THE MAXIMUM ISOTROPIC ENERGY OF GAMMA-RAY BURSTS

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GRB jets

• GRBs are extremely efficient lighthouses!
  • The most luminous GRBs are visible up to $z \geq 8$.
  • However, GRBs require very special conditions:
    • Highly relativistic outflows: $\Gamma \sim 100 \rightarrow$ Doppler boost
    • Beamed outflows $\rightarrow$ The jet energy is radiated in a small solid angle
    • Radio calorimetry & afterglow jet breaks constrain the energy of the jet: $E_{\text{jet}} \leq 10^{51}$ erg
The isotropic equivalent energy $E_{\text{iso}}$

- Lacking information on the jet beaming for most GRBs, we cannot compute the energy radiated by the jet during the prompt emission, instead we compute the \textit{isotropic equivalent energy} $E_{\text{iso}}$.

- $E_{\text{iso}}$ is the energy released during the prompt phase assuming isotropic emission. $E_{\text{iso}}$ is a proxy for the \textit{energy radiated in our direction}. This is our imperfect view to GRB energetics!

- The true energy radiated in $\gamma$-rays is $E_{\text{rad}} = E_{\text{iso}}/f_b$

  $$f_b = 4\pi/\Omega \approx 10^2-10^3$$

*\textit{We study the bright end of the $E_{\text{iso}}$ distribution}*
Calculating $E_{\text{iso}}$

- $E_{\text{iso}}$ is computed according to the formulae:

$$E_{\text{iso}} = \frac{4 \pi D_l^2 S_{\text{bol}}}{1 + z}$$

$$S_{\text{bol}} = S_\gamma \frac{\int_{1/1+z}^{10^4} E N(E) dE}{\int_{E_{\text{min}}}^{E_{\text{max}}} E N(E) dE}$$

- $S_\gamma$ is the fluence measured in the detector energy range, from $E_{\text{min}}$ to $E_{\text{max}}$.

- $N(E)$ describes the shape of the spectrum.

- $E_{\text{iso}}$ is computed in the range $[1-10^4]$ keV in source frame.

! = -0.6

$E_p = 720$ keV
The sample

• To compute $E_{\text{iso}}$, we need GRBs with redshifts and reliable spectral parameters:
  • Spectra from Fermi/GBM (Gruber et al. 2014, von Kienlin et al. 2014) & Wind/Konus (Tsvetkova et al. 2017)
  • Redshifts from optical follow-up of Swift GRBs

• 95 GRBs with redshift $1 \leq z \leq 5$
  • 69 GRBs detected by Wind/Konus (K):
    • Sample threshold: $P_f \geq 3.5 \, \text{ph.cm}^{-2}.\text{s}^{-1}$ in [50-200] keV
    • $P_{\text{med}} = 7.3 \, \text{ph.cm}^{-2}.\text{s}^{-1} - z_{\text{med}} = 1.77$
  • 52 GRBs detected by Fermi/GBM (G):
    • Sample threshold: $P_f \geq 1.05 \, \text{ph.cm}^{-2}.\text{s}^{-1}$ in [50-300] keV
    • $P_{\text{med}} = 5.4 \, \text{ph.cm}^{-2}.\text{s} - z_{\text{med}} = 1.85$
  • 26 events in common
Sampled volume
Konus vs GBM $E_{\text{iso}}$
The observed $E_{\text{iso}}$ distribution

- $E_{\text{iso}}$ is in the range $[2 \times 10^{52} – 4 \times 10^{54}]$ erg
The observed $E_{iso}$ distribution

- $E_{iso}$ is in the range $[2 \times 10^{52} - 4 \times 10^{54}]$ erg
Correcting the Eiso distribution

1. For every GRB in our reference volume (1 ≤ z ≤ 5), we compute its horizon \( z_{\text{max}} \), the redshift at which its peak flux becomes fainter than the sample limiting peak flux.

