GRB Prompt Emission Physics

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Outline of the Talk:

- GRBs: brief historical overview, prompt GRB obs.
- Theoretical framework, prompt emission processes
- Acceleration & Dissipation: Fireball vs. Magnetic
- Magnetic acceleration: steady vs. impulsive, effect of external medium & multiple sub-shells
- GRB lightcurves from magnetic reconnection
- Reconnection + acceleration through K-S instability
- Prompt GRB spectrum: a phenomenological model
GRBs: Brief Historical Overview

- **1967**: 1st detection of a GRB (published in 1973)
- In the early years there were many theories, most of which invoked a Galactic (neutron star) origin
- **1991**: the launch of CGRO with BATSE lead to significant progress in our understanding of GRBs
  - Isotropic dist. on sky: favors a cosmological origin
  - Bimodal duration distribution: short vs. long GRBs
- **BeppoSAX** (1996–2002): led to afterglow discovery (1997) in X-rays, optical, radio (for long GRBs)
This led to **redshift** measurements: clear determination of distance/energy scale (long GRBs) $E_{\gamma,\text{iso}} \sim 10^{52} - 10^{54}$ erg

Afterglow observations provided information on **beaming** (narrow jets: $E_{\gamma} \sim 10^{51}$ erg), event rate, external density, supernova connection ($\Rightarrow$ long GRB progenitors)

**Swift** (2004-?): autonomously localizes GRBs, slews (in $\sim 1-2$ min) and observes in X-ray + optical/UV

Discovered unexpected behavior of early afterglow: rapid decay phase, plateaus, flares, chromatic breaks

Led to the discovery of **afterglow** from short GRBs $\Rightarrow$ **host galaxies**, redshifts, energy, rate, clues for progenitors

**Fermi** (2008-?): high-energy emission – delayed onset, long lived emission, distinct high-energy component*, high $\Gamma_{\text{min}}$, short GRBs show smaller delay + harder spectrum
Prompt GRB Observations ($\lesssim$ MeV)

- Variable light curve
- Duration: $\sim 10^{-2} - 10^3$ sec
- Spectrum: non-thermal $\nu F_{\nu}$ peaks at $\sim 0.1-1$ MeV (well fit by a Band function*)
- Rapid variability, non thermal spectrum & $z \sim 1$ $\Rightarrow$ relativistic source ($\Gamma \gtrsim 100$) (compactness problem: Schmidt 1978; Fenimore et al. 1993; Woods & Loeb 1995;…)

*Note: Band function is a mathematical function used to fit the spectrum of GRBs.
GRB Theoretical Framework:

- **Progenitors:**
  - Long: massive stars
  - Short: binary merger?

- **Acceleration:**
  fireball or magnetic?

- **Prompt \( \gamma \)-rays:**
  Dissipation: internal shocks or magnetic reconnection? Emission mechanism?

- **Deceleration:** the outflow decelerates (by a reverse shock for \( \sigma \lesssim 1 \)) as it sweeps-up the external medium

- **Afterglow:** from the long lived forward shock going into the external medium; as the shock decelerates the typical frequency decreases: X-ray \( \rightarrow \) optical \( \rightarrow \) radio
Candidate Prompt Emission Processes

- **Leptonic:**
  - Synchrotron (optically thin: $\alpha \leq -2/3$; fast cooling: $\alpha \leq -3/2$)
  - Jitter (similar to synchrotron but from tangled B-field; $\alpha \leq 0$)
  - Inverse-Compton or Synchrotron-Self Compton (HE?)
  - Photospheric (not always BB, $-1 \leq \alpha \leq 1$; also from high-$\sigma$)

- **Hadronic** processes: photopair production $(p + \gamma \rightarrow p + e^+e^-)$, proton synchrotron, pion production interaction or $p$-$p$ collisions
  - The neutral pions decay into high energy photons $\pi^0 \rightarrow \gamma\gamma$ that can pair produce with lower energy photons producing a pair cascade

- **Still unclear** – we are largely guided by observations
  - composition $\Rightarrow$ acceleration $\Rightarrow$ dissipation $\Rightarrow$ emission

$\frac{dN}{dE} \propto E^\alpha$ below $E_{\text{peak}}$ (Kaneko et al. 2008)
**Theory: Fireball vs. Poynting Flux**

*Meszaros & Rees 92, Katz 94, Sari & Piran 95
† Shemi & Piran 90, Goodman 86, Paczynski 86,…
†† Thompson 94, Usov 94, Meszaros & Rees 97, Katz 97,…

