Recent results on jets inferred properties

Tsivi Piran
The Hebrew University, Jerusalem
and
Ehud Nakar

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GW170817 - the second multimessenger event

This was not a regular sGRB viewed off axis (Matsumoto, Nakar, TP, 19a,b)

See Nakar 2019 for an excellent review on all aspects of 170817
The Initial Phase

$\theta_{\text{obs}} = 69^\circ$

$\text{Massive core ejecta}$

$t = 0.00 \text{ s}$

Credit: Ore Gottlieb
The Initial Phase

\[ \theta_{\text{obs}} = 20^\circ \]

Earth viewing angle
GW 170817 Afterglow

From Troja + 2020
Viewing angle estimates

\[ \Theta_{\text{obs}} \]

- Lazzati et al. 19
- Ryan et al. 19
- Hajela et al. 19
- Wu & MacFadyen 19
- Troja et al. 19
- Lamb et al. 19
- Lamb et al. 19
- Hotokezaka et al. 19
- Hotokezaka et al. 19
- Ghirlanda et al. 19
Afterglow modeling

The Blast wave (Blandford McKee 76)

\( E \) - Energy
\( n \) - external density
\( \Gamma \) - the Lorentz factor
Synchrotron Radiation

The shock accelerate electrons and generates magnetic fields

$\varepsilon_e$ - electrons’ equipartition parameter

$p$ - electrons’ distribution power law index

$n(\gamma) \propto \gamma^{-p}$

$\varepsilon_B$ - magnetic equipartition parameter

Sari, TP, Narayan 98
Jet Break (Sari + 99)

Figure 2: Optical and infrared light curves of the transient afterglow of GRB990123 from 4 hours to 23 days after the burst.

$\Gamma \approx 1/\theta_j$

Kulkarni + 99
Jets dynamics

Van Eerten + 2018

Granot + 2001
Orphan Afterglow

Can we estimate the viewing angle from the afterglow peak?
Orphan afterglow light curve

\[ t_p \propto \left( \frac{E}{n} \right)^{1/3} \left( \theta_{\text{obs}} - \theta_j \right)^2 \propto \frac{l}{\Gamma^2 c} \]

\[ F_{\nu,p} \propto \left[ E n^{p+1} e_e^{p-1} e_B^{p+1} \theta_j^{-2p} \right] \nu^{-\frac{p-1}{2}} D^{-2} \left( \frac{\theta_{\text{obs}}}{\theta_j} \right)^{-2p} \]

\( \nu \) - observed frequency
\( F_{\nu} \) - observed flux
\( t_p \) - peak time
\( E \) - Energy
\( N \) - external density
\( \varepsilon_e \) - electrons’ equipartition parameter
\( p \) - electrons’ distribution power law index
\( \varepsilon_B \) - magnetic equipartition parameter
\( D \) - distance

Nakar + 2003; Nakar, Tp 2020
Numerical Examples
Viewing angle estimates
Unnoticed Degeneracy at work (e.g. Hajela 2019)

\[ Y_B \propto 1/\theta_j \]
Breaking the symmetry
Centroid motion
Superluminal Motion

\[ \nu \approx c\Gamma \approx c/\theta_{\text{obs}} \]
$\langle h \rangle = 1 \times 10^{-23} m_T^{2/3} \mu f_{100}^2 r_{100}^{-1}$

frequency will change on a timescale

$\tau = f/\dot{f} = 7.8 m_T^{-2/3} \mu^{-1} f_{100}^{-8/3} \text{s}$

$r_{100} = 7.8 f_{100}^{-2} (\langle h_{23} \rangle \tau)^{-1}$

H$_0$ from GW (Schutz, 1986)
The viewing angle

\[ h_+ = \frac{2M_z^{5/3} (\pi f(t))^{2/3}}{D_L} \left[ 1 + \cos^2(\theta) \right] \propto \cos(\theta) \]

\[ h_\times = \frac{4M_z^{5/3} (\pi f(t))^{2/3} \cos(\theta)}{D_L} \propto \cos(\theta) \]

\[ r_{\text{100}} = 7.8f_{\text{100}}^{-2}(\langle h_{\text{23}} \rangle \tau)^{-1}f(\theta) \]
$H_0$ from GW 170817 (Abbott + 17)

$\theta < 40^\circ$
With centroid motion (Hotokezaka + 18)

\[ v \approx 3 - 4c = \Rightarrow \Gamma \approx 3 - 4 = \Rightarrow \theta \approx 0.25 - 0.33 \]


$H_0$

- Abbott+ 2017 15% error in $H_0$
- Hotokezaka + 2018 7% error in $H_0$
Errors in $H_0$

- Distance estimate. $D \propto \cos(\theta)/D$

- The viewing angle $\delta \cos(\theta) \approx \theta \delta \theta$

- GW amplitude $\delta h/h \approx (S/N)^{-1} \propto D$

- Proper motion (determination of $v$) $\delta v \propto v_p/v \propto 1/D$

=> Need intermediate distance merger.

GW 170817 was almost at optimal distance
Error budget in GW 170817

- Abbott + 15%  \( (\delta \theta \approx 15\% - \text{dominated by viewing angle error}) \)
- Hotokezaka + 7%  \( (\delta \theta \approx 2\% ; \ \delta v_p \approx 6\% ; \ \delta h \approx 5\% ) \)
Future Samples

• To get to 1% error we need either
  • > 200 low quality events $1\% = 15\% / \sqrt{N_{\text{low}}}$
  • > 16 high quality events $1\% = 4\% / \sqrt{N_{\text{high}}}$

• Concerns about systematics

O3 rates => measurements $H_0$ with GW from BNS mergers are unlikely to resolve the $H_0$ tension in the near future.
Conclusions

• There is a degeneracy in the afterglow light curve between the observing angle and the width of the jet that produced the emission.

• Light curve along is insufficient to determine the observing angle or any other parameter of the jet.

• Observing angle can be determined from higher quality data beyond just the light curve.

• This limits “high quality” mergers to be “local” limiting their rate regardless of the GW detectors sensitivity.

• Still a small number of “high” quality events can supersede in the final results the larger number of “low” quality events.