Leptonic-Hadronic Modeling of Extended High-Energy Emission from Fermi LAT GRBs

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Extended HE Emission from LAT GRBs

Bright LAT GRBs show significant high energy emission extending after the low energy emission disappear below detection threshold.

\begin{center}
\begin{tikzpicture}
\begin{axis}[
    width=\textwidth,
    xlabel={\(T - T_0\) [s]},
    ylabel={Flux \([\text{ph cm}^{-2} \text{s}^{-1}]\)},
    xmode=linear,
    ymode=linear,
    xmin=1e0,
    xmax=1e3,
    ymin=1e-3,
    ymax=1e2,
    ytick={1e-3, 1e-2, 1e-1, 1e0, 1e1, 1e2},
    yticklabels={\(10^{-3}\), \(10^{-2}\), \(10^{-1}\), \(10^{0}\), \(10^{1}\), \(10^{2}\)},
    xtick={1e0, 1e1, 1e2, 1e3},
    xticklabels={1, 10, 100, 1000},
    legend pos=north east,
    grid=both,
    grid style={line width=0.5pt, draw=gray!50},
    area style,
]

% Add your data points here
\end{axis}
\end{tikzpicture}
\end{center}

\begin{center}
\begin{tikzpicture}
\begin{axis}[
    width=\textwidth,
    xlabel={\(T - T_0\) [s]},
    ylabel={Photon Index},
    xmode=linear,
    ymode=linear,
    xmin=1e-3,
    xmax=1e3,
    ymin=-3.5,
    ymax=-1.5,
    ytick={-3.5, -3.0, -2.5, -2.0, -1.5},
    yticklabels={-3.5, -3.0, -2.5, -2.0, -1.5},
    xtick={1e-3, 1e0, 1e1, 1e2, 1e3},
    xticklabels={\(10^{-3}\), 1, 10, 100, 1000},
    legend pos=north east,
    grid=both,
    grid style={line width=0.5pt, draw=gray!50},
    area style,
]

% Add your data points here
\end{axis}
\end{tikzpicture}
\end{center}

090902B

\(t^{-1.5}\)
Extended Emission from GRB 090510

Multi-wavelength light curves in γ ray, x ray and UV
Smooth power-law evolution of the fluxes are compatible with afterglow model

De Pasquale et al. 2009
Adiabatic blast wave decelerating in uniform density medium

Blandford-McKee 1976

- Relationship between $t$, $\Gamma$ and $R$:
  \[ R = 2\Gamma^2ac t(1+z)^{-1} \]

- Deceleration time:
  \[ t_{\text{dec}} \approx 1.9(1+z)(E_{55}/n)^{1/3}\Gamma^{-8/3} \text{s} \]
  \[ a = 1 \text{ for coasting} \]
  \[ a = 4 \text{ after decel.} \]

Total KE in blast wave = swept-up material

- Bulk Lorentz factor:
  \[ \Gamma \approx 763(1+z)^{3/8}(E_{55}/n)^{1/8}t_s^{-3/8} \]

- Blast wave radius:
  \[ R \approx 1.4 \times 10^{17}(1+z)^{-1/4}(E_{55}/n)^{1/4}t_s^{1/4} \text{ cm} \]

- Energy injection rate in the forward shock:
  \[ e_{\text{shock}} = 4\pi n m_p c^2 \Gamma^2 \]

- Magnetic field in the FS:
  \[ B' \approx 300(1+z)^{3/8}\varepsilon_B^{1/2}(E_{55}n^3)^{1/8}t_s^{-3/8} \text{ G} \]
Leptonic-Hadronic Synchrotron Model

Both electrons and ions are accelerated in the Forward shock

- Total isotropic-equivalent jet energy: $E_{k,\text{iso}} > E_{\gamma,\text{iso}} \approx 10^{53}$ erg
- Constant density surrounding medium: $n_{\text{ISM}} \approx 1$ cm$^{-3}$
- Jet deceleration time scale: $t_{\text{dec}} \leq 1$ s and $\Gamma_0 \geq 1000$