**Prompt GRB**
- Internal Shocks
  - Particle acceleration
  - $\Rightarrow$ synchrotron $\gamma$-rays (?)
- Reconnection (or other EM instability)

**Afterglow**
- Optical
- Radio
- X-rays
- Ejecta
- Reverse shock
  - Forward Shock (Rees & Meszaros 92)
- Magnetic bubble

Magnetic bubble

Lyutikov & Blandford 02,03
Outflow Acceleration & Dissipation:

- **Fireball**: thermal acceleration (by radiation pressure)
  - Fast (\( \Gamma \propto R \)), robust, allows efficient internal dissipation
  - Baryon kinetic energy eventually dominates
  - Requires a small baryon loading (\( \sim 10^{-5} M_\odot \))
  - Naturally produces internal shocks (dissipate \( \leq 10\% \) of energy)
  - \( n-p \) collisions in a neutron rich outflow

- **Magnetic** acceleration: Poynting flux dominated jets
  - Steady, axisymmetric, ideal-MHD: slow, not robust or efficient
  - Can naturally produce a small baryon loading
  - Gradual dissipation (of alternating fields or instability induced) can enhance the acceleration & contribute to the radiation
  - Strong time dependence: enhances acceleration & dissipation
  - Fast **reconnection** can accelerate particles, produce relativistic turbulence, spikes in lightcurve & high radiative efficiencies
Composition: Fireball vs. Poynting flux

- **Fireball**: $E_{\text{thermal}} \rightarrow E_{\text{kinetic}} \rightarrow E_{\text{thermal}} + E_{\text{radiation}}$
  
  (thermal acceleration; dissipation in internal shocks)

- Relatively well studied

- **Poynting flux** dominated outflows:
  - If no B-field reversal: $E_{\text{magnetic}} \rightarrow E_{\text{kinetic}} \rightarrow E_{\text{thermal}} + E_{\text{radiation}}$
    
    (steady + impulsive magnetic acceleration; internal shocks)
  
  - Field reversals/striped wind: $E_{\text{magnetic}} \rightarrow E_{\text{kinetic}} + E_{\text{thermal}} + E_{\text{radiation}}$
    
    (magnetic reconnection + acceleration)

- Generally less studied
The “σ-problem”: for a “standard” steady ideal MHD axisymmetric flow

- In spherical flows $\Gamma_\infty \sim \sigma_0^{1/3}$ & $\sigma_\infty \sim \sigma_0^{2/3} \gg 1$ ($\sigma_0 = B_0^2 / 4\pi \rho_0 c^2$) but PWN obs. imply $\sigma \ll 1$ after the wind termination shock

- In PWN the solution is dissipation of the striped wind

- However, this doesn’t work well in relativistic jet sources, where a broadly similar $\sigma$ problem persists

- Jet collimation helps, but not enough: $\Gamma_\infty \sim \sigma_0^{1/3} \theta_{jet}^{-2/3}$, $\sigma_\infty \sim (\sigma_0 \theta_{jet})^{2/3}$ & $\Gamma \theta_{jet} \lesssim \sigma^{1/2}$ ($\sim 1$ for $\Gamma_\infty \sim \Gamma_{max} \sim \sigma_0$)

- Still $\sigma_\infty \geq 1 \Rightarrow$ inefficient internal shocks, $\Gamma_\infty \theta_{jet} \gg 1$ in GRBs

- Sudden drop in external pressure can give $\Gamma_\infty \theta_{jet} \gg 1$ but still $\sigma_\infty \geq 1$ (Tchekhovskoy et al. 2009) $\Rightarrow$ inefficient internal socks
Alternatives to the “standard” picture

- **Axisymmetry:** non-axisymmetric instabilities (e.g. the current-driven kink instability) can tangle-up the magnetic field & lead to significant dissipation (Begelman; Spruit; Eichler; Lyubarsky; Giannios;…)

  - If $\langle B_r^2 \rangle = \alpha \langle B_\phi^2 \rangle = \beta \langle B_z^2 \rangle$; $\alpha, \beta =$ const then the magnetic field behaves as an ultra-relativistic gas: $p_{\text{mag}} \propto V^{-4/3}$

  $\Rightarrow$ magnetic acceleration as efficient as thermal

- **Ideal MHD:** a tangled magnetic field can reconnect (Drenkham 2002; Drenkham & Spruit 2002)

