Simulating short gamma-ray burst jets from binary neutron star mergers

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

Computational Challenges in Multi-Messenger Astrophysics
6th October 2020
GW170817 detection timeline

merger

short GRB

GRB170817A

t0 +1.7 sec

X-ray afterglow

radio afterglow

+10.87 hours +9 days +16 days

optical counterpart

kilonova

AT 2017gfo
GW170817 detection timeline

- **merger**
- **short GRB**
  - GRB170817A
- **radio afterglow**
- **optical counterpart**
  - kilonova
  - AT2017gfo

Timeline:
- t0
- +1.7 sec
- +10.87 hours
- +9 days
- +16 days
GRB 170817A

Light curve from Fermi/GBM (50-300 keV)

Light curve from INTEGRAL/SCI-ACS ($\geq$ 100 keV)

Gravitational-wave strain from Hanford + Livingston

$\sim$1.74 sec

Abbott+2017c
GRB 170817A: a peculiar GRB

from GRB and multiwavelength afterglow modelling

observed gamma-rays come from mildly relativistic outflow ($\Gamma \sim 2 - 8$) moving along the line of sight
Canonical SGRB or choked jet?

Lazzati+2018

ordinary SGRB event observed off-axis

viable explanation!

Gottlieb+2017

unsuccessful jet
no canonical SGRB
also viable
VLBI observations

global network of 32 radio telescopes

apparent superluminal motion between 75 and 230 days

source is moving relativistically (and getting closer)

source size < 2 m arcseconds @ 207 days

source is still rather compact!
VLBI observations
global network of 32 radio telescopes

collimated jet (<5 deg), seen ~15-20 deg off-axis
nearly isotropic, mildly relativistic outflow excluded

source size < 2 m arcseconds @ 207 days
source is still rather compact!

between 75 and 250 days

source is moving relativistically (and getting closer)
SGRB jets from BNS mergers

- GW170817
- GRB 170817A

Jet launching mechanism?
- Neutrino driven [X]
- MHD driven [✓]

Remnant/central engine nature?
- BH + accretion disk (Blandford-Znajek)
- Massive long-lived NS (magnetorotational)

Need GRMHD simulations

Ciolfi+2017
Ruiz+2016
Kawamura+2016
Ciolfi+2017
Ciolfi+2019
Ciolfi 2020a
Product of BNS mergers

- BNS
- massive metastable NS
  - short-/long-lived ..
  - or STABLE NS
- BH + TORUS
- prompt collapse
- light disk
- massive/light disk

GW170817

BH + TORUS

GW170817
SGRB jets from BNS mergers

GW170817 + GRB 170817A

jet launching mechanism?

- neutrino driven
- MHD driven

need GRMHD simulations

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BH + accretion disk (Blandford-Znajek)

massive long-lived NS (magnetorotational)

Kiuchi+2014

Kawamura+2016

Ruiz+2016

Ciolfi+2017

Ciolfi+2019

Ciolfi 2020a

Just+2017

Perego+2017
SGRB jets from BNS mergers

GW170817 + GRB 170817A

jet launching mechanism?

- neutrino driven (Just+2017, Perego+2017)
- MHD driven (√)

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Kiuchi+2014

Kawamura+2016

Ruiz+2016

Ciolfi+2017

Ciolfi+2019

Ciolfi 2020a
BNS mergers with long-lived remnant

Ciolfi+2017
Magnetic field amplification and geometry

Kiuchi+2015

Kelvin-Helmholtz Instability
toroidal field amplification

Ciolfi+2019: 100 ms of post-merger evolution

see talk by Carlos Palenzuela

Kelvin-Helmholtz Instability
toroidal field amplification

MagnetoRotational Instability

helical structure
Magnetically driven wind

@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

dynamical ejecta

magnetized remnant NS

- surrounded by dense isotropic environment
- slow steady outflow maintaining a fixed radial density profile
Magnetically driven wind

@50-100 ms after merger

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

massive NS remnant

BH remnant

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 ~250 ms after merger
BNS mergers with much longer evolution

Ciolfi 2020a

- BNS system with chirp mass of GW170817 and $q=0.9$
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- evolution up to $\sim 250$ ms after merger

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

- 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

..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

NS differential rotation

build up of magnetic pressure radial gradient

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

Ruiz+2018

Siegel+2014

Moesta+2020

disordered magnetic field

isotropic outflow

Ciolfi+2019

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 \( <0.01 \)

\[ \rightarrow \text{no way to accelerate up to} \sim 0.995c \text{ (Lorentz factor of 10) or more} \]

