Lessons from GW170817 / GRB170817A

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Exploring the Universe: Near Earth Space Science to Extra-Galactic Astronomy (tribute to S. N. Bose’s 125th birth anniv.); Kolkata, 15 Nov. 2018
Outline of the Talk:

- The dawn of a new Era: Gravitational-Wave Astronomy
- The Extraordinary event GW170817/GRB170817A
- The merger remnant: Black Hole or a massive NS?

The afterglow emission:
- Two main options for the early flux rise: \( r \) vs. \( \theta \) dependence
- Breaking the degeneracy: lightcurves? Images, Polarization
- New observations imply: dominant \( \theta \) dependence (off-axis jet)

Conclusions
Gravitational Wave Astronomy:

- Einstein predicted Gravitational Waves in 1916
- 1st indirect evidence: Hulse-Taylor binary pulsar (1974; ⇒1993 Nobel prize)
- 1st direct detection: LIGO detected a BH-BH merger, GW150914; announced 11 Feb. 2016 ⇒ 2017 Nobel prize

The Nobel Prize in Physics 2017

- Rainer Weiss
  Prize share: 1/2
  Photo: Bryce Vickmark

- Barry C. Barish
  Prize share: 1/4
  Photo: Caltech

- Kip S. Thorne
  Prize share: 1/4
  Photo: Caltech Alumni Association

The Nobel Prize in Physics 2017 was divided, one half awarded to Rainer Weiss, the other half jointly to Barry C. Barish and Kip S. Thorne “for decisive contributions to the LIGO detector and the observation of gravitational waves.”
Gravitational Wave Astronomy:

- **Einstein predicted** Gravitational Waves in 1916
- **1st indirect evidence:** Hulse-Taylor binary pulsar (1974; 1993 Nobel prize)
- **1st direct detection:** LIGO detected a BH-BH merger, GW150914; announced 11 Feb. 2016 2017 Nobel prize
- **5 BH-BH mergers** detected so far, but no EM counterpart
GW 170817 / GRB 170817A:

- First GW detection of a NS-NS merger
- First electromagnetic counterpart to a GW event
  - The short GRB 170817A (very under-luminous, 1.74 s $\gamma$-GW delay)
  - Optical (IR to UV) kilonova emission over a few weeks
  - X-ray (> 9 d) to radio (>16 d) afterglow (still detected)
- First direct association of a sGRB & NS-NS merger* (Eichler+ 1989; Narayan+ 1992)
- First clear-cut kilonova

*(Abbott et al. 2017)
GW 170817 / GRB 170817A:

(Margutti et al. 2018)
GW 170817: distance and host galaxy

- Distance from the GW signal: $D_{GW} = 43.8^{+2.9}_{-6.9}$ Mpc
- Elliptical host galaxy: NGC 4993 at $D = 41.0 \pm 3.1$ Mpc
  (Hjorth+17; $z=0.009783$; located 2 kpc in projection from its center)
GW 170817: the associated kilonova

- The observations require **two components:**
  - blue/fast, lanthanide-poor $M_{\text{ej}} \sim 1–2\% M_\odot$, $v_{\text{ej}} \sim 0.2–0.3c$
  - red/slow, lanthanide-rich $M_{\text{ej}} \sim 3–5\% M_\odot$, $v_{\text{ej}} \sim 0.05–0.2c$
- Synthesized large amounts of heavy elements
  (may dominate the cosmic r-process nucleosynthesis)

![Images showing different scenarios of neutron star interactions](image1.png, image2.png, image3.png)
GW 170817: the type of remnant

- $M_{1,2} = \text{pre-merger NS } M_{\text{gravitational}}$
- post-merger total mass: $M_i = M_1 + M_2$
- Final mass $M_f \approx 0.93 M_i$ due to:
  - GW & neutrino energy losses
  - Mass ejection during the merger

Chirp mass: $\mathcal{M} = \left( \frac{M_1^3 M_2^3}{M_1 + M_2} \right)^{1/5} = 1.188^{+0.004}_{-0.002} M_\odot$ (Abbott+ 2017)
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- A stable NS or SMNS $\Rightarrow P_0 \approx 1$ ms
  $\Rightarrow E_{\text{rot}} \geq 10^{52.5}$ erg, $\tau_{\text{sd}} \approx 20 B_{13}^{-2}$ days
  $\Rightarrow$ would contradict afterglow obs.

