Binary neutron star mergers, short gamma-ray bursts, and kilonovae

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Ciolfi et al. 2019, PRD 100, 023005  ArXiv:1904.10222

TCAN on Binary Neutron Stars Workshop 2020
10th July 2020
GW170817 detection timeline

- merger
- short GRB
  - GRB170817A
- X-ray afterglow
- radio afterglow
- t0 +1.7 sec
- +10.87 hours
- +9 days
- +16 days
- optical counterpart
  - kilonova
  - AT 2017gfo
GW170817 detection timeline

merger

short GRB
GRB 170817A

+1.7 sec

+10.87 hours

+9 days

+16 days

radio afterglow

optical counterpart
kilonova
AT 2017gfo

——
SGRB jets from BNS mergers

GW170817 + GRB 170817A

Jet launching mechanism?
- Neutrino driven
- MHD driven

Remnant/central engine nature?

BH + accretion disk
(Blandford-Znajek)

Massive long-lived NS
(magnetorotational)

Kiuchi+2014
Ruiz+2016
Kawamura+2016
Ciolfi+2017
Ciolfi+2019
Ciolfi 2020a

Ciolfi+2017

Need GRMHD simulations

Ciolfi+2019
SGRB jets from BNS mergers

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- Neutrino driven: X
- MHD driven: ✓

Remnant/central engine nature?
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- Massive long-lived NS (magnetorotational)

Kiuchi+2014
Kawamura+2016
Ruiz+2016
Ciolfi+2017
Ciolfi+2019
Ciolfi 2020a

Need GRMHD simulations
Magnetic field amplification and geometry

Ciolfi+2019: 100 ms of post-merger evolution

see talk by Jay Kalinani

Kelvin-Helmholtz Instability
toroidal field amplification

MagnetoRotational Instability

helical structure
Magnetically driven wind

Ciolfi+2019

@50-100 ms after merger

nearly **isotropic** and **constant** density distribution from ~50 km to ~400 km

Cumulative mass flow across 150 km radius

- strongly magnetized
- non-magnetized

- magnetized remnant NS
  - surrounded by dense isotropic environment
  - slow steady outflow maintaining a fixed radial density profile

Dynamical ejecta

\[ \text{M}_{\text{out}}[M_\odot] \]

\[ t \text{ [ms]} \]
Magnetically driven wind

@50-100 ms after merger

nearly **isotropic** and **constant** density distribution from \(~50\) km to \(~400\) km

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massive NS remnant

BH remnant

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obstacle for jet formation

favourable environment
BNS mergers with much longer evolution

Ciolfi 2020a

- BNS system with chirp mass of GW170817 and $q=0.9$
- two different initial magnetization levels (factor 5 in field strength)
- evolution up to $\sim 250$ ms after merger
BNS mergers with much longer evolution

Ciolfi 2020a

- BNS system with chirp mass of GW170817 and q=0.9
- two different initial magnetization levels (factor 5 in field strength)
- evolution up to ~250 ms after merger

massive NS remnant can produce a collimated outflow
BNS mergers with much longer evolution

Ciolfi 2020a

- BNS system with chirp mass of GW170817 and q=0.9
- two different initial magnetization levels (factor 5 in field strength)
- evolution up to ~250 ms after merger

..but not ubiquitous
Origin and properties of the collimated outflow

Ciolfi 2020a

Outflow energy saturation
~160 ms after merger
change in rotational energy evolution
differential rotation in the NS core is over

NS differential rotation = energy reservoir
Origin and properties of the collimated outflow

Ciolfi 2020a

magnetorotational launching mechanism

magnetic field amplification

build up of magnetic pressure radial gradient

NS differential rotation

acceleration along the rotation axis
Emerging helical magnetic field

Ciolfi 2020a

magnetic push
(radial gradient of magnetic pressure)
aligned dipolar field imposed on differentially rotating NS

collimated outflow

disordered magnetic field

isotropic outflow

earlier disordered field creates obstacle for collimated outflow coming later

helical structure takes time to emerge (and not always does)
Can this collimated outflow evolve into a SGRB jet?

compared to GRB 170817A jet parameters:

- outflow energy is insufficient (or at most marginally consistent)
- outflow collimation is insufficient
- low outflow velocity of $\sim 0.2c$ and energy-to-mass flux ratio $< 0.01$
  
  $\longrightarrow$ no way to accelerate up to $\sim 0.995c$ (Lorentz factor of 10) or more

  outflow is at least 3 orders of magnitude too heavy!

