Constraints on the binary NS merger remnant and outflow structure from EM counterparts of GW170817

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1. What do the **kilonova observations** and **delay between the GW chirp signal and prompt gamma-ray** onset tell us about the **merger remnant**?

2. Can we still use **initially** top-hat jet simulations to model afterglows?

3. Are there any **diagnostics** to help **understand the structure of the outflow** in future such events?

   a. **Flux-centroid motion**  
   b. **Image shape and size**  
   c. **Polarization**
BNS Merger Remnant
4 possible options

- Chirp mass from GW signal

\[ \mathcal{M} \equiv (M_1 M_2)^{3/5} (M_1 + M_2)^{-1/5} \]

\[ = 1.188^{+0.004}_{-0.002} M_\odot \]  

\[(\text{Abbott+17})\]

Maximum mass argument

- **GW 170817:** \[ M_{\text{tot}} = 2.74^{+0.04}_{-0.01} M_\odot \]

- Threshold for direct collapse to BH

\[ M_{\text{th}} \approx 1.415 M_{\text{TOV}} \approx 2.82 M_\odot \]

\[(\text{Bauswein+13, 17; Koppel+19})\]

- Max. mass supported by uniform rotation

\[ M_{\text{max}} = (1.20 \pm 0.02) M_{\text{TOV}} \approx 2.40 M_\odot \]

\[(\text{Breu & Rezzolla '16})\]

- Max. mass supported by differential rotation

\[ M_{\text{max,dr}} \approx (1.54 \pm 0.05) M_{\text{TOV}} \approx 3.08 M_\odot \]

\[(\text{Weih+18})\]

**Assuming:** \[ M_{\text{TOV}} = 2 M_\odot \]
Can it be a supra-massive magnetar?

- Supported by rigid-body rotation and collapses to a BH on the spin-down time.

\[ \tau_{sd} = \frac{I_C^3}{2f\Omega_0^2R_{NS}^6B_0^2} \gtrsim 3.4 \times 10^4 \frac{P_{0,-3}^2}{fB_{14}^2} \text{ s} \]

\[ E_{\text{rot}} = \frac{1}{2}I\Omega_0^2 \sim 10^{52.5} - 10^{53} \text{ erg} \]

- Energy injected by the spinning down NS in the form of an isotropic pulsar-type MHD wind would’ve powered an exceptionally bright afterglow.

- Early afterglow observations ruled out a supra-massive NS
  (e.g. Granot+17; Margalit & Metzger '17; Pooley+18)
Hypermassive NS (HMNS) and mass ejection

\[ M_{\text{ej,blue}} \approx 0.025 \, M_\odot \quad M_{\text{ej,red}} \ll 10^{-2} \, M_\odot \]
\[ \beta_{\text{max,blue}} \lesssim 0.3 \quad \beta_{\text{max,red}} \approx 0.1 \]

before collapse

(Gill, Nathanail, Rezzolla, ‘19; Kasen+17)

Different mass ejection channels and their rates

$M_{\text{tot, kn}}$ (kilonova) $M_{\text{dyn}}$ $M_{\nu, \text{HMNS}}$ $M_{B, \text{HMNS}}$ $M_{\text{tot, ej}}$ (simulations) $M_{\nu, \text{DISK}}$ $M_{B, \text{DISK}}$

$t_{\text{coll}} \simeq 1.14 \text{ s}$

(Gill, Nathanail, Rezzolla, 2019)
Collapse time of HMNS: $t_{\text{coll}} = 1.14^{+0.60}_{-0.50}$ s

