Shining New Light on the Physics of Neutron Star Mergers

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Theoretical Physics Colloquium, Wednesday Dec. 14, 2021
One of the goals of nuclear astrophysics is to identify where and when in the universe the elements were forged.
Cassiopeia A Supernova Remnant
(exploded in 1667 – the last Galactic “naked eye” supernova)

Credit: NASA Chandra X-ray Observatory

Original star ~17 Mₖ

5 light years
“...the calcium in our teeth, the iron in our blood, the carbon in our apple pies were made in the interior of collapsing stars. We are made of starstuff.” Carl Sagan
Origin of the Elements, circa 2008

Gold

Uranium, Plutonium
An Alchemist,
(Jacob Toorenvliet, 1679)

Iron
26 protons, 30 neutrons

Gold
79 protons, 118 neutrons
Cassiopeia A Supernova Remnant
(exploded in 1667 – the last Galactic “naked eye” supernova)

Credit: NASA Chandra X-ray Observatory
What is the neutron star equation of state?

Maximum Mass?

\[ M_{\text{max}} > 2.08 \, M_{\odot} \]
Gravitational Wave Inspiral

\[
\frac{1}{P} \frac{dP}{dt} = \frac{128}{15} \frac{G^3}{c^5} \frac{M^3}{a^4}
\]

Hulse-Taylor Binary Pulsar

**GR Prediction**

\( T_{\text{merge}} = 300 \text{ Myr} \)

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Example Inspiral Gravitational Wave

R. Hurt/Caltech-JPL
LIGO’s First Neutron Star Merger

August 17, 2017 - GW170817

Gravitational-wave time-frequency map

\[ M_{\text{tot}} = M_1 + M_2 \approx 2.74^{+0.04}_{-0.01} M_\odot \]
By measuring the **delay in the arrival time** of the gravitational waves in Louisiana vs. Washington, **the direction of the merger was pinpointed** (towards the constellation Hydra).
Hunt for an Electromagnetic Counterpart

resulting in identification of the host galaxy NGC 4993 at 40 Mpc!
A rapidly fading flare of light was discovered, unlike that ever observed before.
Neutron Star Merger Pathways

binary mass, $M_{\text{tot}}$

$t \sim \text{Myr - Gyr}$

Adapted from Bartos, Brady, Marka 2013
Neutron Star Merger Pathways

binary mass, $M_{\text{tot}}$

t ~ Myr - Gyr

“prompt collapse”

$M_{\text{tot}} > 1.3 - 1.6 M_{\text{max}}$

t ~ 1 ms

Adapted from Bartos, Brady, Marka 2013
Neutron Star Merger Pathways

binary mass, $M_{\text{tot}}$

$t \sim \text{Myr - Gyr}$

“Iinspiral”

$M_{\text{tot}} > 1.3 - 1.6 M_{\text{max}}$

$\Omega$

“prompt collapse”

$t \sim 1 \text{ ms}$

“hypermassive NS” + torus ($\sim 0.1 M_\odot$)

$t \sim 100 \text{ ms}$

Adapted from Bartos, Brady, Marka 2013
Neutron Star Merger Pathways

Binary mass, $M_{\text{tot}}$

- $t \sim \text{Myr - Gyr}$

- $M_{\text{tot}} > 1.3 - 1.6 M_{\text{max}}$

- $M_{\text{tot}} > M_{\text{max}}$

- $t \sim 1 \text{ ms}$

- $t \sim 100 \text{ ms}$

- $t \sim t_{\text{spin-down}}$

- "prompt collapse"

- "hypermassive NS" + torus ($\sim 0.1 M_{\odot}$)

- "supramassive NS"

Adapted from Bartos, Brady, Marka 2013
Neutron Star Merger Pathways

LIGO/Virgo

binary mass, $M_{\text{tot}}$

t ~ Myr - Gyr

$M_{\text{tot}} > 1.3-1.6\, M_{\text{max}}$

“prompt collapse”

“hypermassive NS” + torus ($\sim 0.1\, M_{\odot}$)

t ~ 1 ms

t ~ 100 ms

$M_{\text{tot}} < 1.2\, M_{\text{max}}$

“supramassive NS”

$t \sim t_{\text{spin-down}}$

$M_{\text{tot}} > M_{\text{max}}$

EM Observations

Adapted from Bartos, Brady, Marka 2013
Neutron Star Merger Pathways

LIGO/Virgo
binary mass, $M_{\text{tot}}$

$t \sim \text{Myr} - \text{Gyr}$

“prompt collapse”