- The argument can be reversed to constrain NS EoS & $M_{\text{max}} \leq 2.17M_\odot$
  (also what produces the GRB/afterglow?)

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  (Abbott+ 2017)

(Margutti+18)
GRB 170817A: afterglow observations

$F_v \propto \nu^{-0.61} t^{0.78 \pm 0.05}$

(Mooley et al. 2018)
GRB 170817A: afterglow observations

$$F_v \propto \nu^{-0.61} t^{0.78 \pm 0.05}$$

A rise lasting > 100 days is very unusual!!!

(Mooley et al. 2018)
Analogy to rising $F_v$: X-ray Plateaus

- Possible solutions:
  - Evolution of shock microphysical parameters (JG, Konigl & Piran 2006)
  - Energy injection into ext. shock:
    1. long-lived relativistic wind
    2. slower ejecta catching up (Sari & Meszaros 00; Nousek+ 06; JG & Kumar 06)

- Viewing angle effects

Energy injection into the afterglow shock

1 $\leq a \leq 2.5$ (ISM)

$a \geq 5$ (wind)

$\gamma \sim 3$ (JG, Ramirez-Ruiz & Perna 2005)
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Viewing angle effects (angular)

Energy injection into the afterglow shock:
- $1 \leq a \leq 2.5$ (ISM)
- $a \geq 5$ (wind)

(Vaughan et al. 2006)

Post-jet break
- flat part
- rapid decay $t^{0-1}$
- "usual" decay $t^{1-1.5}$
- $\sim 10^{2.5}$ s
- $\sim 10^4$ s

Energy injection into the afterglow shock

(JG & Kumar 2006)

Radial

Energy injection into the afterglow shock

(JG, Ramirez-Ruiz & Perna 2005)
Off-Axis Afterglow Lightcurves

- The emission is initially strongly beamed away from our L.o.S
- \( F_v \) rises as beaming cone widens
- When beaming cone reaches LoS, \( F_v \) peaks & approaches on-axis \( F_v \)
- The rise is much more gradual for hydrodynamic simulations due to slower matter at the jet’s sides with non-radial velocities

(JG et al. 2001)

(JG, Ramirez-Ruiz & Perna 2005)
GRB170817 outflow structure: prompt, afterglow

- Cocoon model (Kasliwal+17; Mooley+18; Nakar & Piran 18): $r$ & $\theta$ profile

- Cocoon-driven shock breakout can naturally produce the $\gamma$-rays (Kasliwal+17; Gottlieb+17; Bromberg+18; Nakar & Piran 18; Nakar+18)

![Graph showing radio data and cocoon model predictions](image-url)

Radio data (3 GHz)
- $\beta_{\text{max}}=0.8$, $E(\beta \gamma)=5 \times 10^{50} (\beta \gamma/0.4)^{-5}$, $n=0.03 \text{ cm}^{-3}$, $\varepsilon_B=0.003$
- $\gamma_{\text{max}}=3.5$, $E(\beta \gamma)=2 \times 10^{51} (\beta \gamma)^{-5}$, $n=8 \times 10^{-5} \text{ cm}^{-3}$, $\varepsilon_B=0.01$
- Cocoon model from Gottlieb et al. 2017 (radial + angular profile)

(Mooley, Nakar, Hotokezaka, et al. 2018)
GRB170817 outflow structure: the afterglow

- **A structured jet explanation** (Lazzati+17; Margutti+18; Gill & JG 18;...):
  - Simulation of jet breaking out of the Newtonian ejecta near a NS-NS merger site: the *cocoon* energizes the jet’s sides/wings
  - Afterglow dominated by $\theta$ profile

(Lazzati et al. 2018)
**Outflow structure: breaking the degeneracy** (Gill & JG 18)

- The lightcurves leave a lot of degeneracy between models
- The degeneracy may be lifted by calculating the afterglow images & polarization (e.g. Nakar & Piran 2018; Nakar et al. 2018)
- We considered 4 different models including both main types
  - **Sph+ Ej**: Spherical with energy injection $E(>u=\Gamma \beta) \propto u^{-6}$, $1.5 < u < 4$
  - **QSph+ Ej**: Quasi-Spherical + energy injection $E(>u) \propto u^{-s}$, $u_{\text{min},0} = 1.8$, $u_{\text{max},0} = 4$, $s = 5.5$, $\zeta = 0.1$

