_{ns}^4 \Omega^2}{\dot{M}} \right)^{1/3} \]

B_d \sim \text{few } 10^{14} \text{ G}
P \sim 0.8 \text{ ms}
\[ t_{\text{collapse}} \sim 0.1-1 \text{ seconds} \]

BDM, Thompson, Quataert 2018
Implications for NS EOS: $M_{\text{max}}$

Possible Merger Outcomes:

• Immediate black hole ("prompt collapse")

• Differentially rotationally-supported hyper-massive NS (HMNS)

• Rigidly rotating rotationally-supported supramassive NS (SMNS)

• Indefinitely stable NS

Threshold masses depend on EOS

$M_{\text{max}} \approx 1.3-1.6$ $M_{\odot}$

$M_{\text{tot}} = 2.74-2.8$ $M_{\odot}$

GW170817
Implications for NS EOS: $M_{\text{max}}$

Possible Merger Outcomes:

- **Immediate black hole** ("prompt collapse")
- Differentially rotationally-supported **hyper-massive NS** (HMNS)
- Rigidly rotating rotationally-supported **supramassive NS** (SMNS)
- Indefinitely **stable NS**

Too much KN ejecta => $R_{1.6} > 10.7$ km (Bauswein et al. 2013)

Threshold masses depend on EOS

- $M_{\text{max}} \approx 1.2 M_{\odot}$
- $M_{\text{tot}} = 2.74-2.8 M_{\odot}$

GW170817

$M_{\text{max}}$
Supra-massive NS Remnant?

Stable Millisecond Magnetar?

\[ B \sim 10^{14} - 10^{16} \, \text{G} \]

\[ E_{\text{rot}} \sim 10^{52} - 10^{53} \, \text{erg} \]

\[ L_{\text{sd}} = \frac{\mu^2 \Omega^4}{c^3} \approx 1.7 \times 10^{50} B_{15}^2 \, \text{erg s}^{-1} \]

\[ t_{\text{sd}} \approx 147 \, \text{s} \, B_{15}^{-2} \]

Spin-down time < weeks-months unless \( B_d \ll 10^{12} - 10^{13} \, \text{G} \)
Magnetar Remnant Wind/Jet

more powerful magnetar jet

Bucciantini, BDM et al. 2012
Possible Merger Outcomes:

- Immediate black hole ("prompt collapse")
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- Rigidly rotating rotationally-supported supramassive NS (SMNS)
- Indefinitely Stable NS

Threshold masses depend on EOS

Too much KN ejecta
\[ R_{1.6} > 10.7 \text{ km} \] (Bauswein et al. 2013)

Ejecta KE too low
\[ M_{\text{max}} < 2.17 M_\odot \] (Margalit & BDM 17)
WAGER I: What will be the first EM GW-counterpart observed?

- Early UV/optical (neutron precursor, macronova cocoon etc.)
  Mansi, Tsvi, Siegel
- Blue Kilonova (disk wind emission, high Ye etc.)
  Brian, Oliver, Francois, Albino, Sasha
- Red Kilonova (radioactive decay of heavy elements)
  Kasen, Edo, Luke, Meng, Shibata, Gabriel, Stephan, Eddie, Cristina, Yong, Phil, Masaomi, Tominaga,
- Non-thermal Radio, isotropic X-rays, flaring FRB magnetar remnant etc.
  Kenta, Bruno
- Jetted GRB (High energy)
  Rodrigo

Discussion: INT Workshop r-process

August 2, 2017
The Future
At design sensitivity, LIGO/Virgo could detect a NS-NS merger every few weeks.
Same Event, Different Viewing Angle?

Kasen, Fernandez, BDM 2015

Kilonova light curves probe composition & geometry of merger ejecta
Same Geometry, Different Binary Mass

smaller binary mass, longer NS lifetime

“prompt collapse”

long-lived NS

Kasen, Fernandez, BDM, 2015
Supra-massive NS Remnant

Millisecond Magnetar?

\[ B \sim 10^{14}-10^{16} \text{ G} \]
\[ E_{\text{rot}} \sim 10^{52}-10^{53} \text{ erg} \]
\[ L_{\text{sd}} = \frac{\mu^2 \Omega^4}{c^3} \approx 1.7 \times 10^{50} B_{15}^2 \text{ erg s}^{-1} \]
\[ t_{\text{sd}} \approx 147 \text{ s } B_{15}^{-2} \]

Spin-down time < weeks-months unless \( B_d << 10^{12}-10^{13} \text{ G} \)
The First Few Hours...

\[ t_{d,m} = \left( \frac{3mk}{4\pi\beta vc} \right)^{1/2} \approx 3 \text{ hr} \left( \frac{m}{10^{-4} M_\odot} \right)^{1/2} \left( \frac{\kappa}{10 \text{ cm}^2 \text{ g}^{-1}} \right)^{1/2} \left( \frac{v}{0.5 \text{ c}} \right)^{-1/2} \]
The First Few Hours...

"cocoon" emission
(e.g. Gottlieb+17; Kasliwal+17)

BDM+15

\[ t_{d,m} = \left( \frac{3mk}{4\pi\beta vc} \right)^{1/2} \approx 3 \text{ hr} \left( \frac{m}{10^{-4} M_{\odot}} \right)^{1/2} \left( \frac{\kappa}{10 \text{ cm}^2 \text{ g}^{-1}} \right)^{1/2} \left( \frac{v}{0.5 \text{ c}} \right)^{-1/2} \]
The First Few Hours...

any temporally-extended variable ejecta

\[ t_{d,m} = \left( \frac{3m\kappa}{4\pi\beta v c} \right)^{1/2} \approx 3 \text{ hr} \left( \frac{m}{10^{-4} M_\odot} \right)^{1/2} \left( \frac{\kappa}{10 \text{ cm}^2 \text{ g}^{-1}} \right)^{1/2} \left( \frac{v}{0.5 \text{ c}} \right)^{-1/2} \]
Gravitational Waves
Gamma-Ray Burst
Structured Jet / Cocoon
Afterglow (X-ray/Radio)
Blue Kilonova
Red/Purple Kilonova

A Well-Behaved Merger

- Gravitational Waves
- Gamma-Ray Burst
- Structured Jet / Cocoon
- Afterglow (X-ray/Radio)
- Blue Kilonova
- Red/Purple Kilonova
Open Questions

• Why was the blue ejecta mass so high in GW170817?
  – Small NS radius, inadequate simulations, or magnetar wind

• Is the blue KN bright for an edge-on merger?
  – Will the tidal tail block the polar ejecta?

• Did a BH actually form in GW170817?
  – How strong is the dipole field? (magnetic field burial?)
  – What is the GW emission from a supramassive NS?
    Can it compete with magnetic spin-down?

• What is the impact of the GRB jet on the kilonova?
  – Impact of shock heating on nucleosynthesis? Early thermal emission?

• Impact of total binary mass on KN signatures
  – Prompt collapse? Long-lived SMNS

• How will a BH-NS merger look differently than a BNS?
  – Will the blue KN be present? as strong?