$M_{\text{tot}} > 1.3 - 1.6 M_{\text{max}}$

$M_{\text{tot}} > M_{\text{max}}$

EM Observations

$t \sim 100 \text{ms}$

“hypermassive NS” + torus ($\approx 0.1 M_\odot$)

$t \sim 1 \text{ ms}$

GW170817

$t \sim t_{\text{spin-down}}$

“supramassive NS”

adapted from Bartos, Brady, Marka 2013
General Relativistic Hydrodynamical Simulation

Courtesy: David Radice, Wolfgang Kastaun, Filippo Galeazzi
Electromagnetic Counterparts

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

GRB
(t~ 0.1–1 s)

GW170817
$\theta_{\text{obs}} \sim 0.4$

Ejecta–ISM shock
Radio (years)

Kilonova
Optical (t~ 1 day)

Merger ejecta
Tidal tail and disk wind
$\nu \sim 0.1–0.3 \, c$

BH

BDM & Berger 12
Electromagnetic Counterparts

- Delayed 1.7 s after merger
  - time for BH/jet to form?
  - jet propagation?

GW170817

$\theta_{\text{obs}} \sim 0.4$

Merger ejecta
- Tidal tail and disk wind $v \sim 0.1-0.3 \, c$

Kilonova
- Optical ($t \sim 1$ day)

Ejecta–ISM shock
- Radio (years)

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

BDM & Berger 12
• Delayed 1.7 s after merger
  • time for BH/jet to form?
  • jet propagation?
Neutron-Rich Ejecta

“Dynamical”

$M_{\text{ej}} \sim 10^{-3} M_\odot$
$t_{\text{exp}} \sim \text{milliseconds}$
$v_{\text{ej}} \sim 0.3 \, c$

Disk Winds

$M_{\text{ej}} \sim 10^{-2} - 10^{-1} M_\odot$
$t_{\text{exp}} \sim \text{seconds}$
$v_{\text{ej}} \sim 0.1 \, c$
Neutron-Rich Ejecta

“Dynamical”

\[ M_{ej} \sim 10^{-3} \, M_\odot \]
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Disk Winds

\[ M_{ej} \sim 10^{-2} - 10^{-1} \, M_\odot \]
\[ t_{\text{exp}} \sim \text{seconds} \]
\[ v_{ej} \sim 0.1 \, c \]

wind composition depends on neutron star lifetime!
Black Holes are Fussy Eaters

- Accretion via magneto-rotational instability (MRI)
- Hot midplane ($T > 5$ MeV) cooled by neutrinos
- Wind accelerated by “coronal” heating

$M_{ej} \sim 0.3 \, M_{torus}$

Siegel & BDM 17, 18; see also Fernandez+19, Fujibayashi+20
rapid neutron capture (r-process) nucleosynthesis in the decompressing ejecta

Courtesy A. Frebel
R-Process Network (neutron captures, photo-dissociations, α- and β-decays, fission)

\[ T = 3.50 \text{ GK}, \quad n_n = 2.945 \times 10^{-35} \text{ cm}^{-3}, \quad R_{\text{n/s}} = 639.5, \quad s = 0.621 \text{ k}_B/\text{nuc}, \quad t = 0.0131 \text{ s} \]
Final Abundances

2nd peak: xenon, silver

3rd peak: platinum, gold

uranium, thorium

BDM+10

atomic number A

abundance
Radioactive Heating

Radioactive decay

Radioactive Heating

\[ E \sim t^{-1.3} \]

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

BDM+10

see also Li & Paczynski 98
Radioactive Heating

Radioactive decay

$^{56}\text{Ni} + ^{56}\text{Co}$

$E \propto t^{-1.3}$

BDM et al. 2010

cf. Li & Paczyński 98

Observable window
Days after Merger

a "Kilo-nova"

$L_{\text{ej}} = 0.01 M_\odot$

$V_{\text{ej}} = 0.1 c$

BDM et al. 2010
First observation of r-process production

\[ \dot{M}_r \sim 10^{-6} \, \text{M}_\odot \, \text{yr}^{-1} \]

Measured NS merger rate:

\[ R_{\text{BNS}} \sim 13-1900 \, \text{Gpc}^{-3} \, \text{yr}^{-1} \] (LVC 21)

