Theoretical Models for High Energy Radiation from Gamma Ray Bursts

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GLAST Science Working Group/GRB Workshop
September 12, 2002

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• High Energy/ X-ray Observations

• Source Models: Implications for High Energy Radiation
  Supranova/External Shock Model for both prompt gamma rays and afterglow

• External Shock Model: Predictions and Explanations of Narrow $E_{pk}$
distribution observed with BATSE

• High-Energy Radiation Signatures
GRB 940217

⇒ Nonthermal processes

Origin of hard radiation?
1. Synchrotron
2. SSC
3. External Compton Scattering
4. Hadronic Emission (proton synchrotron/photomeson/secondary nuclear production)
Other evidence for high-energy radiation:

Seven GRBs detected with EGRET either during prompt sub-MeV burst emission or after sub-MeV emission has decayed away (Dingus et al. 1998)

Average spectrum of 4 GRBs detected over 200 s time interval from start of BATSE emission with photon index 1.95 ($\pm 0.25$) ($> 30$ MeV)
Observations of TeV radiation with Milagrito (Atkins et al. 2002)
Requires low-redshift GRB to avoid attenuation by diffuse IR background
Transparency Arguments

In comoving frame, threshold condition for $\gamma\gamma$ interactions is

Requires low-redshift GRB to avoid attenuation by diffuse IR background

$$\varepsilon_1 \varepsilon_2' < 2 \Rightarrow \delta < 30(1 + z)\sqrt{E_1 \text{(MeV)} E_2 \text{(GeV)}}$$

$$\tau_{\gamma\gamma} \approx \frac{\sigma_T}{3} \left(\frac{2}{\varepsilon_1}\right) n_{ph}' \left(\frac{2}{\varepsilon_1}\right) r_b, r_b \leq \frac{c t_v \delta}{(1 + z)}$$

$$\delta > 200 \left[(1 + z) d_{28}\right]^{1/3} \left[ \frac{f_{-6} E_2 \text{(GeV)}}{t_v(s)} \right]^{1/6}$$
GRB 970508

Search for Fe K emission at $z = 0.835$ with Beppo-SAX 21-56 ks after GRB
Line at $E = 3.4(\pm 0.3)$ keV; $6.2(\pm 0.6)$ keV in rest frame) at 99.3% significance

Interpretation by Vietri et al. (1999) and Bottcher (2000) as dense torus emission
GRB 970828

36 ks ASCA observation beginning 1.17 days after GRB (Yoshida et al. 1999, 2001)

Emission line at $E \approx 5$ keV; if Fe K$\alpha$, then $z \approx 0.33$

$z = 0.9578$ from [OII] and [NeIII] lines (Djorgovskii et al. 2001)

Reinterpret as Fe recombination edge; absence of Fe K$\alpha$ requires highly nonequilibrium situation (Weth et al. 2000; Yonetoku et al. 2001)
GRB 000214

104 ks Beppo-SAX observation beginning 12 hours after GRB (Antonelli et al. 2000)

Emission line at $E \approx 4.7(\pm 0.2)$ keV; EW $\sim 2$ keV

$\Rightarrow z = 0.47$

Not easily reconciled with binary merger models or collapsar/hypernova models (insufficient mass from presupernova stellar wind)
GRB 991216

3.4 hr Chandra observation beginning 37 hours after GRB (Piro et al. 2000)

Emission line at $E \approx 3.49(\pm 0.06)$ keV with 4.7σ confidence

$\Rightarrow z = 1.00$ (H-like Fe) in agreement with $z = 1.02$ from absorption lines

Weak indication of Fe recombination edge at 4.60 keV

3σ evidence for recombination edge of H-like S at 1.72 keV, H-like S K\(\alpha\) line at 1.29 keV

In accord with supranova model (Vietri and Stella 1998) or decaying magnetar model (Rees and Meszaros 2000)
GRB 990705
Observation of absorption edge at \( \sim 3.8 \) keV during the prompt phase (Amati et al. 2000) in intervals A and B

Photoelectric absorption at Fe K-edge \( \Rightarrow z = 0.86 (\pm 0.17) \)

ESO Observations find \( z = 0.8435 (\pm 0.0005) \) (Andersen et al. 2002)
GRB 990705

Can be explained with strong Fe enhancements; large amount of Fe within 1 pc; strong clumping of ejecta

Probability of observing absorption in He-merger/collapsar model << 1%

Size scale of clumps \(\sim 10^{13} \text{ cm}\)