2. Assuming a GRB world model, we compute \( N_{z_{\text{max}}} \), the number of GRBs in the volume 1 ≤ z ≤ \( z_{\text{max}} \) and \( N_5 \), the number of GRBs in the volume 1 ≤ z ≤ 5.

\[ w = \frac{N_5}{N_{z_{\text{max}}}} \]

\( w \) is the weight of this GRB, used to correct the Eiso distribution. If \( z_{\text{max}} \geq 5 \), \( w = 1 \).
The corrected $E_{iso}$ distribution

- The correction does not change the bright end of the distribution (as expected).
- The correction is stronger for Konus, which is less sensitive, with a closer horizon.
- GBM detects GRBs with $E_{iso} \geq 10^{53}$ erg up to $z \geq 5$. 

![Graph showing the corrected $E_{iso}$ distribution]
Existence of a cutoff $E_{\text{iso}}$

- We compare the data with various GRB models having different redshift distributions (SFR plus density or luminosity evolution).

**We find that an energy cutoff around $E_{\text{iso}} = 3 \times 10^{54}$ erg is required at the level of 99.9%, for all models.**


- This energy cutoff must not be confused with the break of the luminosity function found by various authors in the range $10^{51} – 10^{52}$ erg.
Interpretation?

• There is no straightforward interpretation because the $E_{\text{iso}}$ limit could be associated with the activity of the central engine (energy reservoir and energy extraction), with the beaming of the jet, or with the energy dissipation or radiation processes in the jet.

• Moreover, an upper limit on $E_{\text{iso}}$ does not indicate a limit on the energy of GRB jets: the most energetic GRBs may not have the largest $E_{\text{iso}}$.
  • The geometry of the jet may change.
  • The energy may be radiated outside the keV/MeV energy range.
  • The energy may be emitted outside the electromagnetic spectrum.
  • ...
Conclusions and perspectives

• The GRB isotropic energy shows a cutoff above $E_{\text{iso}} \approx 3 \times 10^{54}$ erg, and there is no indication of a class of very energetic GRBs (e.g. Cenko et al. 2011).

• Energetic GRBs are rare, our study is based on 8 years of observation with Fermi/GBM and 22 years with Wind/Konus.
  • We estimate the rate of GRBs with $E_{\text{iso}} \geq 2 \times 10^{54}$ to be $\sim 5$ yr$^{-1}$.
  • Most of them have no redshift!
  • Swift, Fermi and Wind are planned to operate for several more years.
  • In 2022+ SVOM will contribute 😊

• The $E_{\text{iso}}$ limit may be associated with the activity of the central engine or with the physics of the jet.

• If we find a way to identify GRBs close to $E_{\text{iso}}$ limit, we’ll have very luminous standard candles, visible to $z \geq 10$!
Two additional GRBs

**GRB 180914B:**

$z = 1.096$

(GCN 23246)

$E_{\text{iso}} \approx 3 \times 10^{54} \text{ erg}$

(GCN 23240 and GCN 23246).

**GRB 190530A:**

$z \leq 2.2$

(GCN 24715)

$E_{\text{iso}} \leq 6 \times 10^{54} \text{ erg}$

(GCN 23240).
The most energetic GRBs

• Our sample contains 8 energetic GRBs with $E_{\text{iso}} \geq 2.3 \times 10^{54}$ erg (arbitrary limit):
  • 080916C, 090323, 120624B, 160625B ➔ K+G (and Fermi/LAT)
  • 090902B, 140206A ➔ G only (and Fermi/LAT)
  • 130505A, 130907A ➔ K only

• These energetic GRBs are not special
  • $z = 4.35, 3.60, 2.20, 1.41, 1.82, 2.73, 2.27, 1.24$

• Outside our redshift range, we found one energetic GRB:
  • GRB 110918A at $z=0.984$, with $E_{\text{iso}} = 2.3 \times 10^{54}$ erg detected by Konus
  • We found no energetic GRB beyond $z=5$, despite 1500 Gpc$^3$ in $5<z\leq10$

• We estimate the rate of energetic GRBs to be $\sim 5/\text{yr}/\text{sky}$.