Required r-process yield per merger:

\[ M_r \sim 3 \times 10^{-3} - 0.3 \, \text{M}_\odot \]

GW170817

- total r-process: \( 5 \times 10^{-2} \, \text{M}_\odot \)
- gold \( \sim 10 \, \text{M}_\oplus \)
- platinum \( \sim 50 \, \text{M}_\oplus \)
- uranium \( \sim 5 \, \text{M}_\oplus \)
Kilonova Colors Reveal Ejecta Composition

Light r-nuclei

\[ T \approx 5500 \text{ K} \]

\[ t_{\text{peak}} \approx 1 \text{ day} \]

Heavy r-nuclei with lanthanides

\[ T \approx 2500 \text{ K} \]

\[ t_{\text{peak}} \approx 1 \text{ week} \]

Light r-process

Lanthanides/Actinides
Kilonova Colors Reveal Ejecta Composition

- **light r-nuclei**
  - $T \sim 5500 \text{ K}$
  - $t_{\text{peak}} \sim 1 \text{ day}$

- **heavy r-nuclei**
  - with lanthanides
  - $T \sim 2500 \text{ K}$
  - $t_{\text{peak}} \sim 1 \text{ week}$

...
“Blue” + “Red” Kilonova

Blue (e.g. shock-heated ejecta, magnetar wind)

Red (e.g. disk wind)

fewer neutrons

more neutrons

NS+NS → BH

BDM & Fernandez 14

luminosity vs. time

t ~ day

t ~ week
Two-Component Kilonova

Blue: $\sim 10^{-2} \, M_\odot$, $v \sim 0.25 \, c$

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

Villar+18

“fast blue”

“slow red”

Kasen, BDM et al. 2017
Kilonova Colors Probe Timescale of Black Hole Formation

Fernandez & BDM 2014

Ejected mass in bin [10^{-3} M_{\odot}]

- $t_{ns} = 0$ ms
- $t_{ns} = 10$ ms
- $t_{ns} = 30$ ms
- $t_{ns} = 100$ ms
- $t_{ns} = 300$ ms
- $t_{ns} = \infty$

Lanthanides

Lanthanide Free

Electron fraction $Y_{e,5GK}$

Lippuner+17

Density [g cm^{-3}]

$10^5$ $10^6$ $10^7$ $10^8$ $10^9$ $10^{10}$

$x$ [10^7 cm]

$z$ [10^7 cm]

$0.0$ $0.5$ $1.0$ $2.0$ $2.5$

$0.0$ $0.5$ $1.0$ $1.5$

$0.0$ $0.5$ $1.0$ $1.5$ $2.0$ $2.5$

$0.0$ $0.1$ $0.2$ $0.3$ $0.4$ $0.5$
longer neutron star lifetime

Kasen, Fernandez, BDM, 2015
longer neutron star lifetime

"prompt collapse"

"Red" kilonova in GW170817 disfavors long-lived (>1 s) NS remnant (favoring BH formation)

Kasen, Fernandez, BDM, 2015
LIGO/Virgo

binary mass,

\[ M_{\text{tot}} = 2.74^{+0.04}_{-0.01} M_\odot \]
Neutron Star Merger Pathways

binary mass,

\[ M_{\text{tot}} = 2.74^{+0.04}_{-0.01} M_\odot \]

LIGO/Virgo

EM Observations

“prompt collapse”

M_{\text{tot}} > 1.5-1.6 M_{\text{max}}

too much ejecta (e.g. Bauswein +17, Radice+17)

“hypermassive NS”

M_{\text{tot}} < 1.2 M_{\text{max}}

“supramassive NS”
Neutron Star Merger Pathways

LIGO/Virgo

binary mass,

\[ M_{\text{tot}} = 2.74^{+0.04}_{-0.01} M_\odot \]

EM Observations

“prompt collapse”

too much ejecta
(e.g. Bauswein +17, Radice+17)

M_{\text{tot}} > 1.3-1.6 M_{\text{max}}

Ω

“hypermassive NS”

Kilonova too red
Kinetic energy too low
(Margalit & BDM 17, Shibata+17, Ruiz+18, Rezzolla+18)

M_{\text{tot}} < 1.2 M_{\text{max}}

“supramassive NS”
Neutron Star Merger Pathways

LIGO/Virgo

binary mass,

\[ M_{\text{tot}} = 2.74^{+0.04}_{-0.01} M_\odot \]