Density \(\sim 10^{10} \text{ cm}^{-3}\)

Probability of observing absorption in He-merger/collapsar model << 1%

Bottcher, Fryer and Dermer (2002)
GRB 011211

Long duration ($t_{\text{dur}} \approx 270$ s) GRB at $z = 2.140$ ($\pm 0.001$) $\Rightarrow$ apparent isotropic energy $= 6.3 \times 10^{52}$ ergs

$z_{\text{lines}} = 1.88$ ($\pm 0.06$) $\Rightarrow$ emission in outflowing moving with $\beta \approx 0.1$

Beaming break or constant energy reservoir result $\Rightarrow \theta_j \approx 3-7^\circ$

Claimed line detection of Ka transitions in Mg XI (or XII), Si XIV, SXVI, Ar XVIII, Ca XX

Strongest line at Si XIV $\Rightarrow \approx 10^{48}$ ergs in H-like Kα line

Requires very strong clumping of ejecta to make recombination proceed quickly

Reeves et al. (2002)
Source Models

- **Coalescing Compact Objects**
  - Binary neutron stars known in Galaxy (Hulse-Taylor pulsar)
  - Coalescence by gravitational radiation
  - Expect ~1 coalescence event per Myr per MW Galaxy (too few given beaming fraction)
  - Prompt collapse
  - Expected to be found in elliptical/non-star-forming galaxies
  - Possible candidate for short GRBs

(Eichler et al. 1989; Janka, Ruffert et al.)
- Hypernova/Collapsar Model (Woosley et al.; Paczynski; Meszaros and Rees)
  - Massive Star Collapse to Black Hole
  - Energy released at rotation axis: MHD energy production
  - Two orders of magnitude more energy available; no prediction (?) of constant energy reservoir
  - Requires active central engine
  - Available number of sources
  - No strong evidence for presupernova wind ($n \propto r^{-2}$)
  - Low density surroundings ($0.01 \lesssim n [\text{cm}^{-3}] \lesssim 10$)
Source Models

- **Supranova model** (Vietri and Stella 1999)
  - Two-step collapse to black hole
  - *Super-Chandresekhar* mass neutron star stabilized against prompt collapse by rotation
  - Supernova shell of enriched material
  - In dusty, star-forming regions (except for AIC events)
  - Standard energy reservoir (?)
  - Prompt collapse following long quiescence

*Supranova model more easily explains Iron absorption and fluorescence line observations*
Cartoon: The New Currently Popular GRB Model

- Collapse of NS to BH gives prompt explosion

Supernova Remnant Shell

Pulsar Wind Bubble

Supramassive Neutron Star
Highly Structured SN Remnant Ejecta

Cas A Supernova Remnant
Pulsar Wind Nebulae

Highly inhomogeneous surrounding medium

Crab (plerionic) nebulae
External Shock Model in Uniform Surroundings

Uniform Surrounding Medium

Relativistic (jetted) blast wave

GRB source

Observer
Nonthermal synchrotron radiation in shocked fluid
- Joint normalization to power and number gives
\[ \gamma_{\text{min}} \equiv e_e \left( \frac{p-2}{p-1} \right) \left( \frac{m_p}{m_e} \right) \Gamma ; \dot{E}'_e = e_e \left( dE'/dt' \right) \]

Magnetic field parametrized in terms of equipartition field
\[ \frac{B^2}{8\pi} \equiv 4e_B m_p c^2 n_* (\Gamma^2 - \Gamma) \Rightarrow B \propto \Gamma \]

Injection of power-law electrons downstream of forward shock
\[ \dot{N}(\gamma_e) = N_e \gamma_e^{-p} , \gamma_{\text{min}} < \gamma_e < \gamma_2 \ (\text{comoving } \gamma_e) \]
\[ N_e = 4\pi n_{\text{ext}} x^3 / 3 \]

Maximum injection energy: balancing losses and acceleration rate
\[ \gamma_2 \equiv 4 \times 10^7 / \sqrt{B(G)} \]

Cooling electron break: balance synchrotron loss time with adiabatic expansion time
\[ t'_\text{adi} \equiv x / \Gamma c \equiv \Gamma t \equiv t'_c \equiv \left( \frac{4}{3} c \sigma_T \frac{u_B}{m_e c^2} \gamma_c \right)^{-1} \]
\[ \Rightarrow \gamma_c \equiv \frac{3m_e}{16e_B n_* m_p c \sigma_T \Gamma^3 t} \Rightarrow \gamma_{\text{min}} \propto t^{-3/8} , \gamma_c \propto t^{1/8} \]
Transition from fast to slow cooling – if parameters $e_e, e_B, p$ stay constant