massive NS scenario for SGRBs is disfavoured
Results from Ciolfi 2020a

- GRMHD BNS merger simulations with up to >250 ms of massive NS remnant evolution
- collimated outflow from a massive NS obtained for the first time
- massive NS can launch a collimated outflow, but this outcome is not ubiquitous
- followed the full outflow development, studied the associated energetics and properties
- identified the energy reservoir (NS differential rotation)
- identified the launching mechanism (magnetorotational)
- found indications against the possible production of a SGRB

→ accreting BH scenario is favoured
Results from Ciolfi 2020a

- GRMHD BNS merger simulations with up to $>250$ ms of massive NS remnant evolution
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**next step:** can neutrino radiation alter this conclusion?
A radioactively-powered transient

ejecta in NSNS and NSBH mergers

r-process
capture rate much faster than decay
more than one neutron capture at a time
requires very special conditions:
- High $T$ ($T > 10^9$ K)
- High neutron density ($n_n > 10^{22}$ cm$^{-3}$)

nucleosynthesis of heavy nuclei
radioactive decay on timescales of $>>$ sec
optical/IR signal “kilonova”

heavy element abundances

curtesy of A. Arcones
August 2017 kilonova (AT2017gfo)

lightcurves and spectra consistent with a kilonova!

BNS mergers are confirmed as ideal site for r-process nucleosynthesis

Pian et al. 2017
AT2017gfo: blue and red

1) “blue” kilonova
peaking ~1 day after merger between UV and blue
ejecta expansion velocity ~0.2 - 0.3 c
ejecta mass ~0.015 - 0.025 $M_{\odot}$
opacity ~0.5 cm$^2$/g (lanthanide-poor)

2) “red” kilonova
peaking several days after merger, IR wavelengths
ejecta expansion velocity ~0.1 c
ejecta mass ~0.05 $M_{\odot}$
opacity ~10 cm$^2$/g (lanthanide-rich)

which type of merger ejecta can explain the blue/red kilonova?
AT2017gfo: blue and red

1) “blue” kilonova ➔ ???

peaking ~1 day after merger between UV and blue
ejecta expansion velocity ~0.2 - 0.3 c
ejecta mass ~0.015 - 0.025 $M_{\text{sun}}$
opacity ~0.5 cm$^2$/g (lanthanide-poor)

2) “red” kilonova ➔ likely disk winds

peaking several days after merger, IR wavelengths
ejecta expansion velocity ~0.1 c
ejecta mass ~0.05 $M_{\text{sun}}$
opacity ~10 cm$^2$/g (lanthanide-rich)

which type of merger ejecta can explain the blue/red kilonova?
AT2017gfo: blue and red

1) “blue” kilonova

peaking ~1 day after merger between UV and blue ejecta expansion velocity ~0.2 - 0.3 c
ejecta mass ~0.015 - 0.025 $M_{\text{sun}}$
opACITY ~0.5 cm$^2$/g (lanthanide-poor)

\[ \downarrow \downarrow \downarrow \]
magnetically driven wind from the massive NS ?
(before its eventual collapse)

expected opacity fits the requirement
\[ \text{e.g. Perego et al. 2014} \]

magnetic enhancement of mass outflow and acceleration to sufficiently high velocities

\[ \rightarrow \text{ to be demonstrated!} \]
Magnetically driven winds and blue KN

Ciolfi & Kalinani 2020

- ejecta velocity
  - \( \sim 0.2 \, c \) marginally consistent with blue kilonova
  - possible further enhancement

- ejecta mass?

\( t = 130 \text{ ms} \)
\( t = 180 \text{ ms} \)
\( t = 230 \text{ ms} \)
Magnetically driven winds and blue KN

Ciolfi & Kalinani 2020

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$t = 130 \, \text{ms}$

$t = 180 \, \text{ms}$

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$M_{\text{out}} \, [M_\odot]$ vs $r \, [\text{km}]$

$M_{\text{out}} \, [M_\odot]$ vs $t \, [\text{ms}]$
Magnetically driven winds and blue KN

Ciolfi & Kalinani 2020

- **ejecta velocity**
  - $\sim 0.2 \ c$ marginally consistent with blue kilonova
  - possible further enhancement

- **ejecta mass**

\[ M_{\text{ej, wind}} \approx 0.010 - 0.028 \ M_\odot \]

to be compared with

\[ 0.015 - 0.025 \ M_\odot \]
A scenario for GW170817

I) the merger produced a metastable massive NS, surviving for a few $\times$ 100 ms
- the massive NS did not produce a jet
- its magnetically driven wind provided the main contribution to the blue kilonova

