Gamma-ray bursts
and
their emission mechanisms

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What are gamma-ray bursts (GRBs)?

Prompt MeV emission (most intense phase, \( \sim 10 \) s duration)
- How is it produced?
- How can it be modeled?
- Fitting models to data: what can we learn?

Afterglow emission (multiwavelength; duration up to several months)
- GeV (+optical+TeV) flashes
Discovery

- Vela satellites (USA)
- 1967: extraterrestrial flash of gamma-rays lasting a few seconds
- First publication: Klebesadel et al. (1973)

Cosmological origin

  - X-ray afterglows
    => accurate positions
    => optical follow-up
    => redshifts (first GRB 970508, z>0.83)
    => cosmological origin

⇒ Huge energy budget

(Meegan et al. 1992)
Fermi Gamma-ray Space Telescope (formerly GLAST)

- Launched on 11 June 2008
- Instruments:
  - Gamma-ray burst monitor (GBM): 8 keV - 40 MeV, FOV: entire unocculted sky
  - Large area telescope (LAT): 20 MeV - 300 GeV, FOV: 20% of the sky
Light curves

**Prompt**
- Duration \(~10\) seconds
- Highly variable
- Apparent energy release \(10^{51} \text{ to } 10^{55}\) erg
- Spectrum single-peaked, maximum near 1 MeV

**Afterglow**
- Duration days to months
- Relatively smooth, usually monotonic light curve
- Energy \(~10\)% of prompt
- Emission from radio to GeV gamma-rays

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**GRB 130427A**

Perley et al. 2014
Light curves

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Perley et al. 2014

GRB 130427A

![Light curve graph]

$E^2 N_e$ (erg cm$^{-2}$ s$^{-1}$)

Photon Energy (MeV)

Flux (Jy)

Time from GBM trigger (d)
Evidence for relativistic motion

Pair production optical depth in a stationary source:

\[ \tau_{\gamma\gamma} \approx 0.2 \sigma_T n_\gamma R \approx 10^{11} \left( \frac{L_{\text{rad}}}{10^{52} \text{erg/s}} \right) \left( \frac{\delta t}{1 \text{s}} \right)^{-1} \]

\[ R \leq c \, \delta t = 3 \times 10^{10} \frac{\delta t}{1 \text{s}} \text{ cm} \]

\[ n_\gamma = \frac{u_{\text{rad}}}{\epsilon_\gamma} = \frac{L_{\text{rad}}}{4\pi c R^2 \epsilon_\gamma} \]

\[ \epsilon_\gamma = 1 \text{ MeV} \quad (\text{observed}) \]

Stationary source would be highly opaque to gamma-rays

\[ \Rightarrow \text{relativistic motion (} \Gamma \geq 100) : \]

- Contracts observed \( \delta t \)
- Decreases comoving density
Birth of a compact object (neutron star or a black hole)
- stellar collapse (long GRBs)
- NS-NS or NS-BH merger (short GRBs)

Hyperaccretion (~ $1M_\odot$/sec) + angular momentum \(\Rightarrow\) pair of collimated jets

Relativistic jet
- burrows through the star \(r \approx 10^{11}\) cm
- accelerates to \(\Gamma = 100 - 1000\)
- expands to transparency (Thomson photosphere at \(r \approx 10^{13}\) cm)
- generates a collimated beam of gamma rays via *internal* dissipation (prompt MeV emission)
- shocks the ambient medium \(\Rightarrow\) multiwavelength afterglow; \(r \geq 10^{16}\) cm
GRB prompt emission

Radiative process/mechanism?

How/where is it generated?
GRB prompt emission: optically thin vs. thick

- Main model classes:
  - Synchrotron shock models
  - Photospheric models

Central engine

L \sim 10^{50} \text{ erg/s}

Jet

Photosphere

\tau_T = 1

\tau_T \gg 1

Heating

Internal shocks

Rad. process: synchrotron

Rad. process: inverse Compton

\Gamma_f

\Gamma_s

\tau_T \ll 1
Peak widths and position

Axelsson & Borgonovo (2015)

Goldstein et al. (2012)
Low-energy slope

Optically thin + radiatively efficient
\[ \Rightarrow \alpha < -\frac{3}{2} \] (synch. or IC)

Preece et al. (2000)
How to generate narrowly peaked spectra?
Photospheric emission

- **Spectral peaks**
  - Narrow: *can* be as narrow as Planck
  - Position
    - Natural scale
    - Observed
      \[ \overline{E}_{ph} \approx 5 - 10 \text{ MeV} \]
      \[ \overline{E}_{pk} \approx 500 \text{ keV} \]
      \[ \implies \text{photon production} \]