“prompt collapse”

too much ejecta
(e.g. Bauswein +17, Radice+17)

M\(_{\text{tot}}\) > 1.3\( - 1.6 \) M\(_{\text{max}}\)

EM Observations

“hypermassive NS”
\( t \sim 100 \) ms

GW170817

M\(_{\text{tot}}\) < 1.2 M\(_{\text{max}}\)

“supramassive NS”

Kilonova too red
Kinetic energy too low
(Margalit & BDM 17, Shibata+17, Ruiz+18, Rezzolla+18)
Neutron Star Merger Pathways

LIGO/Virgo

binary mass,

\[ M_{\text{tot}} = 2.74^{+0.04}_{-0.01} M_{\odot} \]

“prompt collapse”

lower limit on \( R_{NS} \)

(e.g. Bauswein +17, Radice+17)

M\(_{\text{tot}}\) > 1.3 - 1.6 M\(_{\text{max}}\)

“hypermassive NS” + torus

(t ~ 100 ms)

GW170817

M\(_{\text{tot}}\) < 1.2 M\(_{\text{max}}\)

“supramassive NS”

upper limit on M\(_{\text{max}}\)

(Margalit & BDM 17, Shibata+17, Ruiz+18, Rezzolla+18)

M\(_{\text{tot}}\) < M\(_{\text{max}}\)
GW only

GW+EM

No Long-Lived Remnant
Margalit & BDM 17
(Shibata+17, Ruiz+18, Rezzolla+18)

Radius (km)

Mass (M_⊙)

Ozel & Freire 16

LIGO/Virgo+18

Radice+18

Bauswein+17

Inside

BSK20
BSK21
ENG
GNH3
GS1
H4
MS1b
NJL
QMC
SLY
SQM1-3
PAL6
WWF1
WWF2
WWF3
The Future is Bright (and Loud!)

- Similar events to GW170817, observed from different angles
- Different ingoing binary properties => diverse outcomes
- NS-BH mergers, both with and without EM counterparts
Expected Diversity in Kilonovae

"prompt collapse"

Dimmer, redder kilonova

"hypermassive NS"

GW170817

t $\sim 100$ ms

"supramassive NS"

$E_{\text{rot}} \sim 10^{52}-10^{53}$ erg
A Second Neutron Star Merger: GW190425

Unfortunately, no EM counterpart found.
Expected Diversity in Kilonovae

"prompt collapse"

Ω
$t \sim 100 \text{ ms}$

"hypermassive NS"

GW170817

GW190425

"supramassive NS"
Expected Diversity in Kilonovae

“prompt collapse”

GW190425 Kilonova

“hypermassive NS”

GW170817

“supramassive NS”

“magnetar”

- Brighter, faster, bluer kilonova
- Brighter X-rays, radio
Millisecond Magnetar

\[ L_{sd} = \frac{\mu^2 \Omega^4}{c^3} \approx 6 \times 10^{49} \left( \frac{P}{1 \text{ ms}} \right)^{-4} \left( \frac{B_{\text{dip}}}{10^{15} \text{ G}} \right)^2 \text{erg s}^{-1} \]

>> \text{L}_{\text{radioactivity}}
A Vogt-Russell Theorem for Binary Mergers
Margalit & BDM 19

**Binary mass is the dominant variable controlling EM outcome**

- KN and GRB depend sensitivity on stability (~lifetime) of remnant.
- Stability depends mostly on total binary mass $M_{\text{tot}}$.
- Expect abrupt qualitative changes in EM signature at outcome boundaries.
- LIGO/Virgo measure binary mass accurately in low latency (e.g. Biscoveanu+19).
- Prompt public announcement of $M_{\text{tot}}$ can inform EM search strategies/prioritization.
• Filling out matrix enables check on assumptions & EOS constraints
• Unexpected behavior => new/exotic physics (e.g. phase transition inside NS)
Summary: a well-behaved mergerc
Summary: a well-behaved merger
Firsts from GW170817

- Gravitational waves from a BNS merger
- EM counterpart to a GW event (radio, UVOIR, X-ray, gamma-ray)
- Definitive connection to short gamma-ray bursts
- GW & multi-messenger constraints on the neutron star Equation of State
- Direct evidence for the creation of r-process elements
- Cosmological redshift of a GW event and “standard siren” $H_0$ measurement