- Crucial parameters: $\varepsilon_B$, $\eta_A$, $\eta_e$, $k$ and $k_2$ are fitted from data
- Fraction of jet energy: $\varepsilon_A$ and $\varepsilon_e$ are calculated from required spectra
GRB Afterglow - Synchrotron Spectra

**Fast cooling**: $\nu_m > \nu_c$

$F_\nu \propto \nu^{-\beta} t^{-\alpha}$  closure relations

$\nu_c < \nu < \nu_m : F_\nu \propto \nu^{-1/2} t^{-1/4}$

$\nu > \nu_m > \nu_c : F_\nu \propto \nu^{-p/2} t^{-(3/4)(p-2/3)}$

$p$-particle spectral index: $\frac{dN}{dE} \propto E^{-p}$

**Slow cooling**: $\nu_c > \nu_m$

$F_\nu \propto \nu^{-\beta} t^{-\alpha}$  closure relations

$\nu_m < \nu < \nu_c : F_\nu \propto \nu^{-(p-1)/2} t^{-(3/4)(p-1)}$

$\nu > \nu_c > \nu_m : F_\nu \propto \nu^{-p/2} t^{-(3/4)(p-2/3)}$

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*Sari, Piran & Narayan 1998*
Modeling GRB 090510 Data

Use closure relations $F_\nu \propto \nu^{-\beta} t^{-\alpha}$ to determine $\beta$ and $k$ or $k_2$

Note: $e$-synchrotron model alone cannot satisfy the closure relations

- XRT light curve: $t^{-0.74 \pm 0.03}$ in between $\sim 100$ s and 1.4 ks
  - Model with $e$-synchrotron in the fast-cooling and for $\nu_{\text{XRT}} > \nu_{\text{m,e}} > \nu_{\text{c,e}}$
  - $k = (4/3)\alpha_{\text{XRT}} + 2/3 = 1.65 \pm 0.04$ ; $\beta_{\text{XRT}} = k/2 = 0.83 \pm 0.02$

- LAT light curve: $t^{-1.38 \pm 0.07}$ in between $\sim 0.3$ s and 100 s
  - Model with $p$-synchrotron in the slow-cooling and for $\nu_{\text{m,p}} < \nu_{\text{LAT}} < \nu_{\text{c,p}}$
  - $k_2 = (4/3)\alpha_{\gamma} + 1 = 2.84 \pm 0.09$ ; $\beta_{\gamma} = (k_2 - 1)/2 = 0.92 \pm 0.05$
  - $\beta_{\gamma}$ needs to be compatible with measured LAT photon index (and it is)

- Parameters such as $n_{\text{ISM}}$ and $\Gamma_0$ are mainly constrained by $t_{\text{dec}} \leq 0.3$ s
- Parameters such as $E_{k,\text{iso}}$, $\varepsilon_B$, $\eta_e$, $\eta_p$ are set to produce required fluxes
- Parameters $\varepsilon_e$, $\varepsilon_p$ are calculated from other parameters and constrained $< 1$
- UVOT light curve is constrained by XRT ($e$-synchrotron)
- BAT light curve can not be fitted $\Rightarrow$ continued central engine activity
Leptonic-Hadronic Synchrotron Spectra

Protons and electrons

- $p$ is always slow-cooling
- $e$ shifts from fast- to slow- cooling in $2 \times 10^6$ s

$p$ - synchrotron

$(k_2 = 2.84) \quad \nu F_\nu \propto \begin{cases} \nu^{4/3} ; \nu < \nu_{m,p} \\ \nu^{0.08} ; \nu \geq \nu_{m,p} \end{cases}$

$e$ - synchrotron

$(k = 1.65) \quad \nu F_\nu \propto \begin{cases} \nu^{4/3} ; \nu < \nu_{c,e} \\ \nu^{1/2} ; \nu_{m,e} > \nu \geq \nu_{c,e} \\ \nu^{0.18} ; \nu \geq \nu_{m,e} \end{cases}$

LAT emission is dominated by $p$-synchrotron with photon spectrum $\propto \nu^{-1.92}$

Compatible with data

$E_k = 10^{55.3}$ erg
$n = 3 \text{ cm}^{-3}$
$\epsilon_p = 0.3$
$\epsilon_e = 10^{-4}$
$\epsilon_p = 0.5$

