Magnetic Fields & NS Merger Disks

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NS Mergers

- Environments of:
  1. Mass Accretion
  2. Outflows (relativistic jets & disk winds)
  3. r-process nucleosynthesis

Image Credit: Paz Beniamini

Fernandez & Metzger 2015
Kasen et al. 2017
Alexander et al. 2018
Hajela et al. 2019
NS Mergers: GW 170817 / GRB 170917A

Abbott et al. 2017
Alexander et al. 2018
Hajela et al. 2019

Abbott et al. 2019 – I. Christie
What is required to reproduce a NS merger event?

Merger GWs

- sGRB: 0 s ~ 1 s
- Blue KN: ~days
- Red KN: ~wks
- Afterglow: ~yrs

Electron Fraction:

\[ Y_e = \frac{n_e}{n_B} \]

Fernandez & Metzger 2015
What is required to reproduce a NS merger event?

- GRB 170817A engine active for ~few seconds
  Requires simulation times of ~ 4 s (~ 2.5×10⁵ r_g / c)

- NS merger event prefers a predominantly toroidal post-merger magnetic field geometry
  Previous studies have shown that toroidal fields produce very weak jets and little outflows

- sGRBs characteristically have small opening angles (θ_j ~ 16° ± 10°):
  How can we obtain such tightly collimated jets with little mass (~ 0.1 M_☉)?
Simulation Setup

- Included neutrino cooling and nuclear recombination

- Longest running simulations to date, extending. $4.4 \rightarrow 9 \ s \sim 3 \rightarrow 6 \cdot 10^5 \frac{R_g}{c}$

- Variation only in the post-merger magnetic field geometry:
  i. Strong & Weak Poloidal Fields
  ii. Toroidal Field

Diagram of Magnetic Field Geometries

- $M_{BH} = 3 \ M_\odot$
- $a = 0.8$
- $M_{torus} = 0.033 \ M_\odot$
- $Y_e = 0.1$
Poloidal Geometries

- Initially starting with poloidal magnetic flux accretion and jet formation begin at earlier times

Fernandez et al. 2018
Christie et al. 2019
Toroidal Geometry

- Undergoes dynamo-like process for toroidal large-scale poloidal magnetic flux
- For the first time for initially toroidal fields, we have the production of jets!
Jet Power

- Initially poloidal fields produce powerful jets
- Toroidal fields produce weak and intermittent jets!

Christie et al. 2019

Post-Merger Geometry:
- Strong/Weak Poloidal
- Toroidal

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Toroidal Fields Lead to Striped Jets!

- Randomness in dynamo leads to alternating magnetic polarity on BH
- Production of current sheets on BH which propagate through the jet

Normalized Poloidal Magnetic Flux on BH

\[ \phi_{BH} \equiv \frac{\Phi_{BH}}{M_{\text{accr}} t_{g}^2 c^2} \]

Total Magnetic Flux
Northern Jet Flux

Christie et al. 2019
Toroidal Fields Lead to Striped Jets!

- Randomness in dynamo leads to alternating magnetic polarity on BH
- Production of current sheets on BH which propagate through the jet

Christie et al. 2019
(Image Credit: Nick Kaaz)

Simulation Snapshot of Current Density

Christie et al. 2019
(Image Credit: Nick Kaaz)
Toroidal Fields Lead to Striped Jets!

- Current sheets can potentially lead to dissipation and particle acceleration via magnetic reconnection.

*Simulation Snapshot of Current Density*

*Plasmoids Within Reconnection Layer*

*Petropoulou & Sironi, 2018*

*Christie et al. 2019*

(Image Credit: Nick Kaaz)
Isotropie Energy

Post-Merger Geometry:
- Strong/Weak Poloidal
- Toroidal

Jet Power

\[ (\times 10^{52} \text{ erg s}^{-1}) \]
\[ (\times 10^{51} \text{ erg s}^{-1}) \]
\[ (\times 10^{50} \text{ erg s}^{-1}) \]

Isotropic Energy

Christie et al. 2019
Isotropic Energy

Post-Merger Geometry: Strong/Weak Poloidal Toroidal

Isotropic Energy Equivalent for 38 sGRBs

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Christie et al. 2019

Fong et al. 2015

$E_{\gamma, \text{iso}}$

$E_{K, \text{iso}} (e_B = 0.1)$

$E_{K, \text{iso}} (e_B = 0.01)$

$1.3 \times 10^{52}$

$2.2 \times 10^{53}$

$3.6 \times 10^{52}$

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

$10^{51}$ $10^{52}$ $10^{53}$ $10^{54}$

$E_{\text{iso}}$ (erg)