(also see, e.g., Granot+17; Metzger+18)
The delayed GRB onset

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  \[ t_{\text{del}} = 1.74 \pm 0.05 \text{ s} \]
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- The delay time is a combination of three timescales:
  \[ t_{\text{del}} = t_{\text{coll}} + t_{\text{br}}(t_{\text{coll}}) + t_{R} \]

  \[ t_{R} = \frac{R_{\gamma}}{2\Gamma^2 c} = 0.5 \left( \frac{R_{\gamma}}{7.5 \times 10^{11} \text{ cm}} \right) \left( \frac{\Gamma}{5} \right)^{-2} \text{ s} \]

  \[ \Gamma \gtrsim 5 \quad \text{(from pair opacity - Matsumoto+19)} \]

(Gill, Nathanail, Rezzolla, 2019)
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- Jet breakout time depends on the properties of the jet and circum-merger (homologously expanding) ejecta:
  \[ \rho_{\text{ej}}(r < R_{\text{ej}}, t) \propto \frac{M_{\text{ej, blue}}(t)}{R_{\text{ej}}^{3}(t)} \left[ \frac{r}{R_{\text{ej}}(t)} \right]^{-k} \]
  \[ R_{\text{ej}}(t) = \beta_{\text{max}} c t \]
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• We inject a uniform jet and use the semi-analytic model of Bromberg+11 to calculate its breakout time.
HMNS collapse time from delayed GRB onset

$$t_{\text{coll}} = 0.82 \pm 0.15 \, \text{s}$$

$$t_{\text{del}} = 1.74 \pm 0.05 \, \text{s}$$

(Gill, Nathanail, Rezzolla, 2019)
HMNS collapse time

\[ t_{\text{coll}} = 0.98^{+0.31}_{-0.26} \text{ s} \]
Afterglow Emission
Long lasting rise of the afterglow

\[ S_\nu \propto \nu^{-0.6} t^{0.8} \]

(Mooley+2017)

(Margutti+2018)
The initially top-hat jet model failed at explaining the data at early times (e.g., Margutti+18; Mooley+18)

At early times, the model lightcurve rose much more sharply as compared to a shallower rise of the flux.

\[
\begin{align*}
\theta_i &= 5^\circ & E_{k,iso,52} &= 3 & \theta_{obs} &= 14^\circ & n_0 &= 10^{-4} & \varepsilon_B &= 10^{-4} & \varepsilon_e &= 10^{-1} \\
\theta_i &= 15^\circ & E_{k,iso,52} &= 3 & \theta_{obs} &= 24^\circ & n_0 &= 3 \times 10^{-4} & \varepsilon_B &= 3 \times 10^{-4} & \varepsilon_e &= 10^{-2}
\end{align*}
\]

\[\text{(Margutti+18)}\]
We conducted 2D hydro simulations of an initially top-hat jet with Blandford-McKee (1976) self-similar dynamics and derived the afterglow lightcurves by post-processing. (Gill, Granot, De Colle, Urrutia, 2019)

Angular time delay: \[
\frac{t_{\text{obs}, \theta}}{(1 + z)} = \frac{R_0}{c} \left[ 1 - \cos(\Delta \theta) \right] \approx \frac{\Delta \theta^2}{2} t_0 \propto \Gamma_0^{-2/(3 - k)}
\]
Off-axis emission from a structured jet

- Simulation of a jet emerging from non-relativistic NS-NS merger ejecta, giving the jet angular structure (Lazzati+18).

- Also see: Margutti+18; Xie+18
Four diagnostics of outflow structure
Semi-analytic lightcurves from structured jets / cocoons

Also see: Lamb & Kobayashi 18; Troja+18; Fraija & Veres+18; D’Avanzo+18; Troja+17,18; Resmi+18
Afterglow images

• Important properties of the outflow can be derived from afterglow images.

• $\theta_{\text{obs}} = 27^\circ$; assumes local spherical dynamics (no lateral spreading).

(Gill & Granot 18)
Theoretical and numerical works find that magnetic fields are generated by the two-stream / Weibel instability at the collisionless relativistic afterglow shock (Gruzinov & Waxman ’99, Medvedev & Loeb ’99, Silva+03, Frederiksen+04, ..)