Comoving Nonthermal Electron Spectrum

$N_e(\gamma_e) \equiv N_e \gamma_o^{s-1} \gamma_e^{-s}, \gamma_0 < \gamma_e < \gamma_1$

$N_e(\gamma_e) \equiv N_e^o \gamma_o^{s-1} \gamma_1^{-s} (\gamma_e / \gamma_1)^{-(p+1)}, \gamma_1 < \gamma_e < \gamma_2$

Fast cooling

$s = 2$

$\gamma_0 = \gamma_c$

$\gamma_1 = \gamma_{\text{min}}$

Slow cooling

$s = p$

$\gamma_1 = \gamma_c$

$\gamma_0 = \gamma_{\text{min}}$

- $p > 2$
- SSC important when $e_B \ll e_e$
- Uniform (not wind) geometry

$\nu_i = \Gamma \gamma_i^2 eB / [2\pi m_e c (1 + z)]$
Numerical Simulation: Uniform Surrounding Medium

Two peaks in $\nu F_{\nu}$ distribution

Generic rise in intensity until $t_{\text{dec}}$ followed by constant or decreasing flux except in self-absorbed regime

Dominant SSC component for this parameter set

Chiang and Dermer (1999)
Most common prompt
GRB light curve

- Reproduces generic temporal behavior of FRED-type profiles
- Hardness-intensity correlation, hard to soft evolution

1. Near alignment at high energies; lag at lower energies
2. Predictable sequence of energy-dependent temporal indices in rising phase
3. Change in spectral indices between leading and trailing edges of GRB peak follow a well-defined behavior

Dermer, Bottcher, and Chiang (2000)
Numerical Simulation Model of GRB Radiation

- $\nu F_\nu$ spectra shown at observer times $10^i$ seconds after GRB event
- Primary radiation processes: nonthermal synchrotron and synchrotron self-Compton
Dirty and Clean Fireballs: strong GeV/TeV sources

Observed properties most sensitive to initial Lorentz factor of outflow (or baryon loading)

Severe instrumental selection biases against detecting fireballs with $\Gamma_0 << 100$ and $\Gamma_0 >> 1000$

X-Ray Flashes (or X-ray rich GRBs) = Dirty Fireballs

GeV Flashes = Clean Fireballs
No strong evidence for presupernova wind ($n \propto r^{-2}$).

Low density surroundings ($0.01 \lesssim n [\text{cm}^{-3}] \lesssim 10$).

$\phi_{pk}$

$E_{pk}$ Distribution

Explained

$\phi_{pk}$

$E$ (keV)

BATSE bandpass

Clean Fireballs

Dirty Fireballs (= X-ray flashes)
Cosmological Statistics of GRBs in the External Shock Model

- Assume that distribution of GRB progenitors follows star formation history of universe Trigger on 1024 ms timescale using BATSE trigger efficiencies (Fishman et al. 1994)
- Broad distributions of baryon-loading $\Gamma_0$ and directional energy releases are required. Assume power laws for these quantities.
  
  \[-10^{-6} < E_{54} < 1; \quad N(E_{54}) \propto E_{54}^{-1.52}; \quad \Gamma_0 < 260; \quad N(\Gamma_0) \propto \Gamma_0^{-0.25}\]

Unfortunately, rather few clean fireballs

Gamma Ray Light Curves

SSC component introduces a delayed hardening in **MeV** light curves several orders of magnitude below the flux of the prompt emission.

Onset of SSC hardening at MeV energies occurs at $t \approx 10^3$ s, GeV energies at $t \approx 5000$ s.

TeV component roughly coincident in time with prompt MeV radiation.

Can obtain larger ratio of TeV to MeV nF$_n$ flux for dirtier fireballs.

TeV emission also signature of UHECR acceleration.
Internal or External Shock Model?

