Gamma-ray burst afterglow jet analysis in the multi-messenger era

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October 21 2019
Gamma-ray bursts, the global picture

Assuming...
- ...the engine to be a black hole and not a magnetar
- ...the prompt emission to be colliding shells and not e.g. photospheric or reconnection
- ...the jet makes it out, and does not have a radically different profile from shown above
general GRB progress: GRB prompt emission

GRB prompt peak energy (normalized from 561 keV)

Standard paradigm: optically thin synchrotron

Data, using various reconstructions

Over 90% of GRBs are too sharp for optically thin synchrotron standard model!

Yu, van Eerten+ 2015, A&A 583, A129

On the other hand... synchrotron is not that bad a fit even for sharp spectra

Burgess 2019 A&A 629, A69

(but extremely steep electron power laws \( p \gg 2 \))
The "reverse shock" (RS)  

Lateral structure imposed during launching

van der Horst, van Eerten & Fong, ‘observations & theory of gamma-ray burst jets’, New Astronomy Reviews, in prep
van der Horst, van Eerten & Fong, ‘observations & theory of gamma-ray burst jets’, New Astronomy Reviews, in prep

What was usually considered for afterglow modeling and long-term afterglow simulations
We rely on *afterglow* for information.

images from:
van der Horst, van Eerten & Fong
‘observations & theory of gamma-ray burst jets’
New Astronomy Reviews, in prep
GRB afterglow models & closure relations

Theoretical models predict temporal decay slope and spectral shape. Example:
- time: forward shock in homogeneous interstellar medium, no jet structure, relativistic limit
- frequency: slow-cooling synchrotron spectrum above particle injection break
- $p \sim 2.2$ is the power-law slope of the non-thermal electron population $n_e \propto \gamma_e^{-p}$ in energy

Example closure relation: $F_v \propto t^{-\alpha} \nu^{-\beta} \rightarrow 3\beta/2$
general GRB progress: Early jet stages, including breakout also applied to NS mergers

Bromberg+ 2011
Mizuta & Aloy 2009
Zhang & MacFadyen 2006
Nagakura+2014
general GRB progress: An emergent continuum of ejecta velocities

which makes them akin to phenomena like supernovae and tidal disruption events

sample study showing a continuum of supernova and GRB ejecta energies and velocities (circles) (Margutti+ 2014)
general GRB progress: accruing measurements of extremely fast Lorentz factors

\[ \Gamma_0 = 103.36^{+10.27}_{-8.19} \]

Initial ejecta Lorentz factor obtained from reverse shock analysis (Laskar, van Eerten+, 2019 ApJ 884, 121)

A sample of initial Lorentz factors, obtained by various means (Racusin+ 2011)
Reverse shock Lorentz factor estimate

Thanks to early ALMA observations

170817: Start of multi-messenger era for GRBs


Ryan, van Eerten, Piro & Troja 2019, ArXiv 1909:11691
personal 170817 Afterglow timeline

Troja, Piro, van Eerten+ 2017, X-ray discovery Nature paper also proposing a structured jet

Troja, Piro, Ryan, van Eerten+ 2018
- Bayesian comparison spherical cocoon / successful jet models
- prediction steep decay for successful jet model
- analysis including prior directly from GW data

Troja, van Eerten+ 2018 steep decay falsifies choked jet
Broadband GRB data

perform a power-law fit to data points. Interpret using closure relations

First devise a model for a direct fit do do

Semi-analytical model

Basic analytical model (closure relations)

Solve PDE’s decelerating & spreading blast wave

Frequentist fit

Bayesian fit

Frequentist fit

Bayesian fit

Frequentist fit

Bayesian fit

Frequentist fit

Bayesian fit

Build a spectrum template database

Bayesian fit

Bayesian fit

Massive computer simulation jet flow

One or more bespoke simulations

Build a jet simulation template database

Modeling of afterglows
The Scalefit approach (van Eerten & MacFadyen 2012; Ryan, van Eerten+ 2015)