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
- massive NS remnant can launch an MHD-driven 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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MAIN CAVEATS

- much higher resolution
- finite temperature EOS and neutrino radiation
  (e.g. Moesta+2020)

see talk by Carlos Palenzuela
Spritz: a new GRMHD code

Version 1.0: Cipolletta+2020

- Vector potential staggered evolution
- Designed to work within Einstein Toolkit framework
- Support for ideal gas and polytropic EOSs via EOS_Omni
- Undergone extensive 1D, 2D and 3D testing

Version 2.0: Cipolletta+2021

- Support for composition-dependent finite temperature EOS
- ZelmaniLeak neutrino leakage scheme Ott+2012
- Evolution equation of electron fraction
- 1D Palenzuela C2P scheme
- Higher order schemes: WENOZ with HLL4 and HLL6
- Publicly available on Zenodo: 10.5281/zenodo.4350072

adapted from slide by Jay Kalinani
Conservative-to-primitive recovery scheme \textit{RePrimAnd}

Scheme features: \textit{Kastaun+2021}

- Uses root-bracketing scheme
- Always converges to a unique solution (mathematical proof)
- Strong error policy: guarantees to find invalid evolved variables and applies harmless corrections, if necessary
- EOS-agnostic
- Publicly available code along with an EOS-framework on Zenodo: \textit{wokast/RePrimAnd}

Implementation in Spritz: \textit{Kalinani+2021}

- Integrated RePrimAnd library into Einstein Toolkit
- Added option in Spritz to use C2P from RePrimAnd
- Defines and enforces validity range for EOS
- Option to use different error policy within BHs
- Support for fully tabulated EOS underway

List of 3D tests:

- TOV star with internal magnetic field
- NS with external dipolar magnetic field
- Rotating magnetised NS
- Rotating magnetised NS collapse to BH
- Fishbone-Moncrief BH-accretion disk

adapted from slide by Jay Kalinani
Conservative-to-primitive recovery scheme *RePrimAnd*

**NS with extended dipolar field**

- **RePrimAnd**
  - $t = 0.0\,\text{ms}$
  - $t = 10.0\,\text{ms}$
- Magnetic field strength + field lines + density contours

**Fishbone-Moncrief BH-accretion disk**

- Rest-mass density
- Magnetic field strength

adapted from slide by Jay Kalinani
Using \textit{RePrimAnd} in BNS merger simulations

Kalinani+ in prep.

Aguilera-Miret+2020
Connecting with SGRB observations

BNS merger simulations limited to scales ~100ms/1000km

Disconnected from scales relevant for SGRB EM radiation (prompt & afterglow)

Need for models of jet propagation across the environment up to large scales

Incipient jet + environment

Propagation model

Final jet structure
Prompt & afterglow emission

Semi-analytical

Lazzati et al. 2020
Salafia et al. 2020
Hamidani & Ioka

2D/3D HD

Urrutia et al. 2020
Murguia-Berthier et al. 2021

3D GRMHD

Kathirgamaraju et al. 2019
Nathanail et al. 2020, 2021

Lazzati et al. 2018
Towards an end-to-end modelling

common limitation: incipient jet propagates across hand-made and simplified environment
- power-law density profile & homologous expansion or stationary wind
- spherical/axial symmetry

consistent description of BNS merger + jet production + jet propagation across the environment

final goal: constraining properties of the specific merging system via SGRB-related observations
Jet propagation in BNS merger environment

first 3D RHD jet simulations with environment imported from BNS simulation

simulation setup
- PLUTO code Mignone+2007, 2012
- full 3D spherical grid (log r spacing)
- excised region up to 380km radius
- redefinition of atmospheric floor $\rho_{atm} \propto 1/r^5$
- outer boundary 2.5e6 km
- TAUB EOS Mignone & McKinney 2005
- Gravitational pull from central object (2.596 Msun)

jet properties
- top-hat, 10 deg half-opening angle, lorentz factor 3
- luminosity 3e50 erg/s, decaying on 0.3 s timescale
Fiducial model

early evolution near the engine: jet breakout and widening

final outflow properties 1012 ms after merger

angular profiles at jet’s head

adapted from slides by Andrea Pavan
Impact of gravity

Gravity effect:
more turbulence and baryon loading

No gravity:
unperturbed collimation shock

No gravity:
more compact and axisymmetric jet’s head

Larger Lorentz factor
BNS merger vs. hand-made initial conditions

`\rho [\text{g/cm}^3]`

10^1  \quad 10^4

**fiducial**

`t = 232 \text{ ms}`

**spherical**

(delayed break-out time)

adapted from slides by Andrea Pavan
Dependence on collapse/jet launching time

- More collimation and axisymmetry
- Less expansion, lower Lorentz factor
- Delayed breakout time (~90 ms)