1. Relativistic Wind: Large Variation of Lorentz Factors
2. Asymmetric profiles from kinematics

Colliding Shells Produces Generic Pulse Profile (Fenimore et al. 1996)

Synthetic Time Histories (Kobayashi and Sari 2001)
Short Timescale Variability due to inhomogeneities in surrounding medium

- Clouds with thick columns (>4 x 10^{18} \text{ cm}^{-2})
  - Total cloud mass still small (>10^{-4} \text{ M}_\odot)
- Varying cloud radii \ll R/\Gamma

Synthetic Time Histories (Dermer and Mitman 1999)

Cloud sizes \approx 10^{12} - 10^{13} \text{ cm}
in agreement with inferences of absorption in GRB 990705
Standard Simulation

Uniform random distribution
Cloud radius is $10^{13}$ cm (all clouds equal)
Variation in Shell Distance of Outer Edge of Shell

Same as previously but for log-linear

\[ \nu \]

\[ \beta \]

\[ \sigma \]

\[ \gamma \]

\[ \mathbf{F} \]

\[ t \ (\text{sec}) \]

\[ R_2 = 2 \times 10^{16} \]

\[ R_2 = 1 \times 10^{17} \]
Variation in $\Gamma_0$  
Background noise included

![Graph showing variation in $\Gamma_0$ with different values: $\Gamma_0 = 100$, $\Gamma_0 = 500$, and $\Gamma_0 = 300$. The graph includes a time axis (t (sec)) and a y-axis showing fluctuations from $1 \times 10^{-7}$ to $6 \times 10^{-7}$.](image-url)
GeV Gamma Ray Emission from Secondary Nuclear Production

Secondary nuclear production in dense shell surrounding
GRB: explanation for GRB 40217  (Katz 1994)

\[ p+p \rightarrow \pi^0 \rightarrow 2\gamma \]
(no subsequent acceleration required)

Blast Wave Shell Interaction

\[ t/(1+z) = t_* - \frac{r\mu}{c} \]

GRB source  Cloud  Observer

\[ x = r \cos\theta \]
External Compton Component

Requires strong background radiation field (as in blazars)

(Inoue et al. 2002)
**UHECRs from GRBs**  

Waxman (1995); Vietri (1995); Dermer (2002)

- **Typical fluence and rate of BATSE GRBs:**
  - \( F_\gamma \approx 10^{-6} \text{ ergs cm}^{-2} \); \( N_{\text{GRB}} \approx \text{1/day} \)

- **If weakest GRBs at } z \sim 1, \text{ then } d \equiv 10^{28} \text{ cm}
  - \( E_\gamma \approx 4\pi d^2 F_\gamma \approx 10^{51} \text{ ergs}; E_{\text{GRB}} \approx 10^{52} \text{ ergs} \)

- **UHECRs lose energy due to photomeson processes with CMB**
  - \( p + \gamma \rightarrow p + \pi^0, n + \pi^+ \)
  - **GZK Radius** \( x_{1/2} (10^{20} \text{ eV}) \equiv 140 \text{ Mpc} \)
    
    - **Energy density within GZK Radius:**
      - \( u_{\text{UHECR}} \equiv \zeta \varepsilon_{\text{GRB}} (x_{1/2}/c) \approx \zeta E_{\text{GRB}} (140 \text{ Mpc}/c) \)
      - \( \text{day} \times \frac{4\pi}{3} (10^{28} \text{ cm})^3 \)
      - \( \equiv \zeta 5 \times 10^{-22} \text{ ergs/cm}^3 \)
Energetic Hadron Component in GRB Blast Waves

Requires proton acceleration to high energies

Proton synchrotron component observed with GLAST

(Böttcher and Dermer 1999)
Proton Synchrotron Emission

Slow decay of proton emission
Photomeson Production

Intense neutrino, neutron, and ultra-high energy gamma-ray production

Atoyan and Dermer (2002) for blazars
Synchrotron and Compton Neutron-Decay Halos

- Neutrons formed through photomeson processes during cosmic ray acceleration escape from blast wave $n \rightarrow p + e^- + \nu_e$
- Decay of neutrons occurs at $\gamma \approx \gamma_n$
  - Produce nonthermal synchrotron radiation, depending on strength of halo magnetic field
  - Produce nonthermal $\gamma$ rays from Compton scattering of CMB
    - $\gamma$ rays materialize through $\gamma\gamma \rightarrow e^+e^-$
    - Form extended pair and gamma-ray halo
Summary

- **MeV Gamma Ray Observations**
  Well explained as nonthermal synchrotron radiation in relativistic fireball/blast wave model. GRB prompt and afterglow phenomenology explained by a single relativistic blast wave interacting with external medium.

- **Source Model:** External Shock/Supranova Model

- **High Energy $\gamma$-Radiation**
  SSC (definite predictions for FRED/smooth GRBs)
  Other components:
  - Secondary Nuclear Production
  - Proton synchrotron (slow decay)
  - External Compton
  - Photo-hadron (neutron-decay halos; neutrinos)