II) the collapse led to a BH surrounded by a massive disk (~0.1 Msun)
- the accreting BH launched the SGRB jet (possibly via Blandford-Znajek)
- baryon wind form the disk led to the red kilonova

Take-home message

- 2017 BNS merger left important question unanswered on the physical origin of the SGRB jet and the kilonova

- GRMHD simulations of the merger process represent the necessary investigating tool

- we found that massive NS remnants can launch collimated outflows and power blue kilonovae, but to produce a SGRB jet we (likely) need an accreting BH
  Magnetically driven baryon winds from binary neutron star merger remnants and the blue kilonova of August 2017

- **R. Ciolfi** (2020a), MNRAS Letters 495, L66
  Collimated outflows from long-lived binary neutron star merger remnants

- **R. Ciolfi**, W. Kastaun, J.V. Kalinani, B. Giacomazzo (2019), PRD 100, 023005
  The first 100 ms of a long-lived magnetized neutron star formed in a binary neutron star merger

  Intrinsic properties of the engine and jet that powered the short gamma-ray burst associated with GW170817

  Late time afterglow observations reveal a collimated relativistic jet in the ejecta of the binary neutron star merger GW170817

  General relativistic magnetohydrodynamic simulations of binary neutron star mergers forming a long-lived neutron star

**RECENT REVIEW ARTICLES**

- **R. Ciolfi** (2020c), Frontiers in Astronomy and Space Sciences 7, 27, Invited Review for the Article Collection "Gravitational Waves: A New Window to the Universe" (hosted by R. Perna and B. Giacomazzo)
  Binary neutron star mergers after GW170817

- **R. Ciolfi** (2020b), General Relativity and Gravitation 52, 59, Invited Review for the Topical Collection on “Binary neutron star mergers” (Guest Editor N. Stergioulas)
  The key role of magnetic fields in binary neutron star mergers

- **R. Ciolfi** (2018), IJMPD 27, No. 13, 1842004, Invited Review for the Special Issue “Gamma-Ray Bursts in the Multi-Messenger Era” (Guest Editor L. Nava)
  Short gamma-ray burst central engines
BACKUP SLIDES
GRB 170817A: Canonical SGRB? 
Lazzati+2018

special relativistic jet simulation

\[ L_j = 10^{50} \text{ erg/s}, \quad \theta_j = 16^\circ, \quad t_{\text{eng}} = 1 \text{ s} \]
\[ M_{\text{ej}} = 0.6 \times 10^{-2} \, M_{\odot} \]

multiwavelength afterglow calculation

\[ n_{\text{ISM}} \sim 4 \times 10^{-3} \, \text{cm}^{-3} \]
\[ \theta_{\text{obs}} \sim 33^\circ \]

viable explanation!
GRB 170817A: intrinsic jet properties
Lazzati, Ciolfi, Perna 2020

- incipient jet
- interaction with the baryon wind from the massive NS
- final jet properties
  - jet energy and duration
  - terminal Lorentz factor
  - initial opening angle
  - jet launching time
  - wind mass
    (simulation-inspired environment depending on launching time)
  - viewing angle
    - jet core opening angle
    - Eiso
      Lorentz factor of gamma-ray emission
      delay between merger and GRB