- **Non-thermal shape**

Extended (volume) dissipation
Beloborodov, Stern, Svensson (2000)
**Dissipative jets**

- Jets could be dissipative throughout their expansion
  - Recollimation shocks
  - Internal shocks
  - Magnetic reconnection

- Emerging radiation knows about expansion history

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Morsony, Lazzati, Begelman (2007)
Spectral formation in a heated jet

PH. GENERATION
THERMAL SPECTRUM
DIS \rightarrow S \rightarrow I \rightarrow P \rightarrow A \rightarrow T \rightarrow I

R \sim 10^{12} \text{ cm}
\tau_T \sim 10^2

Photosphere
\tau_T = 1

\tau = \frac{1}{2} \text{ PH. GENERATION}

3kT_e \rightarrow h\nu

\nu F_\nu

E_{pk} \rightarrow h\nu

\nu F_\nu

\text{Photon Energy (eV)}

10^{-1} \rightarrow 10^0 \rightarrow 10^1 \rightarrow 10^2 \rightarrow 10^3
Radiative transfer

\[ \frac{1}{r^2 \Gamma} \frac{\partial}{\partial \ln r} \left[(1 + \mu) r^2 \Gamma I_\nu\right] = \frac{r}{\Gamma} (j_\nu - \kappa_\nu I_\nu) \]
\[ + (1 + \mu)(1 - g\mu) \frac{\partial I_\nu}{\partial \ln \nu} - \frac{\partial}{\partial \mu} \left[(1 - \mu^2)(1 + \mu) g I_\nu\right] \]

- **Intensity** \( I_\nu \)
- **Photon angle** \( \mu \)
- **Acceleration parameter** \( g = 1 - \frac{d \ln \Gamma}{d \ln r} \)

Processes: Compton, synchrotron, pair-production/annihilation

**Acceleration:**
\[ \frac{d \Gamma}{dr} = \sigma_T Z \pm \frac{4\pi I_1}{m_p c^3} \]
Spectral formation

- Initial spectrum: Wien
- Peak shifted to lower energies due to photon production
- Broadening starts near Wien radius, proceeds through the photosphere
- Final spectrum: Band

![Graph showing spectra at different stages of expansion](image.png)

- Heating-cooling balance
- $\tau_T \gg 1$

\[ r_{\text{min}} - r_{\text{Wien}} \]

\[ e_{\pm} \text{ pairs} \]

\[ \log(E/L_E) \]

\[ \log(E) \text{ [MeV]} \]
\[ L_{\text{jet}} = 10^{52} \text{ erg s}^{-1} \]
\[ = 300 \]
\[ B = 0.01 \]
\[ \frac{dL_{\text{heat}}}{d\ln R} = \text{const} \]
‘Fits’ to data: GRB 990123

- Simulation parameters:
  - Initial $\Gamma(r_{\text{min}}) = 80$; $r_{\text{min}} = 3 \times 10^{10} \text{ cm}$
  - Final Lorentz factor $\Gamma_f = 590$
  - $\varepsilon_B = 0.02$

![Spectrum (cosmological rest frame)](image)

Fit: Band (Briggs et al. 1999)

$\alpha = -0.6$; $\beta = -3.11$

$E_{pk} = 720(1+z) \text{ keV}; z = 1.6$
Simulation parameters:

- Initial $\Gamma(r_{\text{min}}) = 100$; $r_{\text{min}} = 3 \times 10^{10}$ cm
- Final Lorentz factor $\Gamma_f = 340$
- $\varepsilon_B = 0.1$
- Heating at $\tau < 1$, passive at $\tau > 1$

Phenomenological fit: Band (Golenetskii et al. 2013)

- $\alpha = -0.96$; $\beta = -4.17$
- $E_{pk} = 1.028(1+z)$ MeV; $z = 0.34$
GRB 090902B

- Simulation parameters:
  - Initial $\Gamma(r_{\text{min}}) = 70$; $r_{\text{min}} = 3 \times 10^{10}$ cm
  - Final Lorentz factor $\Gamma_f = 1200$
  - $\varepsilon_B = 0.01$
  - Strong non-thermal heating

Phenomenological fit: Band + power-law (Abdo et al. 2009)
\[ \alpha = 0.07; \beta = -3.9; \Gamma_{\text{pl}} = -1.94 \]
\[ E_{\text{pk}} = 908(1+z) \text{ keV}; z = 1.8 \]
GRB prompt emission: summary

- Dissipative jets
  - Non-thermal narrowly peaked spectra
  - Different heating histories result in a variety of spectral shapes
  - Allows reconstruction of jet properties/expansion history
    with a physical model
(Very) early afterglow: GeV/TeV - optical flashes
Observations: LAT lightcurves

- ‘Regular’ behaviour:
  - Delayed rise
  - Peaks during the prompt: likely not associated with blast wave deceleration
  - Extended monotonic decay (lasts well beyond prompt duration)
- External origin (forward shock)?