$t$ (s)
Jet Opening Angle

Post-Merger Geometry:
Strong/Weak Poloidal Toroidal

Opening Angle of sGRBS

6.4° 13° 4.6°

Opening Angle of Northern Jet

\[ \langle \theta_j \rangle_{\text{all}} = 33_{-27}^{+38} \, (\theta_{\text{max}}=90°) \]

\[ \langle \theta_j \rangle_{\text{all}} = 16_{-10}^{+11} \, (\theta_{\text{max}}=30°) \]

\[ \langle \theta_j \rangle_{\text{meas}} = 6 \pm 1 \]

Christie et al. 2019
Fong et al. 2015

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Mass Accretion & Outflow Rate

Outflow Rate for All Geometries

\[ M_{\text{out}}(t) \propto t^{-2.3} \]

2000 \( r_g \approx 10^9 \) cm

Model | \( M_{\text{accr}} \) (10\(^{-2}\) \( M_\odot \)) | \( M_{\text{eject}} \) (10\(^{-2}\) \( M_\odot \))
--- | --- | ---
BPS | 60 | 2 | 40 | 1.3
BPW | 67 | 2.2 | 30 | 0.99
BT | 71 | 2.3 | 27 | 0.89

Post-Merger Geometry:
- Strong/Weak Poloidal
- Toroidal

Christie et al. 2019
From GW 170817/GRB 170817A, we can infer:

\[
M_{\text{red}} \approx 0.04 \, M_\odot
\]

\[
M_{\text{blue}} \approx 0.025 \, M_\odot
\]
Relativistic Ejecta: Velocity Distribution

Neutron-Rich Material

Electron-Rich Material

Post-Merger Geometry:
- Strong/Weak Poloidal
- Toroidal

Christie et al. 2019

GW 170817
How can we see the kilonova?

For all post-merger geometries:

i. Red material is spread along equatorial plane

ii. Blue material is confined within $\Delta \theta \sim 15 - 25^\circ$
Can we decipher the field geometry from afterglow?

Three GHz Light Curve for Strong-Poloidal Geometry

- The velocity and amount of outflows is sensitive to the post-merger geometry.
- Can we use long-term afterglow observations to constrain the geometry and parameter space?

Lalakos, Christie et al. in prep.
Summary

- Post-merger geometries drastically affect mass accretion, mass outflow, and jet power!
- Jet properties fall within sGRB observations but underpredict those of GW 170817
- Initially toroidal magnetic fields can produce striped jets!

Outlook

- Inclusion of more realistic initial conditions (e.g. neutrino physics)
- Future simulations to include dynamical ejecta

arXiv: 1907.02079
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Caveats (for now!)

- Improvement on the neutrino transport and include neutrino absorption
  - Could provide larger amount of blue material

- Realistic equation of state (e.g. Helmholtz EOS)
  - Change composition and velocities of outflows

- Inclusion of dynamical ejecta
  - Could provide large fraction of blue material
How Can Toroidal Fields Make Jets?

- Previous toroidal simulations showed little outflows and no jets (Beckwith et al. 2008, McKinney et al. 2012)

- A possible mechanism for jets w/o large-scale poloidal flux:
  \[ \alpha - \omega \text{ dynamo} \]
  
  i. \( \alpha \)-effect: poloidal \( \rightarrow \) toroidal via differential rotation
  ii. \( \omega \)-effect: toroidal \( \rightarrow \) poloidal via twisting of magnetic field lines

(Moffat 1978, Parker 1979)
How can we see the kilonova?

Evaluated at:
2000 $r_g \approx 10^9$ cm
$t \sim 0.8$ s

Strong-Poloidal Field
Weak-Poloidal Field
Toroidal Field

Christie et al. 2019
Are there any additional mechanisms worth exploring?

How do properties of outflows (e.g. mass accretion/ejection, composition) vary for increasing torus mass \((0.033 \, M_\odot \rightarrow 0.1 \, M_\odot)\)?

Can we pinpoint the dominant mechanisms for mass ejection? *MRI-driven turbulence or Nuclear Recombination*

Mass Outflow Rate: Strong Poloidal Geometry

\[ r_g \approx 10^9 \, cm \]

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Original
Larger Disk Mass
No Nuclear Recombination

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Christie et al., in prep. (2)
Siegel & Metzger 2017, 2018