Spectral Puzzle of the Off-Axis Gamma-Ray Burst in GW170817

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KI & Nakamura 18, 19
GW170817

1st GW from NS$^2$

NS$^2$ = Short GRB?

~100 sec chirp ⇒ NS-NS

R-process elements

Equation of state

Pacynski 86, Goodman 86
Eichler, Livio, Piran & Schramm 89

>40yr-old Hypothesis

Lattimer & Schramm 74

Relativity, Cosmology, …
GW170817 & sGRB 170817A

3 (of 12) GBM NaI detectors
$T_0=1.74\pm0.05$ sec (68%)
$T_{90}=2.0\pm0.5$ sec

But very weak

$$E_{iso} = 5 \times 10^{46} \text{ erg}$$
KI & Nakamura 18, 19
see also
Meszaros+ 98,
Abbott+ 17, Granot+ 17,
Lamb & Kobayashi 18,
Kasliwal+ 17,
Murguia-Berthier+ 17

Jet-ISM shock
Jet-ISM shock

Ejecta-ISM shock

Jet
\(\Gamma \sim 100\)

Cocoon
\(v \sim 0.2 - 0.4c\)

Merger ejecta
\(v \sim 0.03 - 0.2c\)
(dynamical/shock/wind)

\(\Delta \theta\)

\(\theta_v\)

\(\Gamma^{-1}\)

\(\sim 1\) day opt. macronova

\(\sim 10\) day IR macronova

\(\sim 10\) day IR flare

\(\sim \) months\(\sim \) weeks

X/Radio afterglow

Off-axis sGRB

\(\sim \) sec

\(\sim \) sec

\(\sim \) years

\(\sim \) years
Superluminal Motion

\[ v_{app} \approx 4.1 \pm 0.5 \, c \]

Unresolved

\[ R < 0.2 \text{pc}(1 \text{mas}), \quad < 2 \text{pc}(10 \text{mas}) \]

Not consistent with a spherical source

\[ \Gamma \approx 4 \text{ at } t \approx t_{peak} \]

Mooley+ 18, Ghirlanda+ 19

VLBI sky position
**Off-Axis Jet**

![Graph showing the relationship between viewing angle and isotropic energy]

- $\theta_v \sim \Delta \theta$
- $\Rightarrow$ *Point is bad*
- $E_{\text{iso}} \propto \theta_v^{-6}$
- $E_{\text{iso}} \propto \theta_v^{-4}$

**References:**
- KI & Nakamura 18, 01
- Yamazaki, KI & Nakamura 02, 03, 04
- LVC-GBM-INTEGRAL 17
- Granot+ 17, Kasliwal+ 17
$E_{\text{peak}} - E_{\text{iso}}$ (Amati) Relation

$E_{\text{iso}} \propto \theta_v^{-4}, E_{\text{peak}} \propto \theta_v^{-2}$

for $\theta_v \sim \Delta \theta$

Off-axis to on-axis

$E_{\text{iso}} \sim E_{\text{peak}}^2$

$E_{\text{peak}}^{\text{on}} > 10\text{MeV}??$

inconsistent with the known GRBs

Amati 02, Yonetoku+ 04, Tsutsui+ 13

GRB 170817A
Compactness Problem

$\tau_{\gamma} < 1$

Inferred jet

GRB 170817A

Viewing angle $\theta$ [rad]

Lorentz factor $\Gamma$

Viewing angle $\theta$ [deg]

Matsumoto+ 19

Limit B
Limit C
$\Gamma \theta = 1$
Slowly Rising Afterglow

Slowly rising up to \( \sim 150 \text{d} \)

Inconsistent w/ top-hat jet

Most likely structured jet

\[
S_v \propto t^{0.8}
\]

\( \times (\text{Troja}+, \text{Margutti}+, \text{Ruan}+, \ldots) \) & \( \text{Opt (Lyman}+, \ldots) \) also rise

Mooley+ 17
Structured Jet

Different authors give different structures.