  - magnetic energy $\Rightarrow$ heat (+radiation) $\Rightarrow$ kinetic energy

- **Steady-state:** effects of strong time dependence (JG, Komissarov & Spitkovsky 2011; JG 2012a, 2012b)
Impulsive Magnetic Acceleration: $\Gamma \propto R^{1/3}$

Useful case study:

Initial value of magnetization parameter:

\[ \sigma_0 = \frac{B_0^2}{4\pi\rho_0 c^2} \gg 1 \]

1. $\langle \Gamma \rangle_E \approx \sigma_0^{1/3}$ by $R_0 \sim \Delta_0$
2. $\langle \Gamma \rangle_E \propto R^{1/3}$ between $R_0 \sim \Delta_0$ & $R_c \sim \sigma_0^2 R_0$ and then $\langle \Gamma \rangle_E \approx \sigma_0$
3. At $R > R_c$ the shell spreads as $\Delta \propto R$ & $\sigma \sim R_c/R$ rapidly drops

Complete conversion of magnetic to kinetic energy!

This allows efficient dissipation by shocks at large radii
Our test case problem has no central engine: it may be, e.g., directly applicable for giant flares in SGRs; however:

In most astrophysical relativistic (jet) sources (GRBs, AGN, \(\mu\)-quasars) the variability timescale (\(t_v \approx R_0/c\)) is long enough (>\(R_{\text{ms}}/c\)) that steady acceleration operates & saturates (at \(R_s\)).

Then the impulsive acceleration kicks in & leads to \(\sigma < 1\).
Impulsive Magnetic Acceleration: single shell propagating in an external medium
acceleration & deceleration are tightly coupled (JG 2012)

I. Un-Magnetized “thin shell”, low-σ: strong reverse shock, peaks at \( \gg T_{\text{GRB}} \)

II. Magnetized “thick shell”, high-σ: weak or no reverse shock, \( T_{\text{dec}} \sim T_{\text{GRB}} \)

III. like II, but the flow becomes independent of \( \sigma_0 \)

IV. a Newtonian flow (if \( \rho_{\text{ext}} \) is very high, e.g. inside a star)

\[ \rho_{\text{ext}} = AR^{-k} \]

\[ R_{\text{cr}} \sim R_0\Gamma_{\text{cr}}^2 \sim \left( \frac{ER_0}{Ac^2} \right)^{\frac{1}{4-k}} \]

\[ \Gamma \sim (L/Ac^3)^{1/4}R^{(k-3)/4}, \Gamma \sim (\sigma_0 R/R_0)^{1/3}, \Gamma \sim \sigma_0 \]

\( \sigma_0 > \Gamma_{\text{cr}} \)

\( \sigma_0 = \Gamma_{\text{cr}} \)

\( \sigma_0 < \Gamma_{\text{cr}} \)

\( R_{\text{c}}, R_{\text{u}}, R_{\Gamma} \)

\( R_0, R_{\text{cr}}, R_{\text{NR}} \)

\( \log(\Gamma), \log(R) \)

vary \( \sigma_0 \)
For a long lived variable source (e.g. AGN), each sub shell can expand by $1 + \Delta_{\text{gap}}/\Delta_0 \Rightarrow \sigma_\infty = (E_{\text{total}}/E_{\text{EM,}\infty} - 1)^{-1} \sim \Delta_0/\Delta_{\text{gap}}$

For a finite # of sub-shells the merged shell can still expand

Sub-shells in GRBs can lead to a low-magnetization thick shell & enable the outflow to reach higher Lorentz factors

$\sigma < 1$ shocks: magnetic energy $\rightarrow$ kinetic $\rightarrow$ thermal (+radiation)

$\sigma \gg 1$ shocks: magnetic $\rightarrow$ thermal $\rightarrow$ kinetic (Komissarov 2012)
GRB Lightcurves from Magnetic Reconnection (Beniamini & JG 2015; JG 2016)

- Field reversals at the source can lead to reconnection at large distances:
  millisecond-magnetar $\Rightarrow$ millisecond quasi-periodic variability ($\times$)
  accreting BH $\Rightarrow$ stochastic field-reversal & lightcurve variability ($\checkmark$)

- Reconnection far from the source has a natural preferred direction

- For large ingoing $\sigma$ reconnection leads to local relativistic outward bulk motion at $\Gamma' \sim \text{ few–several} \Rightarrow \text{anisotropic emission}$ in jet’s bulk frame