- The generated field is randomly oriented in the plane transverse to the shock normal.
- Its coherence scale is much smaller than the width of the shock:

\[ \lambda_e = \frac{c}{\omega_p} \sim 2.3 \times 10^7 n_0^{-1/2} \text{ cm} \]

\[ \ll \Delta'_\text{sh} \sim R/\Gamma_{\text{sh}} \sim 10^{14} R_{15} \Gamma_{\text{sh}, 1}^{-1} \text{ cm} \]

- In general, postshock field can be anisotropic

\[ b = \frac{2\langle B^2 \rangle}{\langle B^2 \rangle} \]

- Many works use volume averaged value for \( b=0 \) and assume an infinitely thin shell.
Linear polarization can distinguish between outflow structure and provide insight into magnetic field structure.

Assume random B field:

\[ b = \frac{2\langle B^2 \parallel \rangle}{\langle B^2 \perp \rangle} \]

and infinitely thin shell geometry

Upper limit on linear polarization (Corsi+18)

\[ \Pi \lesssim 12\% \quad (99\% \text{ C. L.}) \]

show that for a structured jet

\[ 0.7 \lesssim b \lesssim 1.5 \]
Assuming the “frozen field” approximation, the radial structure of the magnetic field is
(Granot+99):
\[ B_\parallel(\chi) = B_{\parallel,f} \chi^{1/(8-2k)} \]
\[ B_\perp = B_{\perp,f} \chi^{-1} \]
\[ \chi = 1 + 2(4 - k)\Gamma_{sh}^2 \left( \frac{R - r}{R} \right) \]
(Similarity variable)

Downstream of the shock, the magnetic field becomes more radial:
\[ \xi(\chi) = \frac{B_\parallel(\chi)}{B_\perp(\xi)} = \xi_f \chi^{(7-2k)/(8-2k)} \] (Field anisotropy)
• We integrate over the shocked volume and assume a “frozen-field” approximation
• The field anisotropy just behind the shock is parameterized with $\xi_f$

![Graph showing polarization from volume integration of shocked region](image)

(Gill & Granot, in prep)
We integrate over the shocked volume and assume a “frozen-field” approximation.

The field anisotropy just behind the shock is parameterized with $\xi_f$.

\[ \text{Parameter mapping (Gill & Granot, in prep)} \]

\[ 0.6 \lesssim \xi_f \lesssim 0.9 \]
• Even if the image is unresolved at late times, the flux centroid can yield useful information about the outflow structure.

• Flux centroid motion has been measured from radio observations (Mooley+18):

\[ \theta_{fc} = 2.7 \pm 0.3 \text{ mas} \quad (75 \text{ d} - 230 \text{ d}) \]

• Apparent superluminal motion

\[ v_{app} = (4.1 \pm 0.5)c \]
The mean image size may not be a good discriminator between models.

Structured jets show a larger axial ratio as compared to quasi-spherical outflow models.
Conclusions

- The total mass of the remnant and kilonova observations suggest that the remnant was a hypermassive NS. The total mass of the blue kilonova ejecta and the delay between the GW chirp signal and the prompt gamma-ray onset suggest that the HMNS survived for about 1 s.

- An initially top-hat jet can explain the afterglow lightcurve and image properties near and after the lightcurve peak when the core of the jet is visible to an off-axis observer.

- Semi-analytic models of structured flows are a useful tool to understand the afterglow lightcurve and image properties. However, improved analytic approaches are needed to capture the dynamics of the flow in the trans-relativistic regime.

- The shallow rise in the afterglow of GRB 170817 before the lightcurve peak (~150 d) can be explained by both a wide-angle quasi-spherical flow and a structured jet. The differences between the two models become apparent after the lightcurve peak.

- The three diagnostics – linear polarization, flux centroid motion, and image size & axial ratio will be useful in distinguishing the properties of the flow in future events.

- Linear polarization upper limit of 12% for GW170817 can be used to constrain the anisotropic structure of the postshock magnetic field.