But generally, $E(\theta=0) \gg E(\theta=\theta_v) \rightarrow \text{Exponential}$
Off-Axis Emission

\[ \Gamma = \frac{2000}{1 + (\theta / \theta_c)^{3.8}} \]
\[ \theta_c = 0.059 = 3.4^\circ \]

Off-axis emission dominates line-of-sight emission

Power-law dominates exponential
Surface Brightness

Surface brightness of a structured jet [erg/sr]

\[
E_{\gamma,\text{iso}} = \int \frac{d\Omega}{4\pi} \frac{E_\gamma(\theta)}{\Gamma^4(1 - \beta \cos \theta_\Delta)^3}
\]

\[
\cos \theta_\Delta = \sin \theta \cos \phi \sin \theta_v + \cos \theta \cos \theta_v
\]

Most emission comes from OFF-CENTER neither the jet core & nor line-of-sight
Jet Structure + Beaming

Decaying $E$ + Rising beaming = Peak in off-center

$E_\gamma = \int \frac{d(cos \theta)}{2} \epsilon_\gamma E(\theta) \cdot B(\theta)$

$B(\theta) = \int \frac{d\phi}{2\pi} \frac{1}{\Gamma^4(1 - \beta \cos \theta \Delta)^3}$

KI & Nakamura 19  Polar angle $\theta$ [deg] of the jet
**E_{\text{peak}} - E_{\text{iso}} (Amati) Relation**

Off-center ≠ Jet core

May violate the spectral relation

Predict outliers in a big sample

No compactness problem

Amati relation for sGRBs

KI & Nakamura 19
Future Prospects

Bright GRB for small $\theta_v$

P~20, 5% for $\theta_v<20, 10^\circ$

Caveat: The outer jet is NOT constrained by afterglows

$\Gamma = 2000/[1 + (\theta/\theta_c)^{3.8}]$

$\theta_c = 0.059 = 3.4^\circ$

Isotropic $E_{\gamma,iso}(\theta)$ [erg]

Viewing angle $\theta_v$ of the jet

KI & Nakamura 19
Summary

• **sGRB 170817A: an off-axis jet**
• Spectral puzzle (Amati, Compactness)
• **Off-center**, neither jet core nor line-of-sight
• Baryon-loaded jet or cocoon fast tail
• Predict bright GRB following GWs & outliers of Amati relation
Thank You
Observable Region

Structured jet

Observed angle $\sim 1/\Gamma$
Observable Region

Structured jet

Observed angle $\sim \frac{1}{\Gamma}$
Observable Region

Structured jet

Observed angle $\sim 1/\Gamma$
Observable Region

Structured jet

Observed angle $\sim 1/\Gamma$
Scattered sGRB

Thompson scattering by cocoon

Copy spectrum w/ ~MeV cutoff

\( r_{sc} < 10^{10} - 10^{12} \text{ cm} \)
Formulation

\[ F_{\nu} \approx \frac{1}{d^2} \int r^2 dr \sin \theta \, d\theta \, d\phi \, j_{\nu}, \]

\[ j_{\nu} = \frac{j_{\nu}'}{\Gamma^2 (1 - \beta \cos \theta_{\Delta})^2}, \quad \nu' = \frac{\nu'}{\Gamma (1 - \beta \cos \theta_{\Delta})}, \]

\[ \cos \theta_{\Delta} = \sin \theta \cos \phi \sin \theta_{\nu} + \cos \theta \cos \theta_{\nu}. \]

\[ j_{\nu}' = \frac{1}{(4\pi)^2 r^2} E_{\gamma}'(\theta) f(\nu', \theta) \delta[r - r_0(\theta)] \delta[t - t_0(\theta)], \]

\[ E_{\gamma,iso} = \int dT \int dv \, 4\pi d^2 F_{\nu} \]

\[ = \frac{1}{4\pi} \int \sin \theta \, d\theta \, d\phi \, \frac{E_{\gamma}(\theta)}{\Gamma^4 (1 - \beta \cos \theta_{\Delta})^3} \]

\[ e_{\gamma}E(\theta) = E_{\gamma}(\theta) = \Gamma E_{\gamma}'(\theta), \quad t = T + \frac{r}{c} \cos \theta_{\Delta}. \]
Viewing Angle Probability

\[ h_+ \propto \frac{1}{2} (1 + \cos^2 i) \]

\[ h_x \propto \cos i \]

On-axis GW is strong

\( i \sim 30^\circ \) is probable

GW170817: \( i < 30^\circ \)

Schutz 11
Lamb & Kobayashi 17
Turnovers in Afterglows

Afterglow theory predicts $F_v \sim t^{-p} v^{-(p-1)/2}$ for a jet as observed ($p \sim 2.2$)
YITP Long-term Workshop

Search by “multi-messenger Kyoto”

YITP long-term workshop
Multi-Messenger Astrophysics in the Gravitational Wave Era
September 24 - October 25 2019,
Yukawa Institute for Theoretical Physics, Kyoto University

YKIS 2019
7-11 Oct.
5 days symposium