- Broadband GRB data
- Perform a power-law fit to data points. Interpret using closure relations
- First devise a model for a direct fit do data

Basic analytical model
- Semi-analytical model (closure relations)

Solve PDE's decelerating & spreading blast wave
- Solution PDE's deaccelerating & spreading blast wave

Massive computer simulation jet flow
- Build a jet simulation template database

One or more bespoke simulations

- Frequentist fit
- Bayesian fit

Frequentist fit using repeated radiative transfer
- Build a spectrum template database

Bayesian fit using repeated radiative transfer

Modeling of afterglows

Bayesian fit
5th order WENO, adaptive-mesh refinement, parallel RHD simulation -> \(\sim\)500 GB data
17 levels of refinement, effective resolution of \(10^7\) cells

**SPREADING IS ACTUALLY VERY SLOW**
light curve scale invariance

- compute synchrotron spectrum templates for different jet opening angles and orientations
- Rescale between explosion energies, surrounding densities and synchrotron microphysics model parameters, using dimensional analysis
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All jet numerical simulations show jets get launched with structure.

Long GRBs form additional ‘cocoon’ structure due to interaction with stellar envelope.

Short GRBs potentially form additional ‘cocoon’ structure if sufficient neutron star debris in the launch path (Nagakura 2014, Murguia-Berthier+ 2014)

Ryan, van Eerten+ 2019 (ArXiv 1909.11691)
Our Post-170817 GRB modeling toolkit (Ryan, van Eerten+, ArXiv 1909.11691)

- Broadband GRB data
  - perform a power-law fit to data points. Interpret using closure relations
  - First devise a model for a direct fit do data

- Semi-analytical model
  - Basic analytical model (closure relations)
  - Solve PDE’s decelerating & spreading blast wave
  - Massive computer simulation jet flow
  - Massive computer simulation jet flow
  - One or more bespoke simulations

- Build a jet simulation template database
- Build a spectrum template database

- Frequentist fit
  - Bayesian fit
  - Frequentist fit
  - Bayesian fit
  - Bayesian fit
  - Bayesian fit

modeling of afterglows

- frequentist fit
  - Bayesian fit
initial structure was always there, but only key feature for off-axis observers

\[ \theta_{\text{obs}} = 0.00 \text{ rad} \]

\[ \theta_{\text{obs}} = 0.16 \text{ rad} \]

\[ \theta_{\text{obs}} = 0.32 \text{ rad} \]

\[ \theta_{\text{obs}} = 0.48 \text{ rad} \]


(this is not news: Rossi+ 2002, Dalal 2002, Granot & Kumar 2003, etc...)
Numerical model – afterglowpy
Ryan, van Eerten+ 2019 (ArXiv 1909.11691)

▸ Python interface to a fast C integrator, can drive MCMC.
▸ Evolves jets semi-numerically from ultra-relativistic to Newtonian phases
▸ Includes jet spreading, refreshed shock material, energy injection
▸ Publicly available software tools!

afterglowpy (install with pip)
https://github/com/geoffryan/afterglowpy
some details of the semi-analytical model

\[
\dot{R} = \frac{4u\gamma}{4u^2 + 3}c
\]

shock radius using jump conditions

\[
E = (\gamma - 1)M_{ej}c^2 + \frac{4\pi}{9} \rho_0 c^2 R^3 (4u^2 + 3)\beta^2 f_\Omega
\]

\[
f_\Omega = 2\sin^2 \left(\frac{\theta_j}{2}\right).
\]

Energy conservation

\[
\beta_\perp = \sqrt{\frac{2u^2 + 3}{4u^2 + 3} \frac{\dot{R}}{2\gamma c}}
\]

a lateral spreading sound wave
(truth lies in between sound wave and light speed)

\[
\dot{\theta}_j = \begin{cases} 
0 & \text{if } u > 1/(3\sqrt{2}\theta_c) \\
\beta_\perp c/R & \text{otherwise}
\end{cases}
\]

novel features: fully structured jet evolving from extremely relativistic to non-relativistic using a trans-relativistic equation of state and spreading approximation tuned to simulations