- Larger $\sigma \Rightarrow$ higher $\Gamma'$, larger rec. rate ($v_{\text{in}}/v_A$), harder particle spectrum
Model for GRB Lightcurves (Beniamini & JG 2015)

- Emission from thin locally quasi-spherical reconnection layers / shells
- Each shell moves at $\Gamma \gg 1$ & produces one pulse in the GRB lightcurve
- The emitting plasma moves in two opposite directions in the jet’s bulk frame along the initial $B$ direction (assumed uniform in visible region)
- Emission is either continuous (steady in the jet’s frame), or blob-like
- Emitted spectrum: either a power-law or a Band function
- $\Gamma^2 \propto R^{-m}$, Luminosity $L$ evolves with $R$ as a power-law or log-normal
Model for GRB Lightcurves (Beniamini & JG 2015)

- Pulse width: $\Delta t \approx \Delta t_r + \Delta t_\theta$ & the angular time is reduced by a factor of $\Gamma'$, to $\Delta t_\theta \approx R/2\Gamma^2\Gamma'$
- $\Rightarrow$ Fast variability is possible, limited by $\Delta t_r$
- For isotropic emission pulses tend to be asymmetric: $\Lambda = T_{\text{rise}} / T_{\text{decay}} < 1$
- While a fast rise & slower decay is typically observed, some pulses as rather symmetric

$\Gamma' = 3, 4, 5, 7, 10, 20$
The Shape of Pulses in the Lightcurves

log-normal, $\sigma_{\text{lnR}}=0.01$

log-normal, $\sigma_{\text{lnR}}=0.1$

log-normal, $\sigma_{\text{lnR}}=1$

Power law, $R_f=1.01R_0$

Power law, $R_f=1.1R_0$

Power law, $R_f=2R_0$

$m = a = 0, k = 1$
The Shape of Pulses in the Lightcurves

\[ \Lambda_{50} = \frac{T_{\text{rise},50}}{T_{\text{decay},50}} \]

(\( \Lambda_{50} = 1 \) for symmetric pulses)

\[ \log_{10}(\Lambda_{50}) \]

\[ m = 0 \quad (\Gamma = \text{const}) \]
\[ k = 1 \quad ("\text{steady state" in jet’s bulk frame}) \]
Some Other Pulse Properties

- An isotropic emission can explain the “rapid decay phase” at the end of the GRB prompt emission, or X-ray pulses that decay faster than expected for isotropic emission (“high-latitude” emission), thanks to the shorter angular time $\Delta t_0 \approx R/2\Gamma^2\Gamma'$

- Spectral evolution of pulses:
  - Hard to soft for ($\Gamma' < 2$)
  - intensity tracking ($\Gamma' > 2$)

\[
m = a = 0, \quad k = 1, \quad \Delta R = R_0, \quad \alpha = -1, \quad \beta = -2.3
\]
The Magnetized analog of the Rayleigh-Taylor instability

Hot plasma accumulates in the reconnection layer, and can prevent further reconnection

The heavier hot plasma is unstable in the effective gravity due to the outflow’s acceleration & it drips out of the layer

⇒ enhances reconnection rate ⇒ increases the acceleration & effective gravity ⇒ creates a positive feedback loop
Kruskal–Schwarzchild Instability:
(Gill, JG & Lyubarsky 2017)

Density snapshots

Initial results of 2D RMHD simulations
Some GRBs have correlated prompt optical + γ-ray emission.

Spectrum well fit by phenomenological 3-component model.

Optical–γ-ray lightcurves correlated ⇒ same emission region.
GRB Spectrum: Phenomenological Model
(Guiriec, Kouveliotou, Hartmann, JG, Asano, Meszaros, Gill, Gehrels & McEnery 2016)

- $C_{Th}$: likely photospheric; $\alpha \approx 0.6$ slightly softer than thermal ($\alpha = 1$ where $dN/dE \propto E^\alpha$) perhaps sum over BB with $T(\theta)$.

- $C_{nTh1}$: partial correlation + slight delay w.r.t $C_{Th}$ is natural for internal shocks at larger radius, $R_{IS} > R_{ph}$; $\alpha \approx -0.7$ suggests synchrotron from quasi-thermal electron dist. ($10^{-3} < \sigma < 1$ strong shocks + suppressed DSA, or heating-cooling balance)

- $C_{nTh1}$: strong variability $\Rightarrow$ external shock uncorrelated w. $C_{Th}, C_{nTh1} \Rightarrow$ different region maybe reconnection at $\sigma > 1$ parts of outflow
Thank You