LAT emission is dominated by $p$-synchrotron with photon spectrum $\propto \nu^{-1.92}$

Compatible with data

GRB 2010, Annapolis
S. Razzaque
8/14
Light Curves from Afterglow Modeling

Multiwavelength light curves from combined leptonic-hadronic modelling

Solid lines: \( p \)-synchrotron, Dashed lines: \( e \)-synchrotron

\[
\begin{align*}
E_{k,\text{iso}} &= 2 \times 10^{55} \text{ erg} \\
n &= 3 \text{ cm}^{-3} \\
\Gamma_0 &= 2400 \\
\varepsilon_B &= 0.3 \\
\varepsilon_p &= 0.5 \\
\varepsilon_e &= 10^{-4} \\
\eta_e &= 20(m_e/m_p) \\
\eta_p &= 5000 \\
k &= 1.65 \pm 0.04 \\
k_2 &= 2.84 \pm 0.09
\end{align*}
\]
Absolute GRB Energy

Ratio of gamma-ray to kinetic energy
Too low efficiency?

Not in supernova remnants!

Collimation-corrected energy from jet-break time

$$t_{\text{jet}} \approx 10^5 (1+z) (E_{55}/n)^{1/3} \theta_{-1}^{8/3} \text{ s}$$

Jet-break time during the Earth Occultation: 1.4 ks < $t_{\text{jet}}$ < 5.1 ks

⇒ Jet opening angle: 1 degree < $\theta_{\text{jet}}$ < 1.5 degree

⇒ Absolute jet energy: (3-7)×10^{51} erg

Is there an absolute maximum? 10^{53} erg ⇒ $\theta_{\text{jet}}$ ∼ 6 degree

$E_{\gamma,\text{iso}} \sim 10^{53}$ erg
$E_{\gamma,\text{iso}}/E_{k,\text{iso}} \sim 0.01$

Sari, Piran & Halpern 1999

Dale Frail
LAT Light Curve of GRB 090902B

\[
z = 1.82
\]

Deceleration time

\[
t_{\text{dec}} \approx 1.9(1 + z)(E_{55}/n)^{1/3} \Gamma_3^{-8/3} \text{ s}
\]

Fitting parameters

\[
E_{k,\text{iso}} = 2 \times 10^{56} \text{ erg} ; n = 20 \text{ cm}^{-3}
\]
\[
\Gamma_0 = 900 ; \varepsilon_B = 0.3 ; \varepsilon_p \sim 0.5
\]
\[
\eta_p \sim 2 \times 10^4 ; k_2 \sim 3
\]

\[
E_{\gamma,\text{iso}} \sim 4 \times 10^{54} \text{ erg}
\]
\[
E_{\gamma,\text{iso}} / E_{k,\text{iso}} \sim 0.02
\]

Total energy constraint

\[
E_k \leq 10^{53} \text{ erg}
\]
\[
\theta_{\text{jet}} \leq 2 \text{ degree}
\]

Within 1-10 deg.
Other Processes in the Blast Wave

Opacities for $\gamma\gamma$ pair production and photopion production for maximum energy particles

$\rightarrow$ synchrotron photons are targets for $\gamma\gamma$ and $p\gamma$

$\rightarrow$ maximum $e$-sync. photon $\sim$100 GeV

$\rightarrow$ maximum $p$-sync. photon $>1$ TeV

$\rightarrow$ $\gamma\gamma$ pair production can only be marginally important

Ground-based detectors can probe $p$-synch model
Detectability of $>100$ GeV Gamma Rays

Extragalactic Background Light (EBL) limits distance of the source

GRBs up to $z \sim 0.5$ can be detected at $\leq 200$ GeV

See Joel Primack’s talk
Conclusions

- Detection of GRB 090510 is an extraordinary event
  - Multiwavelength contemporaneous data for the first time from Fermi GBM and LAT, Swift BAT, XRT and UVOT
  - Most energetic short GRB: $10^{53}$ erg compared to typical $10^{49}-10^{51}$ erg

- Emission is complex, involving multiple components
  - Simple afterglow model with electron-synchrotron radiation fails to reproduce multi-wavelength light curves
  - Delay in high-energy, $>100$ MeV, emission with different temporal decay than in other wavelength suggest a different origin