Factor ~3.6 more mass

More collimation and axisymmetry
Less expansion, lower Lorentz factor

adapted from slides by Andrea Pavan
Summary of Pavan+2021

- first 3D RHD jet simulations with environment imported from a BNS merger simulation
- simpler hand-made environments lead to significantly different results
- gravitational pull from central object needs to be included
- outcome may strongly depend on jet launching time
Summary of Pavan+2021

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Work in progress..

**short-term**
- inclusion of magnetic fields (RMHD)
- adaptive mesh refinement

**long-term**
- jet launched consistently in BNS merger simulation
- radiation transport for thermal and non-thermal photons
Take-home message

after GRB 170817A we know that BNS mergers can produce powerful relativistic jets

- GRMHD simulations: necessary tool to investigate launching mechanism and engine nature
- BH engine scenario favoured by current results, but without neutrino emission/absorption/annihilation

MAIN LIMITATION: unresolved MHD instabilities/turbulence

- new GRMHD code Spritz + new c2p scheme RePrimAnd
  ➔ now performing the first BNS merger simulations

- jet propagation and connection to prompt/afterglow SGRB observations so far “detached” from merger dynamics
  ➔ first 3D RHD jet simulations with imported BNS merger environment initial step towards end-to-end consistent description
References

- A. Pavan, R. Ciolfi, J.V. Kalinani, A. Mignone (2021), MNRAS 506, 3483
  *Short gamma-ray burst jet propagation in binary neutron star merger environments*

  *Magnetically driven baryon winds from binary neutron star merger remnants and the blue kilonova of August 2017*

  *Collimated outflows from long-lived binary neutron star merger remnants*

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

- 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*

- D. Lazzati, et al. (2018), PRL 120, 241103
  *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*

**Spritz and RePrimAnd**

- J.V. Kalinani, R. Ciolfi, W. Kastaun, et al. (2021), submitted
  *Implementing a new recovery scheme for primitive variables in...*

- W. Kastaun, J.V. Kalinani, R. Ciolfi (2021), PRD 103, 023018
  *Robust Recovery of Primitive Variables in Relativistic Ideal MHD*

- F. Cipolletta, et al. (2021), CQG 38, 085021
  *Spritz: General Relativistic Magnetohydrodynamics with Neutrinos*

- F. Cipolletta, et al. (2020), CQG 37, 135010
  *Spritz: a new fully general-relativistic magnetohydrodynamic code*

**Recent review articles**

  *Binary neutron star mergers after GW170817*

- R. Ciolfi (2020b), Gen. Rel. Grav. 52, 59
  *The key role of magnetic fields in BNS mergers*

- R. Ciolfi (2018), IJMPD 27, No. 13, 1842004
  *Short gamma-ray burst central engines*
BACKUP SLIDES
GRB 170817A: Canonical SGRB?

Lazzati+2018

special relativistic jet simulation

\[ L_j = 10^{50} \text{ erg/s}, \; \theta_j = 16^\circ, \; t_{\text{eng}} = 1 \text{ s} \]

\[ M_{\text{ej}} = 0.6 \times 10^{-2} \; M_\odot \]

multiwavelength afterglow calculation

\[ n_{\text{ISM}} \sim 4 \times 10^{-3} \; \text{cm}^{-3} \]

\[ \theta_{\text{obs}} \sim 33^\circ \]

**best fit**

an ordinary SGRB event observed off-axis? \( \rightarrow \) viable explanation!
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 → likely disk winds
   - 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\_sun
opacity ~0.5 cm\(^2\)/g (lanthanide-poor)

magnetically driven wind
from the massive NS?
(before its eventual collapse)

expected opacity fits the requirement
e.g. Perego+2014

magnetic enhancement of mass outflow
and acceleration to sufficiently high velocities