- input parameters
- output parameters constrained by observations

<table>
<thead>
<tr>
<th>Model</th>
<th>$\Delta t_{\text{obs}}$ (s)</th>
<th>$\eta$</th>
<th>$\theta_{\text{i.o.s.}}$ ($^\circ$)</th>
<th>$\theta_{\text{i.}}$ ($^\circ$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulations; baseline ($Y_e = 0.5$; $\Gamma_{\text{i.o.s.}} \leq 7$; $m_w$ unconstrained)</td>
<td>$&lt; 0.36$</td>
<td>$&gt; 240$</td>
<td>$23.5^{+5.5}_{-4.5}$</td>
<td>$17.9^{+12.6}_{-11.2}$</td>
</tr>
<tr>
<td>Simulations; $\Gamma_{\text{i.o.s.}} \leq 7$</td>
<td>$&lt; 0.18$</td>
<td>$&gt; 240$</td>
<td>$24.8^{+6.3}_{-3.8}$</td>
<td>$18.4^{+12.5}_{-7.4}$</td>
</tr>
<tr>
<td>Simulations; $m_w \geq 10^{-2}$</td>
<td>$&lt; 0.37$</td>
<td>$&gt; 390$</td>
<td>$23.6^{+4.8}_{-2.5}$</td>
<td>$17.3^{+14.4}_{-13.6}$</td>
</tr>
<tr>
<td>Simulations; $\Gamma_{\text{i.o.s.}} \leq 7$; $m_w \geq 10^{-2}$</td>
<td>$&lt; 0.17$</td>
<td>$&gt; 250$</td>
<td>$24.1^{+6.2}_{-3.6}$</td>
<td>$19.3^{+11.9}_{-11.3}$</td>
</tr>
<tr>
<td>Simulations; $Y_e = 1.0$</td>
<td>$&lt; 0.27$</td>
<td>$&gt; 260$</td>
<td>$22.0^{+5.9}_{-3.3}$</td>
<td>$18.1^{+13.4}_{-13.1}$</td>
</tr>
<tr>
<td>Simulations; $Y_e = 0.2$</td>
<td>$&lt; 0.51$</td>
<td>$&gt; 170$</td>
<td>$25.1^{+5.0}_{-3.8}$</td>
<td>$15.8^{+13.2}_{-13.0}$</td>
</tr>
<tr>
<td>Parametric; baseline ($Y_e = 0.5$; $\Gamma_{\text{i.o.s.}} \leq 7$; $m_w$ unconstrained)</td>
<td>$&lt; 1.1$</td>
<td>$&gt; 150$</td>
<td>$30.3^{+8.9}_{-6.9}$</td>
<td>$10.7^{+8.3}_{-7.0}$</td>
</tr>
<tr>
<td>Parametric; $\Gamma_{\text{i.o.s.}} \leq 7$</td>
<td>$&lt; 0.87$</td>
<td>$&gt; 180$</td>
<td>$34.4^{+6.4}_{-3.6}$</td>
<td>$9.2^{+7.1}_{-4.8}$</td>
</tr>
<tr>
<td>Parametric; $m_w \geq 10^{-2}$</td>
<td>$&lt; 0.87$</td>
<td>$&gt; 420$</td>
<td>$27.5^{+6.0}_{-1.6}$</td>
<td>$16.2^{+13.3}_{-3.2}$</td>
</tr>
<tr>
<td>Parametric; $\Gamma_{\text{i.o.s.}} \leq 7$; $m_w \geq 10^{-2}$</td>
<td>$&lt; 0.57$</td>
<td>$&gt; 800$</td>
<td>$30.7^{+6.9}_{-2.6}$</td>
<td>$16.3^{+13.8}_{-3.2}$</td>
</tr>
<tr>
<td>Parametric; $Y_e = 1.0$</td>
<td>$&lt; 1.0$</td>
<td>$&gt; 170$</td>
<td>$32.3^{+6.4}_{-9.6}$</td>
<td>$9.6^{+7.0}_{-2.5}$</td>
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<tr>
<td>Parametric; $Y_e = 0.2$</td>
<td>$&lt; 1.2$</td>
<td>$&gt; 130$</td>
<td>$30.5^{+8.3}_{-3.8}$</td>
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jet launching time $< 0.4$ s
Magnetic field amplification

- Kelvin-Helmholtz Instability
- MagnetoRotational Instability
  - well resolved 30 ms after merger
  - inactive in the remnant NS core (<10 km from spin axis)

magnetic energy saturation
- clear signs of a physical saturation
- indication of maximum magnetic energy achievable in BNS mergers
- magnetically driven mass outflow takes time to emerge for significant contribution → NS remnant lifetime > 50ms

- mostly over at 200ms → slower neutrino driven wind could then take over and persist for longer time (~1 sec)
What if the remnant collapses?

Relative difference in density collapsing v.s. non-collapsing

No effect above ~200 km

Induced collapse 72 ms after merger

BH mass \( M_{BH} \simeq 2.5 M_{\odot} \)

BH spin \( \chi \equiv Jc/GM^2 \simeq 0.5 \)

Disk mass \( M_{\text{disk}} \simeq 0.1 M_{\odot} \)

\( L_{BZ} \sim 10^{52} \left( \frac{\chi}{0.5} \right)^2 \left( \frac{M_{BH}}{2.5 M_{\odot}} \right)^2 \left( \frac{B_{BH}}{10^{16} \text{ G}} \right)^2 \text{ erg/s} \)

BZ jet likely able to drill through heavy ejecta layer