- I have presented a leptonic-hadronic afterglow model
  - $p$-synchrotron radiation explains high-energy emission
  - $e$-synchrotron radiation explains XRT and UVOT (part) light curves

Multi-wavelength data from more GRBs and detection by ground-based detectors will either provide evidence or constrain $p$-synchrotron radiation model
Detection of GRB 090510

- **Fermi GBM and LAT observations**
  - Trigger on 2009 May 10 at 00:22:59 UT
  - Fluence of the burst: \((T_0 + 0.5 - T_0 + 1.0)\) s
    - \(5 \times 10^{-5}\) erg cm\(^{-2}\) (10 keV - 30 GeV); \(4 \times 10^{-7}\) erg cm\(^{-2}\) (15 keV - 150 GeV)

- **Swift BAT observations**
  - Trigger on 2009 May 10 at 00:23:00 UT
  - \((RA, DEC) = (333.55^\circ, -26.58^\circ)\)
  - Duration: \(T_{90} = 0.3 \pm 1\) s
  - Fluence of the burst: \((T_0 + 0 - T_0 + 0.4)\) s
    - \(4 \times 10^{-7}\) erg cm\(^{-2}\) (15 keV - 150 GeV)

- **Spectroscopic redshift (3.5 days) from VLT/FORS2**
  - \(0.903 \pm 0.003\)
  - \(10^{53}\) erg isotropic-equivalent gamma-ray energy release!
  - Most luminous short GRB detected to-date!!
GBM and LAT Light Curves

Photon arrival info.

- GBM triggered on a weak precursor
- Main GBM emission starts at \( \sim T_0 + 0.5 \) sec
- >100 MeV emission starts at \( \sim T_0 + 0.65 \) s
- >1 GeV emission starts at \( \sim T_0 + 0.7 \) s
- 31 GeV photon at \( \sim T_0 + 0.83 \) s
- Highest from a SGRB
- Extended HE emission
Spectroscopy of GRB 090510

PL component in addition to phenomenological Band Spectrum

$E_{\text{max}} = 3.43 \text{ GeV}$

$E_{\text{max}} = 30.5 \text{ GeV}$
UHECR Signature in GRB Emission

UHECR acceleration in magnetic field and interactions may provide γ ray signature from GRBs, specially in Fermi LAT

- Synchrotron radiation and associated $e^+e^-$ cascade radiation
- Photohadronic interactions with observed keV - MeV γ rays and cascade emission

**GRB 080916C**

- Very high jet bulk Lorentz factor reduces photohadronic cooling
  - Could work in other bright GBM bursts
  - A γ cutoff in HE spectrum would be an indication
- Synchrotron cooling is dominant in high B field

Razzaque, Dermer, Finke & Atoyan, arXiv:0811.1160
Particle acceleration in the forward shock $B$ field

Cooling is dominated by synchrotron radiation in the same $B$ field

- Fast cooling $\gamma_m > \gamma_c$ or $\nu_m > \nu_c$
- All break frequencies evolve with time as the $B$ field (and $\Gamma$) does
Synchrotron Radiation from GRB Jets

- Particle acceleration in the forward shock $B$ field
- Cooling is dominated by synchrotron radiation in the same $B$ field

Injection spectrum

- $dN/d\gamma$
- $\gamma_m$, $\gamma_c$, $\gamma_{sat}$
- $t^{-\delta}$
- $\gamma^{-p}$, $\gamma^{-p-1}$

Cooled spectrum

- $t_{syn} = t_{dyn}$
- $t_{syn} = t_{acc}$

Synchrotron spectrum (slow cooling)

- $F_v$
- $\nu^{1/3}$, $\nu^{-(p-1)/2}$
- $t^{-\lambda}$, $t^{-\eta}$

Minimum LF

Cooling LF

Saturation LF

- Fast cooling $\gamma_m > \gamma_c$ or $\nu_m > \nu_c$; Slow cooling $\gamma_m < \gamma_c$ or $\nu_m < \nu_c$
- All break frequencies evolve with time as the $B$ field (and $\Gamma$) does