MCMC fit to 170817

Gaussian jet case
Ryan, van Eerten+ 2019 ArXiv 1909.11691
### Parameter inferences

Table 3. Parameter estimation priors and marginalized posteriors for the GW170817A afterglow using the afterglowpy Gaussian and power law jet models, including viewing angle constraints from LIGO assuming the Planck value of $H_0$. Given posterior values for each model are the median, 16%, and 84% quantiles. Parameters in the lower section are derived from the posterior distributions of the fit parameters in the upper sections.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Unit</th>
<th>Prior Form</th>
<th>Bounds</th>
<th>Gaussian Jet Posterior</th>
<th>Power Law Jet Posterior</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\theta_{\text{obs}}$</td>
<td>rad</td>
<td>$\sin \theta_{\text{obs}} \times p_{\text{LIGO}}(\cos \theta_{\text{obs}})$</td>
<td>$[0, 0.8]$</td>
<td>$0.40^{+0.11}_{-0.11}$</td>
<td>$0.44^{+0.12}_{-0.12}$</td>
</tr>
<tr>
<td>$\log_{10} E_0$</td>
<td>erg</td>
<td>uniform</td>
<td>$[45, 57]$</td>
<td>$52.96^{+0.97}_{-0.72}$</td>
<td>$52.93^{+1.1}_{-0.75}$</td>
</tr>
<tr>
<td>$\theta_c$</td>
<td>rad</td>
<td>uniform</td>
<td>$[0.01, \pi/2]$</td>
<td>$0.066^{+0.018}_{-0.018}$</td>
<td>$0.046^{+0.013}_{-0.013}$</td>
</tr>
<tr>
<td>$\theta_w$</td>
<td>rad</td>
<td>uniform</td>
<td>$[0.01, 12\theta_c]$</td>
<td>$0.47^{+0.26}_{-0.19}$</td>
<td>$0.238^{+0.071}_{-0.069}$</td>
</tr>
<tr>
<td>$b$</td>
<td>—</td>
<td>uniform</td>
<td>$[0, 10]$</td>
<td>—</td>
<td>$9.03^{+0.70}_{-1.1}$</td>
</tr>
<tr>
<td>$\log_{10} n_0$</td>
<td>cm$^{-3}$</td>
<td>uniform</td>
<td>$[-10, 10]$</td>
<td>$-2.70^{+0.95}_{-1.0}$</td>
<td>$-2.6^{+1.1}_{-1.1}$</td>
</tr>
<tr>
<td>$p$</td>
<td>—</td>
<td>uniform</td>
<td>$[2, 5]$</td>
<td>$2.168^{+0.063}_{-0.0075}$</td>
<td>$2.1653^{+0.0085}_{-0.010}$</td>
</tr>
<tr>
<td>$\log_{10} \varepsilon_e$</td>
<td>—</td>
<td>uniform</td>
<td>$[-5, 0]$</td>
<td>$-1.42^{+0.70}_{-1.1}$</td>
<td>$-1.24^{+0.73}_{-1.2}$</td>
</tr>
<tr>
<td>$\log_{10} \varepsilon_B$</td>
<td>—</td>
<td>uniform</td>
<td>$[-5, 0]$</td>
<td>$-3.96^{+1.1}_{-0.74}$</td>
<td>$-3.76^{+1.1}_{-0.87}$</td>
</tr>
<tr>
<td>$\log_{10} E_{\text{tot}}$</td>
<td>erg</td>
<td>—</td>
<td>—</td>
<td>$50.57^{+0.92}_{-0.66}$</td>
<td>$50.46^{+1.1}_{-0.73}$</td>
</tr>
<tr>
<td>$\theta_{\text{obs}}/\theta_c$</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>$6.12^{+0.18}_{-0.18}$</td>
<td>$9.38^{+0.73}_{-0.56}$</td>
</tr>
<tr>
<td>$\log_{10} E_0/n_0$</td>
<td>erg cm$^3$</td>
<td>—</td>
<td>—</td>
<td>$55.69^{+1.1}_{-0.85}$</td>
<td>$55.62^{+1.2}_{-0.83}$</td>
</tr>
</tbody>
</table>