\[
\frac{\epsilon(\theta)}{\epsilon_0} = \frac{u_{\text{min},0}(\theta)}{u_{\text{min},0}} = \frac{u_{\text{max},0}(\theta)}{u_{\text{max},0}} = \frac{\zeta + \cos^2 \theta}{\zeta + 1}
\]

\[
E(>u) \propto \Gamma \beta_0 u^{-s}
\]

\[
E_{k, \text{iso}} = 10^{50.47} \text{ erg}
\]

\[
u_0 = 10^{-3} \text{ cm}^{-3}
\]

\[
u_{0, \text{min}} = 1.5
\]

\[
u_{0, \text{max}} = 4
\]

\[
s = 6
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- We considered 4 different models including both main types
  - GJ: Gaussian Jet (in $\varepsilon = \frac{dE}{d\Omega}$, $\Gamma_0 - 1$) $\Gamma_c = 600$, $\theta_c = 4.7^\circ$
  - PLJ: Power-Law Jet; $\varepsilon = \varepsilon_c \Theta^{-a}$, $\Gamma_0 - 1 = (\Gamma_c - 1) \Theta^{-b}$, $\Theta = [1+(\theta/\theta_c)^2]^{1/2}$
    $\Gamma_c = 100$, $\theta_c = 5^\circ$, $a = 4.5$, $b = 2.5$
  - As there is a lot of freedom we fixed: $p = 2.16$, $\varepsilon_B = n_0 = 10^{-3}$, $\theta_{\text{obs}} = 27^\circ$
The outflow structure: breaking the degeneracy

- Tentative fit to GRB170817A afterglow data (radio to X-ray)
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The outflow structure: breaking the degeneracy

- New data that came out established a peak at $t_p \sim 150$ days
- The jet models decay faster (slightly preferred by the latest data)

Decay: $\sim t^{-2.2}$
(Mooley+18)
Afterglow Images: $\text{Sph} + E_{\text{inj}}$
Afterglow Images: QSph + $E_{\text{inj}}$

Jet symmetry axis

$\theta_{\text{obs}}$

Direction to observer

$\tilde{x}, \tilde{y}, y$

$\tilde{x}$

$\tilde{y}$

$\theta_{\text{obs}}$

$t = 300 \text{ days}$

$t = 10^3 \text{ days}$

$t = 10^4 \text{ days}$

$t = 10^5 \text{ days}$

$\theta_{\tilde{y}} [\text{mas}]$

$\theta_{\tilde{x}} [\text{mas}]$

$\theta_{\tilde{y}}$

$\theta_{\tilde{x}}$

Log$_{10}(I_\nu/\langle I_\nu \rangle)$

\[ -0.5 \quad 0 \quad 0.5 \quad 1.0 \]
Afterglow Images: GJ, PLJ
Linear Polarization

Assuming a shock-produce B-field with \( b \equiv 2\langle B^2_\parallel/\langle B^2_\perp \rangle \)
Linear Polarization

- Assuming a shock-produce B-field with $b \equiv 2\langle B^2_\parallel \rangle/\langle B^2_\perp \rangle$

\[ 0.7 \leq b \leq 1.5 \text{ for jet models} \]

\[ \theta_{\text{min}}(t) = \theta_c \]

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New: upper limit on linear pol. @ 2.8 GHz (Corsi + 2018)
Afterglow Images: **flux centroid, size, shape**

- The flux centroid motion: a potentially powerful diagnostic
- It may be hard to tell apart models based on the image size alone, but a much higher axis-ratio is expected for jet models
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(Mooley et al. 2018)
Afterglow Images: uniform jet simulations
(JG, De Colle & Remirez-Ruiz 2018)
Conclusions:

- GW170817/GRB170817A is a unique event with a wide range of implications
- First secure association of a sGRB with a NS-NS merger, but the sGRB is atypical (its afterglow, very low $E_{\gamma,\text{iso}}$)
- Merger Remnant: BH or HMNS $\rightarrow$ BH $\Rightarrow M_{\text{max}} \leq 2.17 M_\odot$
- Two main types of explanations for the rising afterglow flux energy distribution with proper velocity ($r$) or with angle ($\theta$)
- Possible diagnostics to distinguish between them
  - The post-peak flux decay slope
  - Flux centroid motion or image axis ratio
    (challenging with image size or polarization alone)
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- Possible diagnostics to distinguish between them:
  - The post-peak flux decay slope.
  - Flux centroid motion or image axis ratio (challenging with image size or polarization alone).
- New flux centroid motion observations: $\beta_{\text{app}} = 4.1 \pm 0.5$. 