Flux above 100 MeV
Emission mechanism

- **Synchrotron?**
  - Theoretical limit: a few $10 \text{ MeV}$ (comoving)
    $$\Rightarrow \sim 10 \text{ GeV} \text{ (observed)}$$
  - Observed: $95 \text{ GeV} @ 243 \text{ s}$, $32 \text{ GeV} @ 34 \text{ ks}$ (GRB 130427A)
  - Kumar & Barniol Duran (2009)
  - Asano et al. (2009)
  - Razzaque et al. (2010)
  - Ghisellini (2010)
  - E.g. Nakar & Piran (2010)

- **Inverse Compton**
  - Bosnjak et al. 2009
  - Toma et al. 2011
  - GeV peak during prompt $\Rightarrow$ intense IC cooling by prompt radiation
Proposed mechanism: inverse Compton scattering of prompt MeV radiation in the forward shock in a pair-enriched external medium

Prompt radiation pair-loads and pre-accelerates the ambient medium ahead of the forward shock (Beloborodov 2002)

Shock heated (*not* accelerated) pairs upscatter prompt MeV photons to GeV

- Can be modeled from first principles
- Relies only on well understood physics
Flash peaks when:

- Early decay due to fast evolution of $\gamma_{\text{inj}}$ and $Z_{\pm}$

$\gamma_{\text{inj}} \approx \sqrt{\frac{E_{\text{GeV}}}{E_{\text{MeV}}}} \approx 30$

$Z_{\pm} \approx 10^4$ - pair loading
Light curve

- Delayed rise
- Peak during the prompt
- persists well after prompt ends

External medium:
Progenitor wind

\[ \dot{M} = 10^{-5} M_{\text{Sun}} / \text{yr} \]

Wind parameter

\[ A = \frac{r^2}{2.5 \times 10^{11} \text{ g cm}^{-1}} \]

Beloborodov, Hascoet, IV (2013)

Non-thermal particle acceleration NOT required
4 adjustable parameters

\[ A = r^2 \]

<table>
<thead>
<tr>
<th>GRB</th>
<th>( E_{\text{GRB}} ) (10^{54} \text{ erg} )</th>
<th>( T_{\text{GRB}} ) [s]</th>
<th>( T_p / T_{\text{GRB}} )</th>
<th>( z ) (^d)</th>
<th>( \Lambda^e ) (10^{11} \text{ g/cm} )</th>
<th>( \Gamma_{\text{ej}}^f )</th>
<th>( \epsilon_{\text{rad}}^g )</th>
<th>( \epsilon_B^h )</th>
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<td>0.8</td>
<td>( 10^{-3} \leftrightarrow 2 \times 10^{-4} )</td>
</tr>
</tbody>
</table>

Hascoet, IV, Beloborodov (2013)
Hascoet, IV, Beloborodov (2013)
GeV+optical flash: GRB 130427A

- GeV-emitting particles also radiate optical via synchrotron
  - Optical peaks simultaneously with GeV (Vestrand et al. 2014)
  - Forward shock magnetization: $\varepsilon_B = \text{a few } \times 10^{-4}$
GeV+optical flash: GRB 120711A

Entire complex optical light curve reproduced by 4-parameter model
TeV flash

- Intrinsic TeV fluence can rival GeV (even MeV)
- Timescale – minutes
- Accessible to current TeV observatories (e.g. Veritas, MAGIC)
TeV detection

Detector threshold ~50-100 GeV

Attenuation at z=1:
- 0.5 @ 0.1 TeV
- 0.005 @ 0.3 TeV

Narrow window around 0.1 TeV for detection

Domínguez et al. (2011)
GeV (+optical) flashes: summary

- Forward shock in a pair-loaded Wolf-Rayet wind
- Radiative mechanism:
  - GeV/TeV: inverse Compton
  - optical: synchrotron
- Emitting particles quasi-thermal – no dependence on poorly understood physical processes
- Yields $\Gamma$ and external medium density (+ shock magnetization if optical flash observed)