Ryan, van Eerten+ 2019 (ArXiv 1909.11691)
Thinking through the model features: Shaping a light curve through jet structure

**NEW** closure relations:

\[ g = (\theta_V - \theta) \frac{d \log E}{d\theta} \approx \frac{1}{4} \frac{\theta_V^2}{\theta_C^2} \text{ (Gaussian Jet)} \]

\[ t^{3(1-2p+g)/(8+g)} \]

GW170817A
\[ \alpha = 0.9 \]
\[ \implies g = 8.2 \]
\[ \implies \theta_V \approx 6\theta_c \]

Ryan, van Eerten+ 2019 (ArXiv 1909.11691)
New open questions: prompt GRB, structure & photospheric radius

A fireball containing Baryons would also have electrons providing opacity that tends to imply optically thin prompt emission only natural near the jet tip:

GRB 170817 would have been typical if seen on-axis, but was atypical off-axis?

\[ R_d \sim \Gamma^2 c \delta t \sim 3 \cdot 10^{13} \delta t^{-1} \Gamma^2 \text{ cm for the dissipation radius} \]

\[ R_\gamma \sim \sigma_T E_{iso} / 4\pi R^2 m_p c^2 \Gamma, \text{ from } \tau = \sigma_T n R \equiv 1 \text{ and } \Gamma = E_{iso} / M c^2 = E_{iso} / n m_p V \]

for the photospheric radius

Where did the gamma rays for GRB 170817A really come from?
Line of sight? Reprocessed emission originating from closer to the jet axis?

*see also discussions in Matsumoto, Nakar & Piran 2019, Shoemaker & Murase 2018 etc.*
New open questions: different paths to structured jets

Hajela+ 2019, ArXiv 1909.06393
A *boosted* fireball, not a cocoon / jet emergence model

Ryan+ 2019, ArXiv 1909.11691
General Gaussian structured jet
New open questions: so what about $p$?

GRB 170817A : $p = 2.17$ tight constraint

- Not reasonable to interpret measurement as some mid-point between relativistic and non-relativistic given larger $p$ sample.

- But BIG question remains: why DOESN’T $p$ evolve for 170817A? How can different GRBs pick a different $p$ value and stick with it even when evolving over all these scales?
Electron cooling, Inverse Compton cooling, etc.

spectra around 150 days, `typical' GRB parameters, `typical' off-axis view

Extended absence of cooling break does not appear to be big issue for off-axis view case
Summary

GRB field has been progressing steadily separate of 170817...
- random example: prompt emission data analysis under ongoing refinement (are spectra too sharp?)
- random example: better understanding break-out & cocoons phases
- random example: better and more constraints on (large) initial Lorentz factors
- random example: an emerging continuum of ejecta kinetic energies GRB<->SN
- (simulation-based) template fitting is maturing (using mapping of synchrotron templates)

GRB 170817A was nevertheless a game-changer that cannot be ignored
- First multi-messenger joint Bayesian data analysis (focus on jet orientation to observer)
- A forced recalibration of jet models: lateral jet structure inescapable
- Simulation-based fitting has responded: structured jets, boosted fireballs...
- semi-analytical models structured jets now available, including updated ‘closure-relations’
- 170817 prompt gamma-rays remain puzzling: from cocoon breakout? reprocessed jet emission?
- An extremely clear but puzzling view of electron shock-acceleration (ie $p$ is and stayed 2.17)

By now numerous papers have been published on 170817A, and this presentation only carved a narrow and biased path through this vast and growing landscape....