to be demonstrated!
Magnetically driven winds and blue KN

Ciolfi & Kalinani 2020

✓ ejecta velocity

~0.2 c marginally consistent with blue kilonova

possible further enhancement

✓ ejecta mass

$M_{ej, \text{wind}} \simeq 0.010 - 0.028 M_\odot$

to be compared with

$0.015 - 0.025 M_\odot$
post-merger outflow at 300km

- magnetically driven mass outflow takes time to emerge for significant contribution $\rightarrow$ NS remnant lifetime $> 50$ms
- mostly over at 200ms $\rightarrow$ slower neutrino driven wind could then take over and persist for longer time ($\sim 1$ sec)
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>$\Delta t_{\text{merge}}$ (s)</th>
<th>$\eta$ (s)</th>
<th>$\theta_{\text{l.o.s.}}$ (°)</th>
<th>$\theta_0$ (°)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulations; baseline ($Y_e = 0.5$; $\Gamma_{\text{l.o.s.}} \leq 7$; $m_w$ unconstrained)</td>
<td>$&lt; 0.36$</td>
<td>$&gt; 240$</td>
<td>$23.5^{+5.8}_{-4.5}$</td>
<td>$17.9^{+12.6}_{-3.2}$</td>
</tr>
<tr>
<td>Simulations; $\Gamma_{\text{l.o.s.}} \leq 7$</td>
<td>$&lt; 0.18$</td>
<td>$&gt; 240$</td>
<td>$24.6^{+4.1}_{-3.3}$</td>
<td>$18.4^{+1.2}_{-1.4}$</td>
</tr>
<tr>
<td>Simulations; $m_w \geq 10^{-2}$</td>
<td>$&lt; 0.37$</td>
<td>$&gt; 390$</td>
<td>$23.6^{+4.8}_{-4.5}$</td>
<td>$18.1^{+3.3}_{-1.8}$</td>
</tr>
<tr>
<td>Simulations; $\Gamma_{\text{l.o.s.}} \leq 7$; $m_w \geq 10^{-2}$</td>
<td>$&lt; 0.17$</td>
<td>$&gt; 250$</td>
<td>$24.1^{+5.2}_{-3.6}$</td>
<td>$19.3^{+1.9}_{-1.9}$</td>
</tr>
<tr>
<td>Simulations; $Y_e = 1.0$</td>
<td>$&lt; 0.27$</td>
<td>$&gt; 260$</td>
<td>$22.0^{+5.8}_{-3.3}$</td>
<td>$18.1^{+13.4}_{-3.1}$</td>
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<tr>
<td>Simulations; $Y_e = 0.2$</td>
<td>$&lt; 0.51$</td>
<td>$&gt; 170$</td>
<td>$25.1^{+5.0}_{-4.0}$</td>
<td>$15.8^{+13.2}_{-1.9}$</td>
</tr>
<tr>
<td>Parametric; baseline ($Y_e = 0.5$; $\Gamma_{\text{l.o.s.}} \leq 7$; $m_w$ unconstrained)</td>
<td>$&lt; 1.1$</td>
<td>$&gt; 150$</td>
<td>$30.3^{+8.0}_{-8.0}$</td>
<td>$10.2^{+3.8}_{-8.8}$</td>
</tr>
<tr>
<td>Parametric; $\Gamma_{\text{l.o.s.}} \leq 7$</td>
<td>$&lt; 0.87$</td>
<td>$&gt; 180$</td>
<td>$34.4^{+6.4}_{-8.6}$</td>
<td>$9.2^{+7.0}_{-1.8}$</td>
</tr>
<tr>
<td>Parametric; $m_w \geq 10^{-2}$</td>
<td>$&lt; 0.87$</td>
<td>$&gt; 420$</td>
<td>$27.5^{+6.0}_{-7.0}$</td>
<td>$16.2^{+11.3}_{-3.2}$</td>
</tr>
<tr>
<td>Parametric; $\Gamma_{\text{l.o.s.}} \leq 7$; $m_w \geq 10^{-2}$</td>
<td>$&lt; 0.57$</td>
<td>$&gt; 800$</td>
<td>$30.7^{+6.2}_{-8.0}$</td>
<td>$16.3^{+13.8}_{-2.0}$</td>
</tr>
<tr>
<td>Parametric; $Y_e = 1.0$</td>
<td>$&lt; 1.0$</td>
<td>$&gt; 170$</td>
<td>$32.3^{+6.4}_{-8.2}$</td>
<td>$9.6^{+4.0}_{-1.5}$</td>
</tr>
<tr>
<td>Parametric; $Y_e = 0.2$</td>
<td>$&lt; 1.2$</td>
<td>$&gt; 130$</td>
<td>$30.5^{+8.1}_{-4.8}$</td>
<td>$10.8^{+8.5}_{-4.6}$</td>
</tr>
</tbody>
</table>

jet launching time $< 0.4$ s